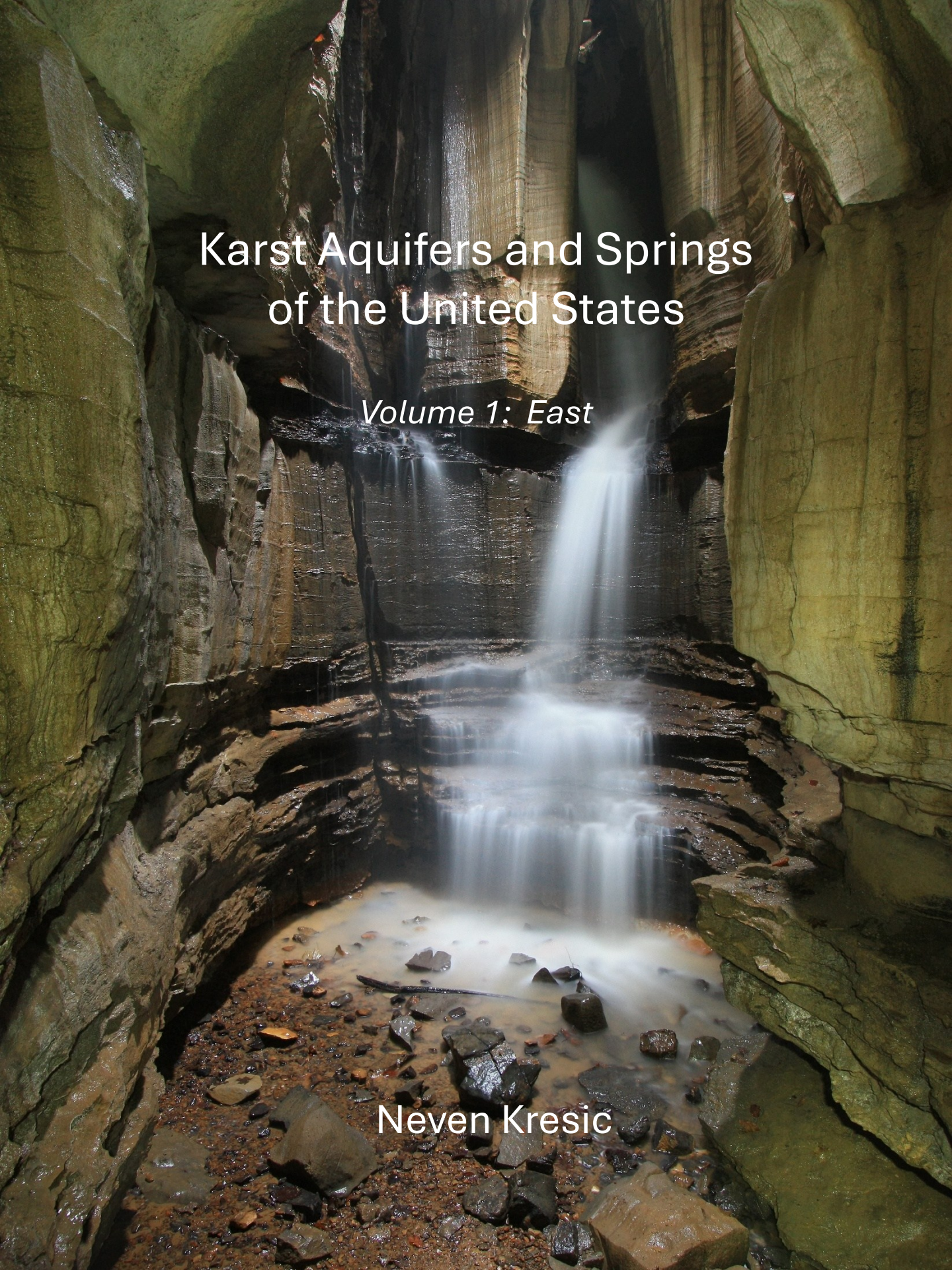


Karst Aquifers and Springs of the United States

Volume 1: East

Neven Kresic

Karst Aquifers and Springs of the United States

Volume 1: East

Neven Kresic



Karst Aquifers and Springs of the United States

Copyright notice: The content of this book is granted fair use for nonprofit educational and noncommercial uses provided the source (this book) and specific references to figures, photographs, and any parts of the book are fully acknowledged. Figures and photographs that are copyrighted, or otherwise not originally created by the author of the book, as noted in the captions, cannot be copied, or transmitted or shared in any form, digital, printed, optical, or otherwise, or utilized in any information storage and retrieval system without written permission from the copyright owners and authors of the individual figures and photographs as noted. The pdf file of the book is free for downloading from the web sites listed in the book and can be re-posted and shared by all educational, academic, and non-commercial, non-profit institutions, without any restrictions.

©2026 Groundwater Academy

ISBN: 979-8-9896285-3-7

Front cover: Grotto Cave, Marion County, Tennessee. Photo copyright Alan Cressler, all rights reserved. Used with permission.
Back cover: Gilchrist Blue Spring in Florida (top); and Maiden Spring in Virginia (bottom)—photo courtesy of Phill Lucas.

The author is grateful to the following for hosting the electronic (pdf) version of *Karst Aquifers and Springs of The United States* on their web sites for free download.



The Groundwater Academy provides free publications, quantitative tools, and interactive visualizations for environmental professionals and the general public. Through our collaborative and educational platform, we support the protection and sustainable management of groundwater resources and springs around the world. Visit us at www.groundwateracademy.org



MIKAS (Most Important Karst Aquifer Springs) is a project by the Karst Commission (KC) of the International Association of Hydrogeologists (IAH) aimed at creating the first list of the most important karst springs at both the global and national levels, representing the natural heritage of countries with karst.Visit us at https://mikasproject.org/



HydroGeoCenter specializes in providing training and expertise in hydrogeology, groundwater modeling, and groundwater remediation for industry, regulatory agencies, and academia. With our video courses, online and on-demand training, and consulting services, you can learn directly from the experts and take your skills to the next level. We can help you with consulting and groundwater modeling for the following: water supply; sustainable agriculture; contaminant fate and transport; groundwater remediation; hydraulic control in mining and construction. Visit us at www.hydrogeocenter.com



designAmerica Consulting, LLC provides quantitative consulting services for energy and environmental applications. Our projects are interdisciplinary and multi-media by nature, and our approach is collaborative while maintaining a focus on privacy. We aim to redefine consulting through outcomes-based approaches and interactive, digital deliverables. To facilitate this modeling, data visualization and analysis, we have created our own artificial-intelligence system, pbdot, which runs on Berget AI in Sweden. Visit us at www.pbdot.com

About The Author

Neven Kresic is an independent groundwater consultant with more than 40 years of experience focused on groundwater and surface water consulting, research, and teaching. He specializes in characterizing and analyzing complex groundwater systems for water supply and groundwater remediation projects and is an expert in the application of numerical models for designing remedial alternatives including simulation of contaminant fate and transport in groundwater. Over the course of his career, Dr. Kresic served in lead technical roles at major national and international engineering and environmental consulting companies based in the United States.

Dr. Kresic has worked on numerous projects for a variety of U.S. and international clients including federal, state, and local agencies; industries such as water, transportation, and power utilities; and oil, petrochemical, chemical, mining, and construction companies. He was Senior Fulbright Scholar at the United States Geological Survey in Reston, Virginia, and the George Washington University, Washington, D.C., where he conducted novel research on characterizing and modeling groundwater flow and contaminant fate and transport in fractured rock and karst aquifers. Prior to coming to the United States in 1991, Dr. Kresic was professor of groundwater dynamics at the University of Belgrade, former Yugoslavia.

Dr. Kresic taught academic courses and professional workshops in hydrogeology, groundwater resources, groundwater modeling, and groundwater remediation at universities, government agencies, and conferences around the World. He authored and co-authored numerous papers and eight books on the topic of groundwater. Dr. Kresic is a founding member of the Ground Water Modeling Interest Group sponsored by the National Ground Water Association, and former Co-chair of the Karst Commission of the International Association of Hydrogeologists. He is past Vice President for International Affairs of the American Institute of Hydrology and was committee member of the Groundwater Management and Remediation Specialty Group of the International Water Association, and Chair of the Board of Directors of Karst Waters Institute (KWI).

Through Groundwater Academy, Dr. Kresic and his collaborators support the protection and sustainable management of groundwater resources and springs around the world.

TABLE OF CONTENTS

Introduction 1

Chapter 1 Water in Karst 10

1.1 Karst and Karstification 10

1.1.1 Sinkholes 30

1.2 Types and Characteristics of Karst Springs 34

1.2.1 Spring vs. River Rise..... 48

1.3 Web Resources..... 57

Chapter 2 Karst Aquifers of the United States: The East..... 58

2.1 Floridan Aquifer 59

2.1.1 Biscayne Aquifer 67

2.2 Appalachian Plateaus, and Interior Low Plateaus Karst Aquifers..... 68

2.3 Valley and Ridge Karst Aquifers 76

2.4 New York, and New England Karst Aquifers 80

2.4.1 New York Karst Aquifers 80

2.4.2 New England Karst Aquifers 86

2.5 Castle Hayne Aquifer 94

Chapter 3 Important Karst Springs of the United States: The East..... 96

3.1 Florida..... 96

3.2 Georgia..... 152

3.3 Alabama..... 178

3.4 Tennessee..... 194

3.5 Indiana..... 219

3.6 Ohio..... 230

3.7 Kentucky..... 237

3.8 Virginia..... 256

3.9 West Virginia..... 301

3.10 Maryland..... 323

3.11 Pennsylvania..... 343

3.12 New Jersey and New York..... 386

References and Select Readings..... 398

Introduction

Groundwater in karst environments has long intrigued scientists and non-scientists alike due to its many fascinating facets. It feeds the world's largest springs, many of which enabled the establishment of the first urban centers in human history and continues to serve as a reliable source of water supply to the present day; it creates a mysterious and sometimes frightening underground world of caves (Fig. 1); it supports living creatures often unique to specific locations (Fig. 2); it behaves unpredictably as it can sometimes rise tens of feet after heavy rains in the matter of hours (Fig. 3) giving life to numerous temporary springs and increasing the flow of permanent springs 1000-fold.



Figure 1 Arrival of Charon on a boat from a cave believed to be an entrance to Hades, the Greek underworld. Illustration by Gustave Doré in the Pollard and Moss 1885 edition of Dante Alighieri's Inferno, Plate 9, Canto III—Charon.



Figure 2. Endangered and Federally protected Devil's Hole pupfish, one of the world's rarest fish. It lives only in one cave in Nevada, in the Ash Meadows National Wildlife Refuge which is under constant threat from mining interests. Photo by O. Feuebacher, U.S. Fish & Wildlife Service.

Using karst aquifers and springs for water supply was mastered by the Romans who preferred their water to any other source. In virtually all Mediterranean countries that were part of the Roman Empire, there are remains of numerous Roman aqueducts originating at karst springs, some of which are preserved in almost full glory (Fig. 4.)



Figure 3 Encounter with a summer storm in Bat River Cave, Minnesota Cave Preserve. *Upper left*: Cave passages were dry before the storm. *Upper right*: After sudden intense storm on August 18, 2007, a waterfall occurred where a dry ceiling existed before (4:03 pm); *Lower Left*: The water begins to rise and becomes turbulent (4:17 pm); *Lower right*: Seconds after this photo was taken it was almost impossible to stand in the passage without getting swept away (4:59 pm). The cavers escaped by the ladder extending from the newly drilled vertical shaft to the cave. Photographs courtesy of John Ackerman.



Figure 4 *Left*: Vrelo Jadar is a first magnitude karst spring (average discharge rate is 9.8 m^3/s or 346 cfs) utilized for the water supply of Split, the largest Dalmatian port in Croatia (photo by Zoran Stevanović). This spring was used for millennia and was tapped by the Romans for the water supply of the Palace of Emperor Diocletian. Water was conveyed to the palace by an aqueduct, preserved to this day (*top right* photo by Ivo Eterović). *Bottom right*: Reconstruction of the Palace in its original appearance upon completion in 305 AD by the French town planner Ernest Hébrard, published in 1912 (E. Hébrard and J. Zeiller: Spalato, le Palais de Dioclétien, Paris, 1912.) Diocletian retired to this palace near his birthplace Salona (Solun in Croatian). It is the largest and best-preserved example of Roman palatial architecture in the world. It is now the core of the Split's Old Town, designated a UNESCO World Heritage Site in 1979.

The custom of building handsome fountains at the end point of aqueducts that brought karst water to Rome was revived in the fifteenth century, during the Renaissance. The Trevi Fountain (Fig. 5) is the largest Baroque fountain in the city and one of the most famous fountains in the world, fabled for its water clarity. The city of Rome still relies on large karst springs for its water supply (Fig. 6).



Figure 5 The Baroque Trevi Fountain in Rome designed by Nicola Salvi and finished in 1762. Water for the fountain is brought via Aqueduct Vergine, the revived ancient underground aqueduct Aqua Virgo, from the 13 km distant karst spring Salone. According to a legend, thirsty Roman soldiers asked a young girl for water. She directed them to the springs that later supplied the aqueduct. The source was named the Aqua Virgo after her.



Figure 6 Outflow from the pumping station at karst springs of Peschiera which are in the Velino River valley, a few miles upstream of Cittaducale in the province of Rieti. The springs are the largest in central Apennines with an average flow rate of 17 m^3/s (600 cubic feet per second, cfs). They are collected and diverted to supply Rome and much of the surrounding area.

Karst aquifers are present on all continents and numerous oceanic islands with outcrops on over 20% of the land surface, with more being covered by insoluble rocks. As the importance of water resources and their sustainability is becoming critical worldwide, karst aquifers are receiving rapidly increasing attention due to the many challenges related to their characterization, management, and protection.

Introduction

A warning of what may soon be happening to many karst regions around the world, some of which have been experiencing sinkhole hazards for generations already, is the unfolding catastrophe in Turkey described in an article by Liz Cookman published in The Guardian on February 28, 2026. Below are some excerpts and photographs from this alarming article (https://www.theguardian.com/world/2026/feb/28/i-live-in-constant-fear-surge-in-giant-sinkholes-threatens-turkeys-farmers):

"Every night I pray before I go to bed and when I wake up I pray again," said Sik. "I live in constant fear that a sinkhole will take my house."

Konya, part of the once-fertile Central Anatolia region, gave life to ancient civilisations, including what is believed to be the world's first agricultural society, at Çatalhöyük, in about 8,000BC. It is dotted with the remnants of water cults, Hittite sacred springs and Roman aqueducts, and once offered vital watering holes to traders on the Silk Road.

Now, though, the land is drying up. Turkey is on the brink of a major drought crisis, with almost 90% of the country at risk of becoming desert.

Sinkholes are appearing in farmland in the region at an increasing pace. Experts say there are now almost 700, causing uncertainty and devastation for the farmers who live and work there.

Konya has always been geologically prone to sinkholes because much of the region lies on bases of limestone and other soluble rocks, but in recent decades intensive agriculture has led to heavy groundwater extraction for irrigation. As water tables drop, underground cavities lose the support that once held them up.



Figure 7 *Left*: Sinkholes in a farmer's field in Karapınar, Turkey. *Right*: The number of sinkholes and related shallow collapse structures in Turkey's Konya Plain is approaching 3,000. Experts attribute the dramatic rise to regional drought and unsustainable groundwater pumping for agriculture. Photographs by Emre Çaylak. From The Guardian, February 28, 2026.

While no state in the United States with a significant presence of karst is immune to sinkhole development due to anthropogenic influences (e.g., see Fig. 8), the problem is nowhere more drastic than in Florida (Fig. 9). The exploding population and acreage of irrigated agricultural land are putting enormous pressure on groundwater extraction from the Floridan Aquifer, resulting in dropping aquifer levels and increasing sinkhole hazards.

According to the United States Geological Survey (USGS), karst aquifers in the United States, covering roughly 18-20% of the land surface, provide about 40% of the nation's groundwater used for drinking (Karst Aquifers | U.S. Geological Survey). These highly productive, soluble limestone/dolomite systems, including the Edwards Aquifer in Texas and the Floridan Aquifer, both of which are among the most prolific in the world, are crucial for public water supply, agriculture, and industry.




Figure 8 *Left*: A sinkhole collapse that occurred early Sunday morning August 13, 2006, in Nixa, Missouri is responsible for the disappearance of a garage and the Chevy Cavalier once parked inside. Photo courtesy of Doug Gouzie. *Right*: Golly Hole sinkhole in Alabama, one of the largest in the United States, suddenly opened on December 2, 1971, in northern Calera, Shelby County. Photo by George Sowers, printed with kind permission of Francis Sowers.




Figure 9 Winter Park sinkhole occurred during the spring of 1981. It severed two city streets, truncated a municipal swimming pool, swallowed a house, and damaged an automobile repair shop together with several automobiles parked behind it. The final hole diameter was more than 300 ft (90 m) with the cone-shaped opening approximately 50 ft (15 m) deep through clayey sands. Below was a 60 ft (18 m) diameter cylindrical opening in a soft, porous limestone, possibly an old collapse sinkhole in the limestone. Movement was apparently triggered by wide fluctuations in the groundwater level from well pumping and possibly aggravated by leaking of the swimming pool. Photographs by George Sowers, printed with kind permission of Francis Sowers.

Examples of the catastrophic influence of aquifer pumping on karst water resources that sustain aquatic life and the environment in general are numerous in the United States and around the world. One such example is Comanche Springs in Fort Stockton, Pecos County, Texas:

Introduction

These artesian springs, issuing from a Comanchean limestone groundwater reservoir, formerly flowed as much as 66 ft^3/s, and served the Comanche and other Indians for uncounted hundreds of years. From 1875 on the springs were the basis for an irrigation district which supplied water to 6,200 acres of cropland. Heavy pumping of the aquifer lowered the water table so that the spring discharge began to fall off in May 1947. The irrigation district sought an injunction in 1954 to restrain pumping which interfered with the normal flow of Comanche Springs. The injunction was denied by the courts, and the springs ceased to flow in March 1961. (Gunnar Brune, 1975: Major and Historical Springs of Texas, Texas Water Development Board Report 189, Austin, TX.)



Figure 10 *Left*: Aerial view of Comanche Springs pool in 1938, at the time a popular tourist destination in Fort Stockton, Texas. The springs ceased to flow due to excessive groundwater pumping for irrigation. Photo courtesy of Fort Stockton Historical Society. *Right*: The main spring at Comanche Springs looks like this most of the year. Once a perennial, strong spring, it now flows as an intermittent trickle when irrigation pumping stops and there is enough recharge from above-average rainfall in the recharge area. Photo by Brian Hunt.

The following excerpts are from a press release by Texas State University entitled "Texas springs in crisis: New study highlights overwhelming increase in dry springs":

New research from The Meadows Center for Water and the Environment at Texas State University uncovers a concerning decline in the state's groundwater resources, finding that the number of dry springs has nearly tripled since the early 1980s.

Co-authored by Robert E. Mace, Ph.D., Meadows Center Executive Director, and Nohemi Galaviz, a Texas State undergraduate research assistant, the study revisits and builds upon the seminal work of Gunnar Brune's 1975 report, "Major and Historical Springs of Texas," and his subsequent 1981 book, "The Springs of Texas, Volume 1." As Texas' acknowledged expert on springs, Brune's publications cataloged the state's major and historical springs, forming the foundation of our knowledge today.

"For the first time in nearly half a century, we looked at the status of major and historical springs across the state to see if more springs had gone dry. Indeed, more—many more—have failed over the past 50 years," Mace said.

"The data speaks volumes about the growing demands on our groundwater resources and some of the consequences of meeting those demands," Mace said. "As groundwater use in the state continues to rise, the resulting decrease in springflow jeopardizes not only our groundwater and surface-water supplies but also the ecosystems that rely on these springs."

Jayme Blaschke | February 28, 2024

The disappearance of springs due to large-scale groundwater withdrawals from aquifers is not unique to arid or semi-arid regions with low rainfall and low natural aquifer recharge such as Comanche Springs. Fig. 11 shows historic Kissengen Spring in Florida, located near the city of Bartow in Polk County. This once mighty spring served as a popular recreational area for decades and had an average flow of about 29 ft^3/s (19 million gallons per day, MGD). Kissengen Spring was included in the anthological publication by Oscar Meinzer of the USGS titled *Large Spring in The United States*, published in 1927, as one of the largest in Florida. The cessation of flow, both at Kissengen Spring and at many minor springs in the upper Peace River basin, was related to the regional lowering of the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer from 1937 to 1950 for as much as 60 feet, due to heavy groundwater pumping for phosphate mining (Peek, 1951). Permanent cessation of the spring flow occurred in April 1960. The spring never flowed again and today only a small mud pot marks the location where, for many years, it provided joy to countless visitors (Fig. 11).

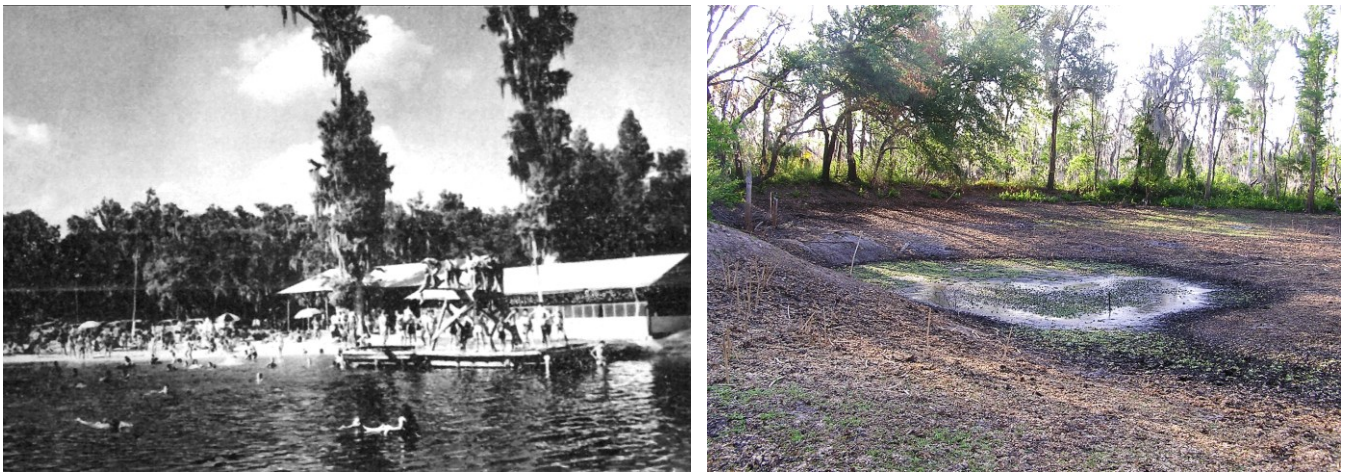


Figure 11 *Left*: Historic photo of Kissengen Spring which remains dry to the present day after all flow ceased in 1960. (From Peek, 1951.) *Right*: Location of former Kissengen Spring in 2006. Courtesy of United States Geological Survey.

Fountain of Sorrow: The Deplorable Fate of Kissengen Springs

From People for Protecting Peace River Inc.—3PR; https://protectpeaceriver.org/

No one person is responsible for the loss of Kissengen Springs, but all signs point to the culpability of an industry and a kind of mass hypnosis that not only allowed the destruction of the springs, but has never held the perpetrators accountable for what happened. On the contrary they accepted their blood money. It's obvious, isn't it? When you walk through miles of useless degraded land, overgrown with invasive vegetation where there are still old cast-off rusty pipes and wires strewn around and huge mine pits gouging the earth a stone's throw from where the springs once prospered, it's obvious what happened to the springs. Yet just down the road, there lies "Mosaic Peace River Park" with its historical brass plaque that says, "The spring ceased to be a tourist destination after the groundwater was captured for other uses." The historical society obviously dared not utter the word "phosphate" since it was the mother of all phosphate mines and fertilizer production that donated the land to the public. The industry mined it and effectively destroyed the natural order that had prevailed there since the dawn of time, and then returned it to the public as a gift, and people bowed their heads and expressed their gratitude.

Introduction

Under relentless pressure from Florida citizens, activists, and many different organizations concerned with the catastrophes facing beautiful Florida springs, the State Legislature in 2016 enacted the Florida Springs and Aquifer Protection Act which specifies 30 "Outstanding Florida Springs". In Statue 373 one can read:

The Legislature finds that the water quantity and water quality in springs may be related. For regulatory purposes, the department has primary responsibility for water quality; the water management districts have primary responsibility for water quantity; and the Department of Agriculture and Consumer Services has primary responsibility for the development and implementation of agricultural best management practices. Local governments have primary responsibility for providing domestic wastewater collection and treatment services and stormwater management. The foregoing responsible entities must coordinate to restore and maintain the water quantity and water quality of the Outstanding Florida Springs.

It remains to be seen if this act will have an effect. In the meantime, those concerned with the sustainability of groundwater resources and the destiny of Florida springs remain concerned, some are skeptical, and some are raising their voices disillusioned with what they see happening as illustrated in the following excerpts from a blog by Dr. Robert Knight, Director of The Howard T. Odum Florida Springs Institute entitled "The Future of Florida Springs" which contains his remarks delivered at a panel discussion held at the University of Florida on April 1, 2023:

But the documented and worsening ecological health of Florida's priceless springs provides ample evidence that Florida's political leadership is not working to fix these problems. Much of the tax dollars being directed to "springs protection" are, in fact, spent on projects that have had no measurable spring benefits. Springs health impairments continue to worsen with every passing year.

This is an unacceptable fate for Florida's most unique and precious natural resources and presents a clear danger for the sustainability of the Floridan Aquifer. The future livability of the Springs Region is not just threatened – it is already substantially diminished. (https://floridaspringsinstitute.org/springsblog/)

The Santa Fe River, fed by karst springs, is a particularly sad story about the mismanagement and demise of Florida's water resources:



Figure 12 *Left*: Foam floating on dark, tannin water of the Santa Fe River in December 2023, just yards away from the Sink pool. *Right*: Santa Fe Sink was choked with green algae, other organisms, white foam, and various debris including pieces of construction lumber and other human-made objects. Photographs taken in December 2023.

In 1983, the Suwannee River Coalition described the Santa Fe River as one of Florida's "most valuable rivers ecologically" as it was in excellent condition. Although they reported problems with exotic vegetation like hydrilla or water hyacinths, it was still classified as "one of the cleanest, healthiest, and least disturbed rivers of its size in the southeastern United States." In the past the Suwannee River Coalition similarly described the St. Johns River as a popular place for Floridians to fish, sail, and swim before pollution had gotten so bad and the dissolved oxygen content so low that fish populations diminished, and the unappealing aesthetics drove visitors away. The 1983 coalition report included an eerie warning to avoid the degradation of the Santa Fe River: "To permit a similar fate for the Santa Fe River would be an irresponsibility of the first magnitude. We must protect this river and it is essential that we designate the Santa Fe River system an Outstanding Florida Water so that it will be enjoyed by generations to come." (Florida Springs Institute, 2020a.)

And yet, the State of Florida, Potentially Responsible Parties (PRPs), and indeed the citizens of Florida all failed miserably. They let down the Santa Fe River, its springs, and its Rise, as attested by the photographs in Fig. 12 taken exactly 40 years after the eerie warning.

This book builds on the materials presented in *Notable Springs of The United States* (Kresic, 2024) which is free for download from various websites such as Groundwater Academy (www.groundwateracademy.org) and Karst Waters Institute (KWI, https://karstwaters.org/2024/10/new-open-access-book-on-springs-of-the-us-available-by-kwi-board-member-neven-kresic/). The two books are the result of the author's work, as the coordinator for North America, on project MIKAS (Most Important Karst Aquifer Springs; https://mikasproject.org/) by Karst Commission (KC) of The International Association of Hydrogeologists (IAH).

The main goal of this project was to create the first list of the most important karst springs at the global, as well as national levels, representing world and national natural heritage for each country. The importance of each spring is based on historical, aesthetic, economic, scientific and ecological criteria, at the same time recognizing that the five criteria may not be present at all springs and that specific circumstances of each country should be taken into consideration ("Something that is important in one country does not have to be important in others."). Hundreds of karst springs from 30 States in the United States were compiled for the Karst Commission project by the author. Their descriptions are included in this book, most of them accompanied by photographs. General primers on karst, types of karst springs, and major karst aquifers of the United States are also included.

This book, in color and in full resolution, is also available in print on Amazon.

The author is grateful to many colleagues and institutions that provided photographs and information on the karst springs. Special thanks go to Alan Cressler, John Moran, Chuck Sutherland, Phil Lukas, Gregg Eckhardt, Dave Bunnell, Arthur Palmer, Katie Fite, Joseph Honings, Calvin Wolter, Sam Panno, Jake Stacken, Martin Larsen, John Barry, Gheorghe Ponta, Ryan Maurer, Joel Maynard, William Orndorff, Bill Jones, Calvin Alexander, Nenad Marić, Zoran Stevanović, Alex Mikszewski, John Burtner, David Kreamer, Gretchen Baker, Hyrum Tennant, David Rhea, Todd Kincaid, Hannah Schacht, Tom Provezis, Ben Estes, Katarina Kosič Ficco, Mike Ficco, Amy M. Hourigan, Alan Fryar, Donna Leight, Andrew Wagner, Judith Judee Lyon, and Lydia Sizemore.

Chapter 1 Water in Karst

1.1 Karst and Karstification

Karst is a scientific term named after the geographic district between Slovenia and Trieste, Italy, which has a very distinct landscape. It is a Germanized word for "carso" (in Italian) and "kras" (in Slovene); all three words are derived from the Indo-European word "kar" or "karra," which means rock. The following definitions of karst and karst topography are based on the 1960 edition of the American Geological Institute Dictionary of Geology.

In karst, the limestone rocks are honeycombed by caverns and openings dissolved by groundwater. Most of the drainage is underground and the land is left dry and relatively barren. The landscape is dotted with sinkholes, interspersed with abrupt ridges, and irregular protuberant rocks. Dry valleys are common, and valleys containing streams often end abruptly where the latter plunge into underground channels and caves, sometimes to reappear as large springs miles away. These features are so characteristic of the Karst district of the eastern Adriatic coast that the name karst has been applied to them elsewhere.

Some common words from the Slavic languages of the Karst region have become international scientific terms describing karst features, mainly thanks to the Serbian geomorphologist Jovan Cvijić who in 1893 was the first to defend a doctoral thesis and publish a scientific monograph exclusively devoted to karst: Das Karstphänomen (The Karst Phenomenon). These include *doline* (sinkhole), *ponor* (sink), *jama* (pithole), and *polje* (large, closed depression with flat bottom characteristic of the Dinaric karst). During the following two decades, Cvijić laid the theoretical foundation of many past and current developments in karst geomorphology and hydrogeology by authoring over 40 publications devoted entirely or mostly to karst phenomena. Much of his original work and numerous drawings illustrating the origin of various karst forms and the nature of groundwater flow in karst terrains have since been republished, copied, or otherwise reaffirmed by many. Examples of typical hand drawings made by Cvijić in support of his concepts and illustrating karst features analyzed on his extensive journeys throughout the Balkans and Europe are provided in Figures 1.1 and 1.2.

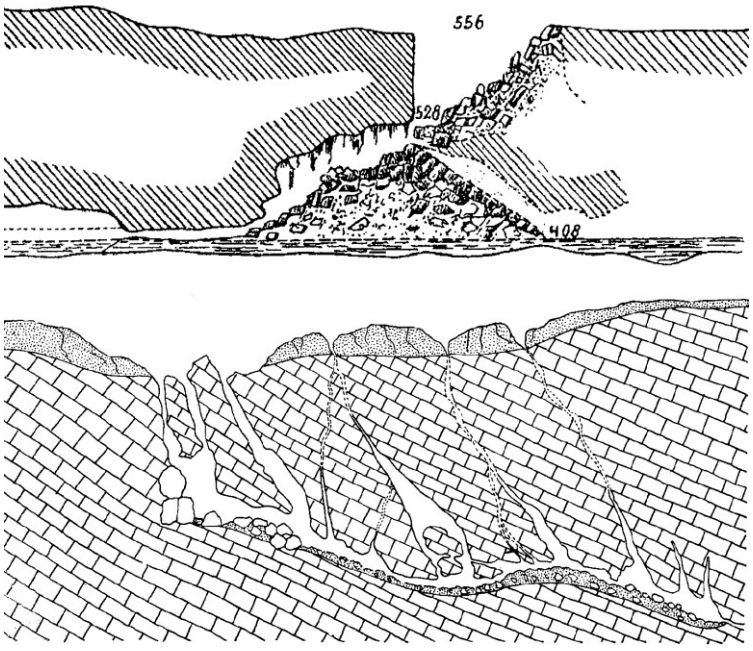


Figure 1.1 Cvijić's drawings accompanying his explanations of the morphogenesis of different karst landforms. *Top*: Collapse sinkhole. *Bottom*: Alluvial sinkholes aligned over karst cavities in underlying limestone. From Cvijić, 1893.

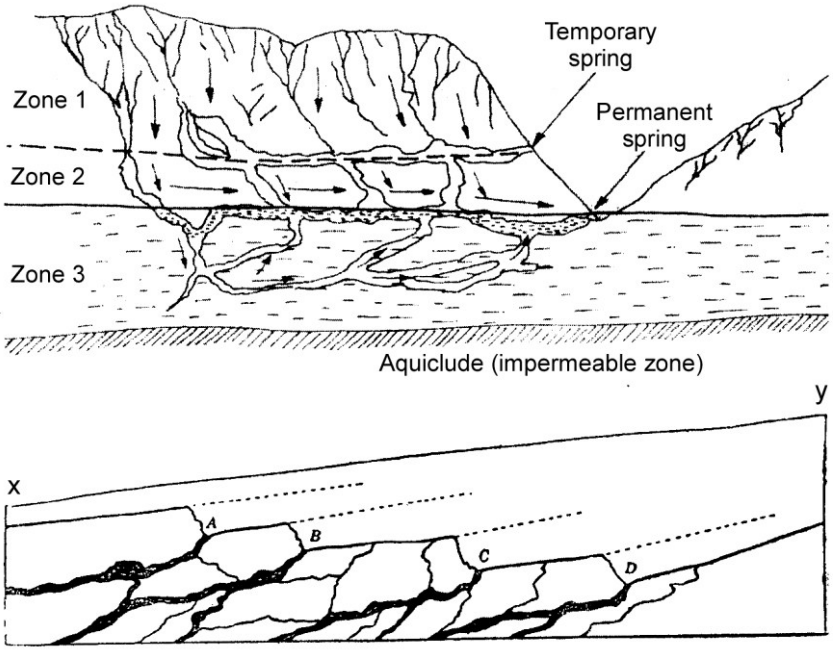


Figure 1.2 Cvijić's sketches illustrating concepts of groundwater flow in karst. *Top*: Schematic section of a karst aquifer with three zones: (1) dry zone with percolation only; (2) transition zone of varying level with both percolation and saturated groundwater flow during high water table; (3) permanently saturated zone, including conduits with ascending flow (English annotation added). *Bottom*: successive lowering of ponors (sinks) of streams in karst creating blind valleys; x-y denotes pre-karstic valley. (From Cvijić, 1918; also available in Stevanovic and Mijatovic, 2005.)



Figure 1.3 *Left*: Underground flow of the Reka River, which sinks into the world-famous *Škocjan Caves* in Slovenia and empties into the Gulf of Trieste, can be accessed in a few deep pits-caves. The longest of them is *Kačna jama* cave near Divača, Slovenia, which impresses with its picturesque abyss entrance 186 meters deep, which in the lower part extends into a huge hall 60 meters high. Photo by Peter Gedei. *Right*: Rokina Bezdana Cave in Croatia. Photo by Dinko Stopić.

Photographs in Figs. 1.3 through 1.11 illustrate some of the spectacular features of the classic Dinaric karst (many more photographs are available in a free-for-download book entitled *The Land of Karst, A Visual Story* (Kresic and Stevanovic, 2023); download is available at www.groundwateracademy.org; and the academic Research Gate site https://www.researchgate.net/publication/383145893_The_Lands_of_Karst_A_visual_Story.





Figure 1.4 *Left*: *Prerast* in Vratna River Gorge, one of many natural bridges in eastern Serbia. Photo by Aleksandra M. Stevanović. *Right*: Karst spring waterfall "Skakavica" on Grabovica river in Montenegro. Photo by Dobrislav Bajović Bajone.



Figure 1.5 Underground canyon of *Škocjanske jame* (Škocjan Caves) in Slovenia. It is criss-crossed by precipitous paths and was fully explored already in the 19th century. After sinking, the Reka River penetrates deep into the cave and descends over rapids and falls along its entire length, until it reaches an unpassable syphon. The vertical drop from the swallow hole to the syphon exceeds one hundred meters. Note lit tourist path and bridge in the upper left for scale. The cave was designated World Natural Heritage site by UNESCO in 1986, one of only four caves in the world to receive this status. Photo by Borut Lozej.

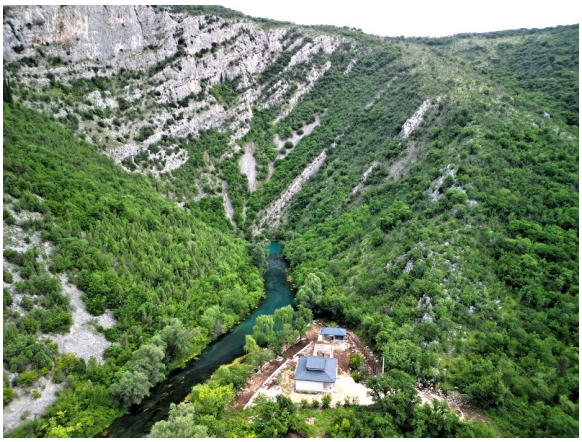


Figure 1.6 *Left*: Ombla Spring (*Vrelo Omble*) is the largest individual karst spring in the world, with the recorded long-term average discharge rate of 24.4 m^3/s (862 cfs). Before diversion of some of the flow of the sinking Trebišnjica River in the spring's vast watershed for hydropower generation at HE Dubrovnik, the average discharge rate was 33.8 m^3/s (1194 cfs). The multi-decadal continuous daily measurements are officially conducted by the Croatian Water Management Agency. The spring is of ascending type, issuing at contact between Mesozoic limestones and impermeable Eocene flysch on the Adriatic coast. It is used for the water supply of Dubrovnik. *Right*: Aerial view of Ombla Spring and the river (Dubrovačka Rijeka) originating from it. Photo courtesy of Antun Maškarić.



Figure 1.7 Buna Spring (*Vrelo Bune*) near Mostar, Bosnia and Herzegovina is a deep siphonal (vauclusian-type) spring and the second largest individual karst spring in the world with a recorded long-term average discharge rate of 23.7 m^3/s (837 cfs). Multi-decadal continuous daily measurements are officially conducted by the Water Management Agency of Bosnia and Herzegovina. The spring issues at contact of Cretaceous limestone and Eocene flysch, along a major regional fault which is marked by dissolution cavities at various elevations – evidence of the lowering of locations of discharge. Elevation of the siphon in the submerged cave is 68 m (223 ft) below discharge level. The spring is one of only three springs included on the list of World Geoheritage Sites by the International Union of Geological Sciences. The other two are also karst springs, Wakulla Spring in Florida, and Fontaine de Vaucluse in France.
https://iugs-geoheritage.org/designations/





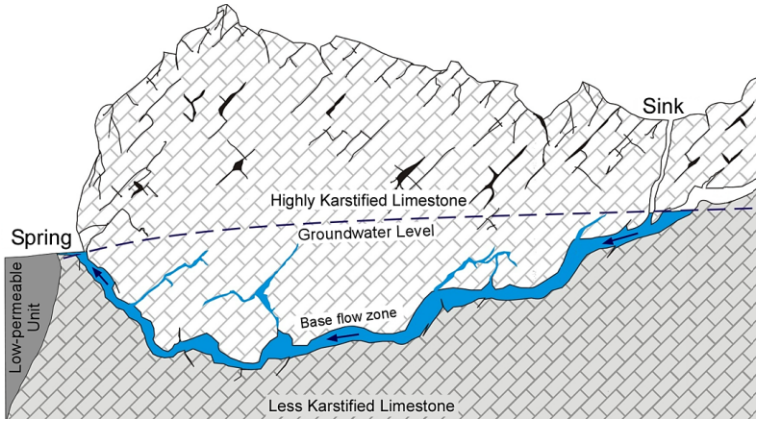


Figure 1.8 Vauclusian-type Little Buna Spring (*Vrelo Bunice*) is the third largest individual karst spring in the world with the long-term average discharge rate of 20.25 m^3/s (715 cfs) and a whopping mean maximum rate of 207 m^3/s. (7310 cfs). Multi-decadal continuous daily measurements are officially conducted by the Water Management Agency of Bosnia and Herzegovina. Two sister springs, *Vrelo Bune* and *Vrelo Bunice* are only 2.5 miles apart and jointly constitute the largest "spring group" in the world if Florida standards were applied (44 m^3/s or 1554 cfs combined long-term average discharge rate). This extraordinary flow creates a spectacular site at the confluence of the Buna River and the Neretva River, the largest tributary of the eastern Adriatic (Fig. 1.9). For comparison, the two largest spring groups in the United States are Malad Gorge Springs and Thousand Springs in Idaho with average discharge rates of 1229 cfs and 1198 cfs respectively. They both issue from young basalts, often referred to as *pseudokarst* (see Volume 2 of this book and Chapter 4 in Kresic, 2024). Photographs by Robert Oroz, courtesy of *Snaga lokalnog*, a five-year program of the former American Agency for International Development (USAID) that worked to empower local communities in foreign countries. Conceptual cross-section from Saša Milanović.

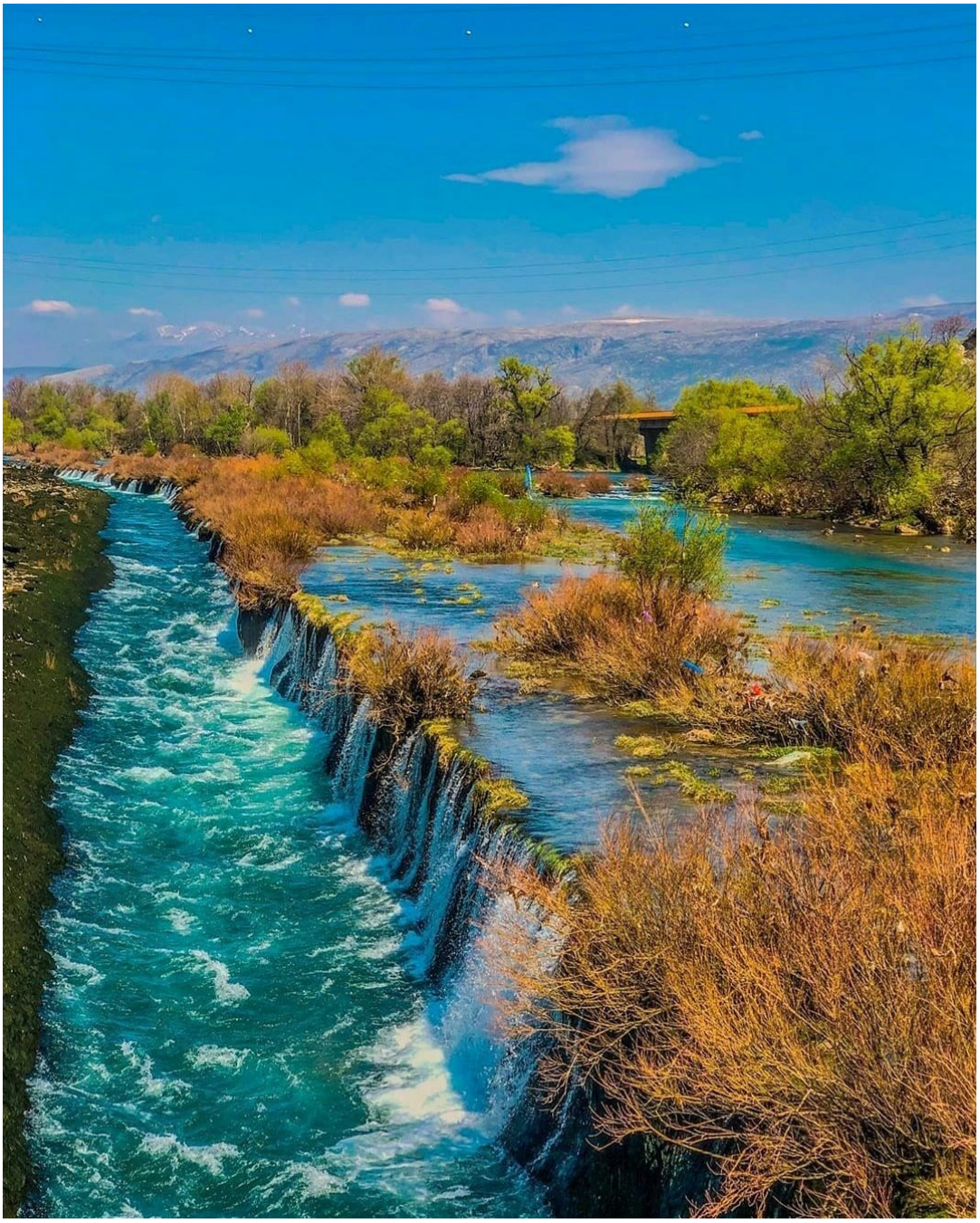


Figure 1.9 Spectacular confluence of the Buna River (on the right, formed by waters of Buna and Little Buna Springs) and the Neretva River (on the left), 9 miles south of Mostar, Bosnia and Herzegovina. “Nera-Etwa" is believed to be an ancient Illyrian name for the Neretva River. It is commonly translated to mean "Flowing Goddess", or "Heavenly Water". Photo available at https://www.facebook.com/visitherzegovina/photos/

What sets karst aquifers apart from any other hydrogeologic environment is the nature and dynamics of surface water-groundwater interactions, and their unique porosity, often referred to as triple porosity, which consists of the rock matrix (initial, primary) porosity, the porosity of fractures (secondary porosity), and the porosity of solution openings (tertiary porosity: enlarged fractures, karst channels, conduits, and all cavities in general). The solution

openings are created by the chemical and mechanical erosion of water percolating into the rock from the land surface and through unsaturated soils, and its enrichment with dissolved carbon dioxide along the way.



Figure 1.10 Glavaševo Vrelo, headspring and the largest spring of the Cetina River near the village of Cetina in Dalmatia, Croatia. This vauclusian-type spring is exceptionally deep, with divers descending 150 meters (490 feet) without reaching the bottom. Average discharge rate is 3 m^3/s (106 cfs). The spring is used for water supply and swimming is prohibited. In recent years, the spring acquired a new name "Eye of the Earth", thanks to a campaign of savvy tourism officials. Photo courtesy of Branimir Jukić.



Figure 1.11 Vrelo Sopot in Boka Kotorska Bay, Montenegro is the largest intermittent karst spring in the world, exceeding 300 m^3/s (10,600 cfs) when flowing after heavy rains. Most of the year the spring is dry and the vast karst aquifer of the Orjen Mountain is drained by a nearby submarine spring. The Orjen Mountain has the highest precipitation rate in Europe (close to 5,000 mm/year). Photo courtesy of Saša Milanović.

The interaction between water and soil rich in carbon dioxide creates a weak carbonic acid which accelerates dissolution of soluble carbonate rocks: primarily limestone, dolomite, marble, and gypsum. The following equations express the general reactions between calcium carbonate and the CO_2–water system:

$$CO_2 + H_2O = H_2CO_3 = H^+ + HCO_3^-$$
$$HCO_3^- = H^+ + CO_3^{2-}$$
$$CaCO_3 + H^+ = Ca^{2+} + HCO_3^-$$



Figure 1.12 Cavities of varying size discovered at a deep (seen dewatered here) construction site in Hartsville, Tennessee. Consolidated old Paleozoic limestones have low matrix porosity of less than 5% but high secondary and tertiary porosity as they are intensely fractured and karstified. Photographs by George Sowers; printed with kind permission of Francis Sowers.

The density, size, and geometry of cavities created by carbonate dissolution in karst aquifer networks can vary by many orders of magnitude depending on site-specific characteristics such as mineral composition, stratigraphy, tectonic fabric, recharge mechanisms, and position of the erosional base. One of the most common errors made by hydrogeologists not experienced in karst is to rely solely on investigative borings and monitoring wells when developing a conceptual model for their site. Declaring that the aquifer (site) is non-karstic based on three, five or even ten borings that did not encounter a large "void" is a typical example. Similarly, a non-karst hydrogeologist may conclude that the aquifer is not karstic because test wells cannot produce "large" yields that, somehow, are expected from a karst aquifer. Fig. 1.12 illustrates these points. One can easily imagine a boring advanced into the large cavity shown on the left photograph or the smaller cavity on the right photograph. In such cases hardly any hydrogeologist would argue that the limestone is not karstified (an inexperienced driller not equipped for drilling in karst may even lose some of his/her equipment when this happens). One could also imagine another boring completed in solid rock adjacent to either cavity that could be used, by some, as "evidence" of non-karst.

The situations shown on Fig. 1.12 can happen at any depth within a karst aquifer including hundreds or thousands of feet below ground surface and below the water table. The depth to which karstification has progressed, the so-called base of karstification, is not uniform and varies from site to site. The degree of karstification and fracture density generally decrease with depth but can locally reach much greater depths. As the erosional basis for karst groundwater discharge is not necessarily at a static elevation and may be constantly lowered due to surface stream incision, sea level regression, or other factors, the depth of karstification and the depth to water table would consequently increase in time as well. For example, in some areas of the Dinaric carbonate platform in Europe the depth to the water table exceeds 1000 meters, while cavities and voids of varying size have been discovered with investigative drilling at depths of several thousand meters below sea level.

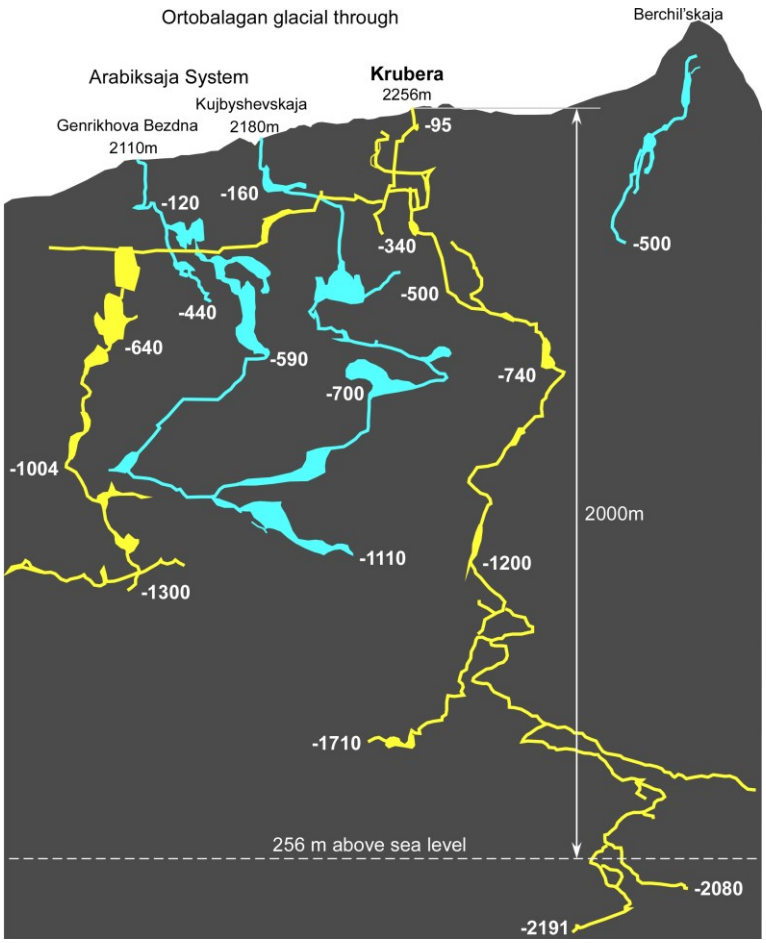


Figure 1.13 Combined cave profile along the axis of the Ortobalagan valley, Western Caucasus, breakaway republic of Abhazia (formerly in Georgia). Krubera Cave is shown in yellow (bottom of the cave is 2191 meters below ground surface), other caves in blue. Simplified from Klimchouk, Samokhin, and Kasian, 2009. Printed with permission from the authors.

Even more impressive are examples of deep karstification on the Arabica Karst Massif, part of the Western Caucasus mountains bordering the Black Sea. The Krubera Cave (Fig. 1.13) in the breakaway republic of Abhazia (formerly in Georgia) is the second deepest cave in the world: 2191 meters or 7188 feet as of May 2022 (the nearby Veryovkina Cave is the world's deepest at 2212 meters or 7257 feet). Krubera has a very steep profile and reveals an enormous thickness of the vadose zone. The lower boundary of the vadose zone (the top of the phreatic zone) is at an elevation of about 110 m above sea level (asl) at low flow. Submarine discharge along the Black Sea coast is reported at depths up to ~400 m below sea level (bsl). A large, closed submarine depression is revealed at the sea floor next to the Arabika Massif, with its deepest point at ~400 m bsl. These facts point to the possibility that the main karst system in Arabika could have originated in response to the Messinian salinity crisis (5.96–5.33 Ma) when the Black Sea (Eastern Paratethys) could have almost dried up, as did the adjacent Mediterranean where a dramatic sea-level drop is well established. Further development of the thick vadose zone and the super-deep caves have been caused by subsequent uplifts during the Pliocene-Pleistocene (Klimchouk et al., 2009.)

Similarly, along the coasts of Florida in the United States, Yucatan in Mexico, and the Caribbean islands there are numerous submarine springs and submerged deep sinkholes and cave passages testifying that the sea level in the past was also lower (Figs. 1.14 and 1.15).

Paleokarst is a term usually used to describe karst features (voids, cavities) at any depth explained by the burial of carbonate sediments below non-soluble rocks. The carbonates were karstified at earlier times when exposed at the surface or when in near-surface settings. These paleo cavities may subsequently be filled with clastic deposits

or may remain open. In some cases, the existence of karstification at great depths (several miles or so) can be explained by the fact that the same general area with carbonate rocks may have been subject to multiple periods of karstification depending on geologic and tectonic history. In thick karst aquifers developed in active geologic environments it is often possible to find very permeable zones, together with large karst conduits, at greater and varying aquifer depths. These zones may indicate the position of a paleo water table where karstification intensity was high.

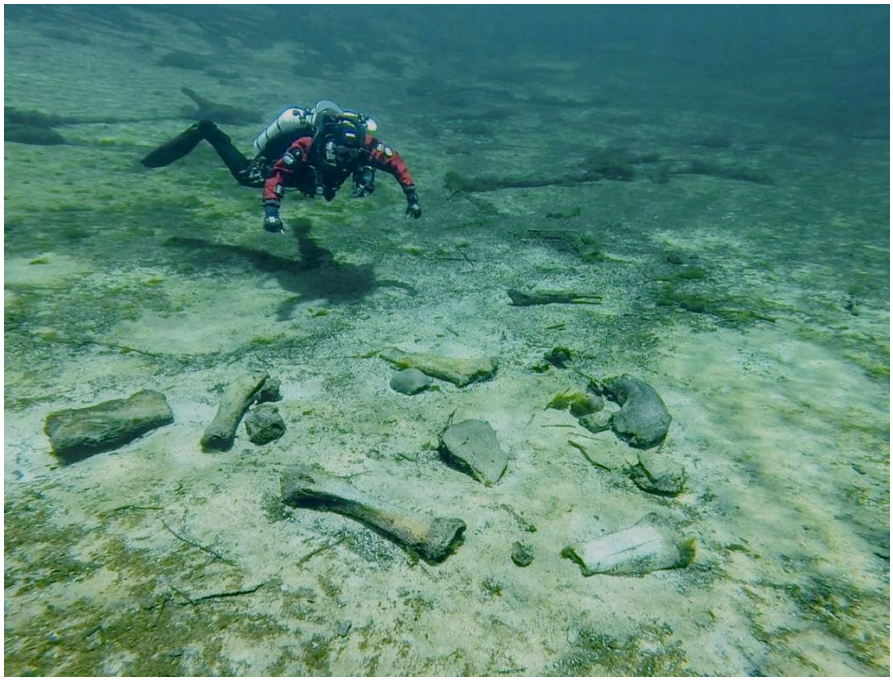


Figure 1.14 Diver Casey McKinlay swims over mastodon fossils in the Wakulla Spring vent. In a West Florida State University documentary Finding the First Floridians, one can learn that fossils are well preserved in springs and sinkholes. One can also learn about Florida's lower aquifer levels during the last ice age, when humans and mastodons coexisted. Photo by David Rhea, Woodville Karst Plain Project.



Figure 1.15 Blue hole on East Caicos is a deep submerged sinkhole. The limestone in which numerous caves in the Turks and Caicos Islands are formed is young, Pleistocene-age biogene reef limestone, roughly 120,000 to over 195,000 years old. The primary porosity of such reef limestones is generally high, with values often ranging from 30% to over 40% (e.g., Diaz et al, 2019). For more information see Lace, et al., 2016, Coastal Cave Survey Times of the Islands Caving In for Science - Times of the Islands. Photo courtesy of Caves, Blue Holes and Sinkholes | Visit Turks and Caicos Islands.

In any case, open karst cavities at great depths may be preserved even where pressure increases to lithostatic values, due to the high rigidity of limestone and dolomite. Numerous such examples from around the world are provided by Andreychouk et al. (2009) including from North America where data reveals that Mesozoic and Paleozoic carbonate rocks may exhibit enhanced secondary porosity, up to 15-20%, at depths up to 10 km. As concluded by the authors, available data unequivocally indicate that karst can develop throughout the entire section of the Earth's crust that is accessible by drilling. The distribution of karst voids at different depths is irregular.

Relatively large cavities, with dimensions exceeding meters, occur in the top few kilometers. Smaller pores, vugs, and enlarged fractures prevail deeper. The authors note that this spatial heterogeneity can be exaggerated, at least partly, by the technical difficulties of identifying large cavities at great depths.

In a series of publications, Palmer (1991, 2007), Klimchouk (1992, 1994, 2011) and Klimchouk et al. (2000) established the concept of hypogenic (endogenic) karst, previously largely ignored by karst hydrogeologists trained in traditional karst settings. As mentioned earlier, the well-established concept, applicable to many open hydrogeologic structures, explains the karstification to be the result of carbonate rock dissolution by infiltrating (descending) waters enriched with soil and atmospheric CO_2, the so called *exogenic* or *epigenic* karst. In contrast, *hypogenic* karst is created by ascending waters that, in addition to CO_2, may carry upwards other acidic fluids such as sulfuric acid and dissolved H_2S, the origin of which is deep (endogenic) due to metamorphism, magmatic, and tectonic processes. Dissolution of carbonates by ascending groundwater is enhanced in semi-confined and confined hydrogeologic settings where cross-formational diffuse flow of the acidic fluids can take place over large areas and create karst cavities by slowly "eating away" the rock mass (Fig. 1.16). This process can result in the formation of very convoluted and extensive karst cavities along previously weakened portions of the rock (such as due to fracturing and faulting) as well as in relatively competent rock. Hypogenic karst does not have to be deep and exclusively the result of dissolution by endogenic fluids such as sulfuric acid. The sufficient triggers for its development are an ascending groundwater flow and some degree of the carbonate aquifer confinement with less permeable rocks. In many cases there will be an overlap between the ascending and descending flows (i.e., the hypogenic and exogenic karst respectively), especially at the locations of regional groundwater discharge.

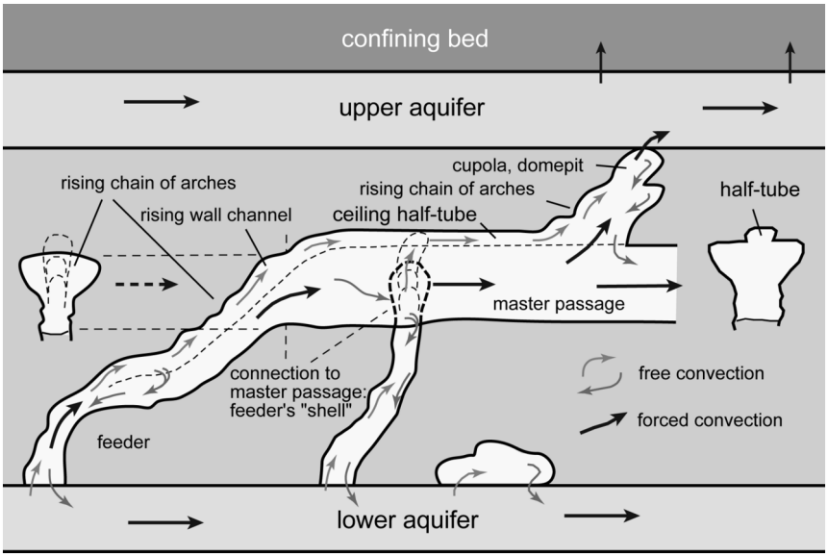


Figure 1.16 Morphologic suite of rising flow, diagnostic of hypogenic transverse origin of caves. Modified from Klimchouk, 2011; printed with original permission from the author.

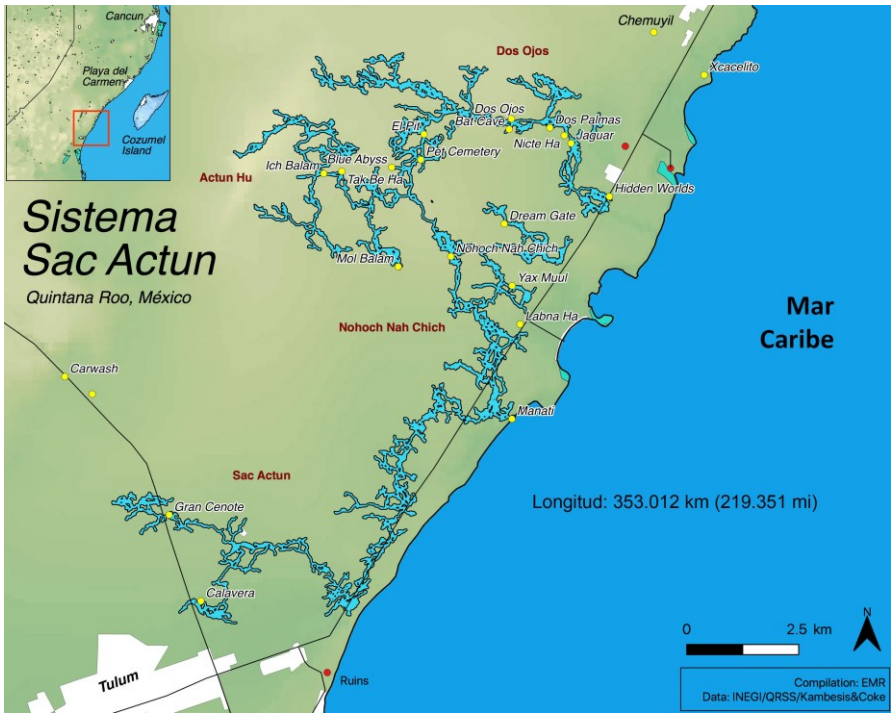
In summary, the only relevant characteristics of an aquifer to be qualified as karstic is that a portion of groundwater flow in it is taking place through a network of interconnected channels, conduits, and various other voids created by dissolution of the rock. These voids can be the result of several physical and chemical processes involving descending (infiltrating) water, as well as ascending groundwater that may also carry acidic fluids such as dissolved H_2S, sulfuric acid, and CO_2 from greater depths. Regardless of the actual mechanism involved, the relative size and the number of interconnected karst voids are irrelevant. If they are present, at any scale, the aquifer is karstic.



Figure 1.17 Lechuguilla Cave in New Mexico is the most impressive example of a hypogenic cave in the United States. It is situated within the 265–259 million-year-old Capitan Reef Complex in the Guadalupe Mountains. The sulfuric acid process left behind unusual mineral deposits not typically found in other caves, such as impressive gypsum chandeliers shown here in The Chandelier Ballroom. Because of its extreme fragility and scientific value, access to the cave is strictly limited to approved researchers and exploration teams; it is not open to the public. Photo courtesy of Art Palmer.

Unfortunately, there still are some misinterpretations of the true nature of karst which may lead to an unwanted propagation of conceptual errors that become entrenched in professional practice. One example is the following quote from Zerga (2024) which is an apparent citation from the book by Ford and Williams (2007): "*Karst cannot be produced solely by a significant amount of rock solubility. Rock structure and lithology are also significant factors. Karst is often poorly developed in soluble rocks with extremely high primary porosity (30–50 %).*"

It of course goes without saying that the above statement is far from the truth. Some of the most spectacular and longest caves, deep sinkholes, and largest karst springs in the United States and around the world are developed in *soluble rocks with extremely high primary porosity (30–50 %);* for example, see the following discussion and Figs. 1.14 and 1.15, Figs. 1.18 through 1.21, Fig. 1.28, Fig. 1.37, and Fig. 1.46.



In a paper entitled "Cave Development on the Caribbean coast of the Yucatan Peninsula, Quintana Roo, Mexico", Smart et al. (2006) explain a number of conditions for development of one of the most fascinating collections of surface and subsurface karst landforms in the world.

Figure 1.18 Map of submerged cave passages of *Sistema Sac Actun* in Mexican state Quintana Roon on Yucatan Peninsula north of Tulum. Courtesy of Dr. Emiliano Monroy-Ríos, Northwestern University. This map and many more maps, photographs, visuals, and descriptions of the fascinating Yucatan karst features are available at https://sites.northwestern.edu/monroyrios/

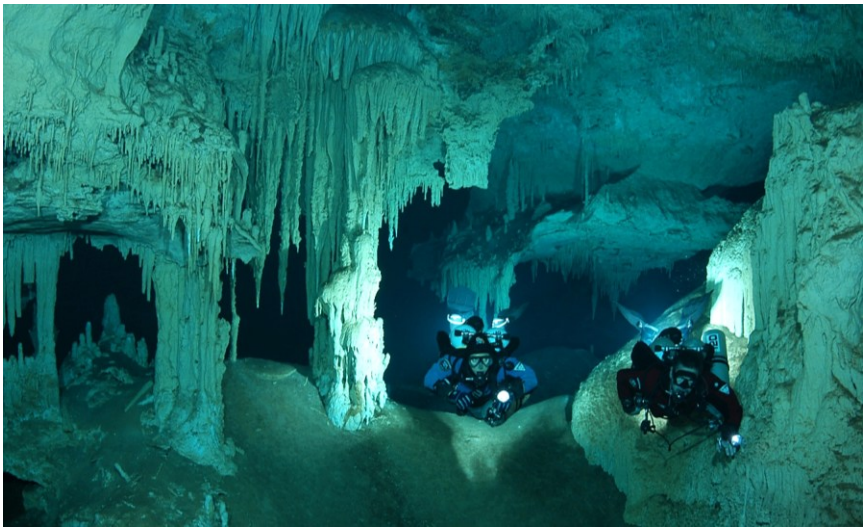


Figure 1.19 *Nohoch Nah Chich*, situated north of Tulum in the state of Quintana Roo, Mexico was once a standalone, famous cave system; it was connected to the *Sistema Sac Actun* in 2007, significantly expanding the overall length of the underwater network. The abundant speleothems were formed before the cave was submerged due to rising sea level after the last major glaciation. Photo courtesy of David Rhea, Global Underwater Explorers.

Below are couple of excerpts from this excellent work as related to the previously discussed incorrect statement that "Karst is often poorly developed in soluble rocks with extremely high primary porosity (30–50 %)."

The limestones may still be diagenetically immature, with a high primary porosity and presence of metastable carbonates, while the ubiquitous fracture sets of telogenetic karst are generally absent."…"*However, across most of the study area, the preferred cave inception flow pathways are probably associated with linked vug porosity and developed by random linkages between dissolution-susceptible fragments and existing voids.*"

The area of Quintana Roo in Yucatan, Mexico features hundreds of miles of submerged cave passages formed in young Pleistocene limestones which have a primary porosity ranging from 29% to 50%. This includes the longest submerged cave system in the world, *Ox Bel Ha* (the name "Ox Bel Ha" is Yucatec Maya for "Three Paths of Water".) As of early 2026, it has a surveyed length of approximately 336.6 miles (541.7 kilometers).

The title of the world's longest submerged cave has frequently changed hands between *Ox Bel Ha* and *Sistema Sac Actun* (White Cave), now the second longest with 228.7 miles (368 km) of surveyed passages as of 2026.



Figure 1.20 Cenote Oxman, about 25 miles east of Chichén Itzá, Yucatan. Photo by Carlos Rosado van der Gracht, courtesy of Yucatan Magazine. The word "cenote" comes from the Mayan word "dz'onot", which means "cavern with water". It describes a natural pit in limestone terrain, formed by the collapse of the top of a cavern. These large water holes played a very important role in the life of the Maya. The Yucatán has virtually no surface rivers because all the water drains directly into the porous limestone. For the ancient Maya, cenotes were therefore not just scenic wonders; they were the indispensable source of life—the only reliable year-round water supply in a dense jungle.



Figure 1.21 Devil's Ear Spring, part of the Ginnie Springs cave system in Gilchrist County, Florida. This submerged cave system, approximately 5.7 miles long, is developed within the Ocala Limestone, which is an Eocene-aged limestone, making it approximately 34 to 38 million years old. The primary porosity of the Ocala Limestone at Ginnie Springs is remarkably high for a rock of its age, typically averaging around 30% to 40% (Florea and Vacher, 2009). Unlike older "telogenetic" limestones (such as those in Kentucky's Mammoth Cave), which often have primary porosities of only 2–3%, the Ocala Limestone acts like a massive, hard sponge. Ginnie Springs achieved an unrivaled fame among scuba divers of all skill levels when Jacques Cousteau dove here in 1974 and praised the crystal-clear water (72°F year-round) as "visibility forever." It is the international hotspot for scuba diving. Photo by John Moran; all right reserved, printed with permission.

Cave passages in soluble carbonate sediments provide an invaluable insight into the role geologic fabric plays in the development of karst and the control of groundwater flow directions. Such passages, developed by dissolution along initial discontinuities in the rock mass, are literary evidence "written in stone". An illustrative excerpt from an excellent publication by Swezey et al. (2017) follows below. It illustrates the impact of geologic fabric on karst development and inckudes Figs. 1.22 through 1.24.

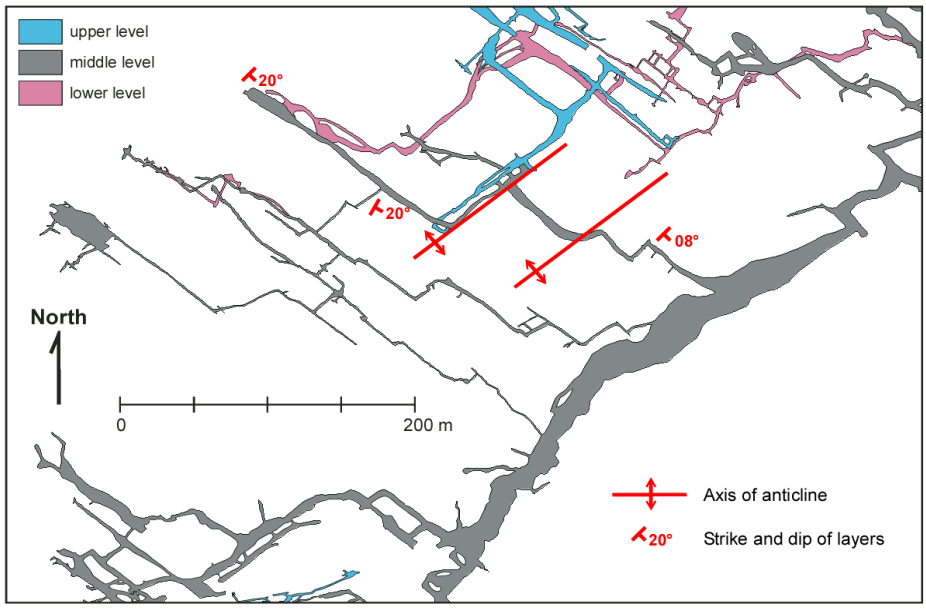


Figure 1.22 Section of map of Butler Cave – Sinking Creek Cave System, Bath County, Virginia showing mapped cave passages. Modified from Swezey et al., 2017, *Geologic controls on cave development in Burnsville Cove, Bath and Highland Counties, Virginia*. From the Blue Ridge to the Beach: Geological Field Excursions across Virginia. The Geological Society of America Field Guide 47; originally modified from White, 2015.

Collectively, the structural and stratigraphic setting of Burnsville Cove influences cave passage morphology. For example, many of the cave passages are tall and narrow, and follow joints. Other cave passages are relatively wide and have flat ceilings and (or) floors. Such passages typically form where the cave ceiling and (or) floor follows a bedding plane. Yet other cave passages have arched ceilings where the passages follow folds in the strata."…"In some instances, both bedding planes and joints exert strong controls on passage morphology, leading to a trapezoid passage profile with a narrow inverted V-shaped cavity at the top of the trapezoid shape.



Figure 1.23 Examples of fissure control on development of passages in caves of Highland and Bath Counties, Virginia. All photos courtesy of Phil Lucas.



Figure 1.24 Lost Cove Cave twilight, Crow Creek, Mr. and Mrs. Harry Lee Carter Natural-Scientific State Natural Area, Franklin County, Tennessee. The cave passage is developed along bedding planes. Photo courtesy of Chuck Sutherland.

Faults are one of the key structural elements that influence the development of preferential flow paths in karst aquifers and groundwater flow directions at various scales. They often form hydraulic boundaries for groundwater flow in both consolidated and unconsolidated rocks. They may have one of the following three roles: (1) preferential pathways for groundwater flow, (2) storage of groundwater due to increased porosity within the fault (fault zone), and (3) barriers to groundwater flow due to decrease in porosity within the fault. The following discussion by Meinzer (1923) illustrates these points:

> *Faults differ greatly in their lateral extent, in the depth to which they reach, and in the amount of displacement. Minute faults do not have much significance with respect to ground water except, as they may, like other fractures, serve as containers of water. But the large faults that can be traced over the surface for many miles, that extend down to great depths below the surface, and that have displacements of hundreds, or thousands of feet are very important in their influence on the occurrence and circulation of ground water. Not only do they affect the distribution and position of aquifers, but they may also act as subterranean dams, impounding the ground water, or as conduits that reach into the bowels of the earth and allow the escape to the surface of deep-seated waters, often in large quantities. In some places, instead of a single sharply defined fault, there is a fault zone in which there are numerous small parallel faults or masses of broken rock called fault breccia. Such fault zones may represent a large aggregate displacement and may afford good water passages.*

As discussed by Hatcher (1995), joints frequently form adjacent to brittle faults. Movement along faults commonly produces a series of systematic fractures in which spacing decreases closer to the fault zone, and the number of sets of joints increases. It is for this reason that fault zones in carbonate sediments and other rocks that do not have significant fine-grain fraction (sandstones are an example) do act as preferential flowpaths and can collect and transfer significant quantities of groundwater. Some of the largest springs in the United States and worldwide owe their existence to faults. For example, San Marcos and Comal Springs of Central Texas are the largest springs in the southwestern United States. The artesian springs emerge at the base of the Balcones Escarpment, a series of large-displacement faults that force the water of the karstic Edwards aquifer to discharge at he land surface (Figs. 1.25 and 1.26). Other good examples of fault-controlled springs are springs in the classic Dinaric karst of former Yugoslavia, some of which are the largest in the world (see Fig. 1.7).

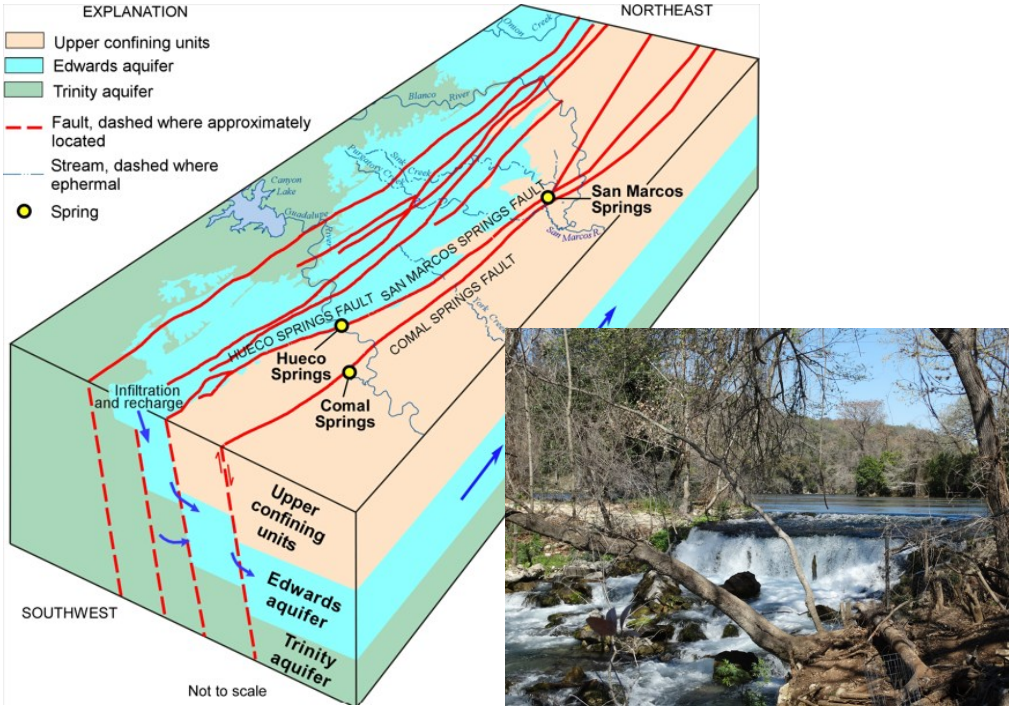


Figure 1.25 *Left*: Idealized block diagram of the Edwards aquifer in the vicinity of Comal, Hueco, and San Marcos Springs, south-central Texas. Modified from Musgrove and Crow, 2012. *Right*: Eastern overflow from the discharge basin of San Marcos Springs, Texas.



Figure 1.26 *Left*: Barton Springs Fault, Austin, Texas. On the left is Georgetown Formation, and on the right side is the Edwards Group. Photo by Brian Hunt (available at https://www.austingeosoc.org/geo-photos/). *Right*: Typical fault in the Balcones Fault Zone, Edwards Aquifer, Texas. Photo courtesy of Gregg Eckhardt.

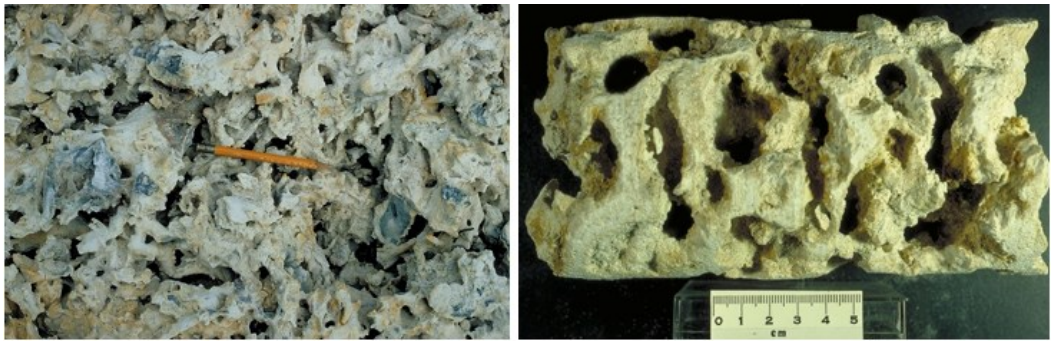


Figure 1.27 Young Florida limestones such as Miami oolite of the Biscayne aquifer have very high primary porosity (left photo) which, together with the dissolution-enhanced secondary ("vuggy") porosity (right photo), makes them one of the most prolific karst aquifers in the world. High-capacity municipal wells commonly produce more than 1,000 gpm with drawdown less than 1-2 feet. Photographs by George Sowers, printed with kind permission of Francis Sowers.

In young Eocene limestones such as those of Floridan and Biscayne Aquifers in Florida, development of cavities and preferential flow paths is seemingly chaotic and much less influenced by fractures and faults compared to old, consolidated Mesozoic and Paleozoic carbonates. This is illustrated in Figs. 1.27 and 1.28 where both the scale of drilling core samples and the cave images resemble sponge-like structures. Because of the very high primary porosity (porosity formed by lithogenesis, i.e., during rock formation), which is enhanced by dissolution, these karst aquifers are the most prolific in the United States.



Figure 1.28 *Left*: Map of the Weeki Wachee Springs Cave System, Florida. Courtesy of Karst Underwater Research. *Right*: Screenshot of a diving video at Radium Springs, Georgia, October 31, 2015, taken by Guy Bryant with divers Kelly Jessop and Peter Buzzacott. Note high "sponge" ("vuggy") porosity of the upper Eocene Ocala limestone due to dissolution. Video available on YouTube (CDroHO56F-Y)

One very important aspect of karstification is that the conduit/channel network continues to expand both vertically (Fig. 1.29) and laterally. Consequently, groundwater connections, i.e., flow directions, can often develop across topographic drainage divides when carbonate deposits are sufficiently thick and extensive. This is true for both local and regional scales of interest. The two most obvious results of this inconsistency between topographic and groundwater divides in karst terrains are sinking and dry streams (Figs. 1.31 through 1.33) and large springs.

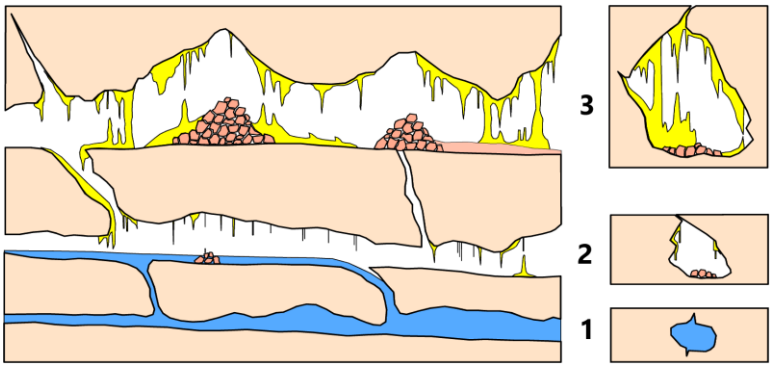


Figure 1.29 Main phases in cave development. (1) Initial stage: phreatic conduit being developed below water table by dissolution. (2) Intermediate stage: cave passage with permanent to intermittent flow on the floor, vertical erosion and dissolution of rock transfers most of the flow to the lower level; speleothems starting to form, occasional rock fall. (3) Last phase of cave development—permanently dry passages with a variety of abundant speleothems. From Kresic, 2013.



Figure 1.30 Relict of an initial tubular (phreatic) conduit in Mammoth Cave, Kentucky, now rarely active and reshaped by downcutting towards lowered karstification base. Photo courtesy of Nenad Marić.

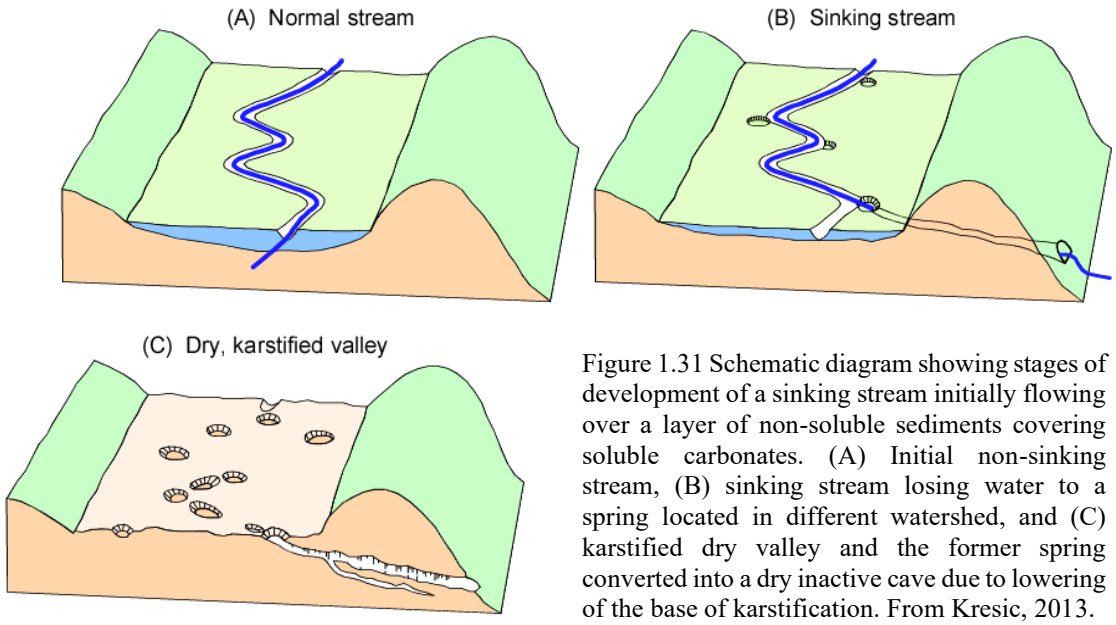


Figure 1.31 Schematic diagram showing stages of development of a sinking stream initially flowing over a layer of non-soluble sediments covering soluble carbonates. (A) Initial non-sinking stream, (B) sinking stream losing water to a spring located in different watershed, and (C) karstified dry valley and the former spring converted into a dry inactive cave due to lowering of the base of karstification. From Kresic, 2013.



Figure 1.32 *Left*: Recharge into Kiwi Sinkhole, near Driftwood, Texas. Photo courtesy of Brian Hunt. *Right*: Whirlpool over Crippled Crawfish Cave on the losing Onion Creek when flowing, near Austin, Texas. Photo courtesy of David Johns.

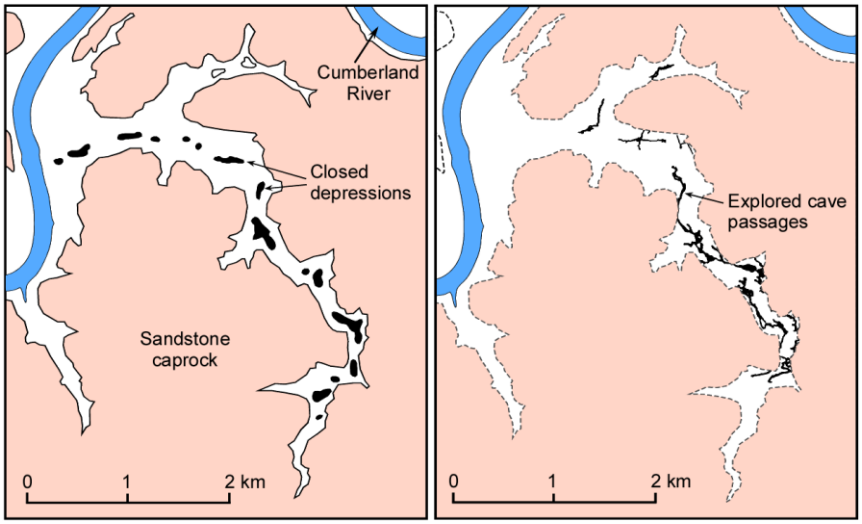


Figure 1.33 *Left*: Closed surface depressions in the Cave Creek dry valley, Pulaski County, north-central Kentucky. Stream erosion breached low-permeable caprock of sandstone and shale and exposed underlying limestone in which these depressions are developed. *Right*: Three-dimensional network of cave passages totaling 17 km in length closely follows the valley axis. Modified from Ewers, 1985; cave information provided courtesy of Louis Simpson.

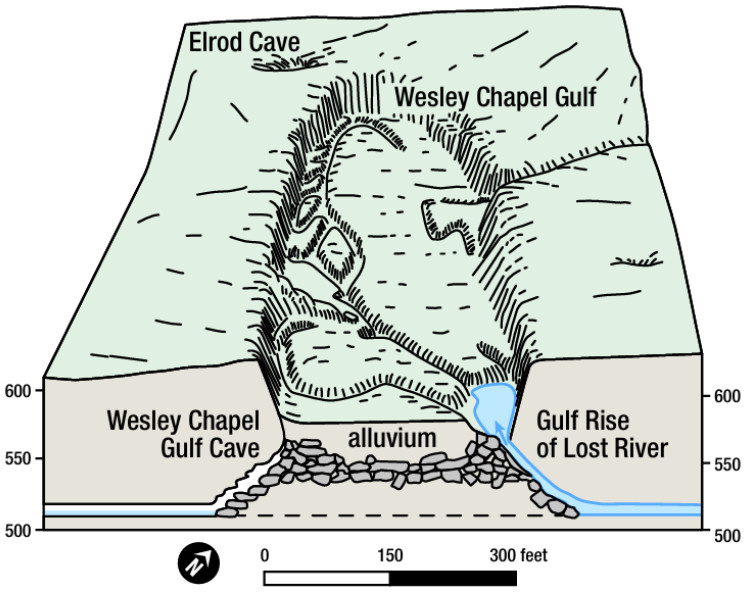


Figure 1.34 Idealized block diagram showing subterranean drainage at Wesley Chapel Gulf, Lost River watershed, Indiana. From *Lost River Field Trip for the Indiana Water Resources Association* by Richard L. Powell. Wesley Chapel Gulf is owned by the U.S. Forest Service and was declared a *National Natural Landmark* in 1972. The steep perimeter of this collapse sinkhole encloses about 8.3 acres and contains an alluvial floor of 6.1 acres. Nearly the entire floor of the gulf is an alluvial flood plain created by deposition of sediment from storm waters discharged from the Gulf Rise of Lost River located in the southeast end of the gulf. A submerged cave passage with a diameter of about 3 feet descends about 160 feet to a large passage about 10 feet high and 30 feet wide for a distance of at least 200 feet (S.D. Maegerlein, 1983, personal communication). During the time that the gulf was mapped in 1931, Malott (1932, p. 294) counted around 100 swallow holes in the floor of the gulf.

To emphasize, the three most important characteristics of groundwater flow in karst aquifers are: (1) natural groundwater divides often do not coincide with surface water (topographic) divides as a result of losing, sinking, and dry streams; (2) groundwater velocities in conduits could be extremely high, on the order of hundreds of meters or more per day; and (3) aquifer discharge is often localized through large karst springs, which have subsurface drainage areas commonly larger than the topographic ones.

A large permanent karst spring usually represents the end point of an integrated karst water system, developed both at the land surface and in the subsurface. Such a system is sometimes referred to as *springshed*, the term commonly used in Florida (Fig. 1.35).

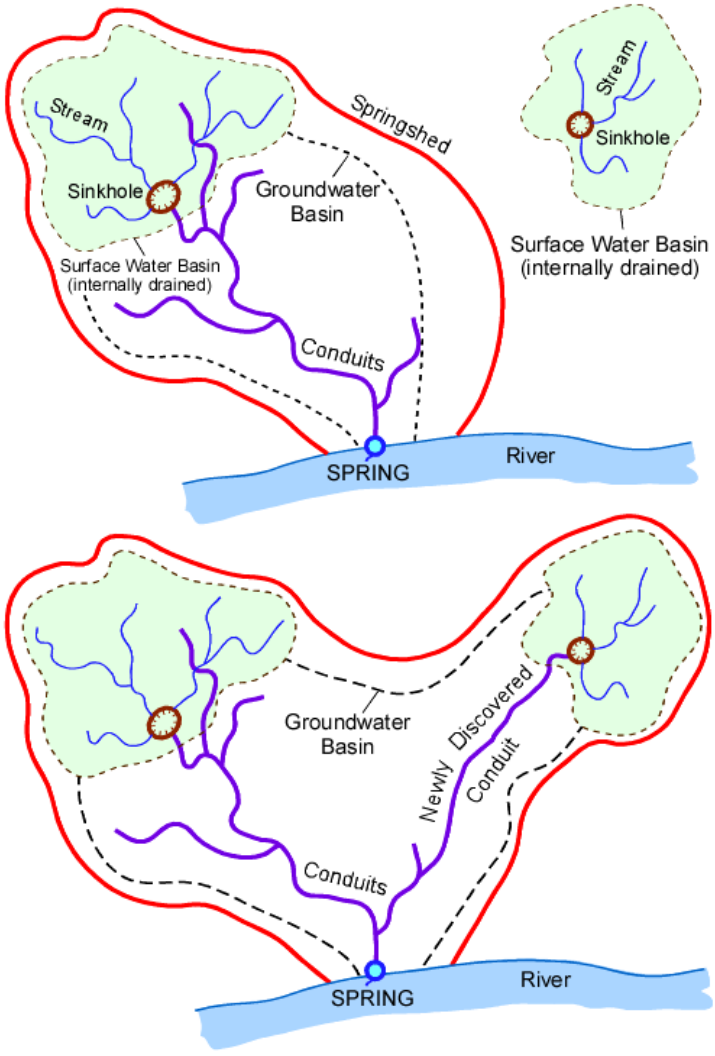


Figure 1.35 *Top*: Springshed boundary depicting surface water and groundwater basins. *Bottom*: Revised springshed boundary based on results of cave diving exploration and tracer tests that confirm the presence of conduits connecting a nearby surface water basin to the springshed. Modified from Arthur et al., 2002.

Dye tracing, the only direct method for determining drainage areas of karst springs and karst groundwater drainage areas in general, often results in unexpected connections (Fig. 1.36). These connections may vary in time depending on the season and major recharge events so that dye tracing tests must be repeated with different dyes and for different hydrologic conditions to accurately determine groundwater flow directions and delineate surface and subsurface drainage areas of interest. Assessing temporal variation of groundwater flow directions and hydraulic heads in the aquifer is a critical step for any project in karst for which a conceptual model is being developed.

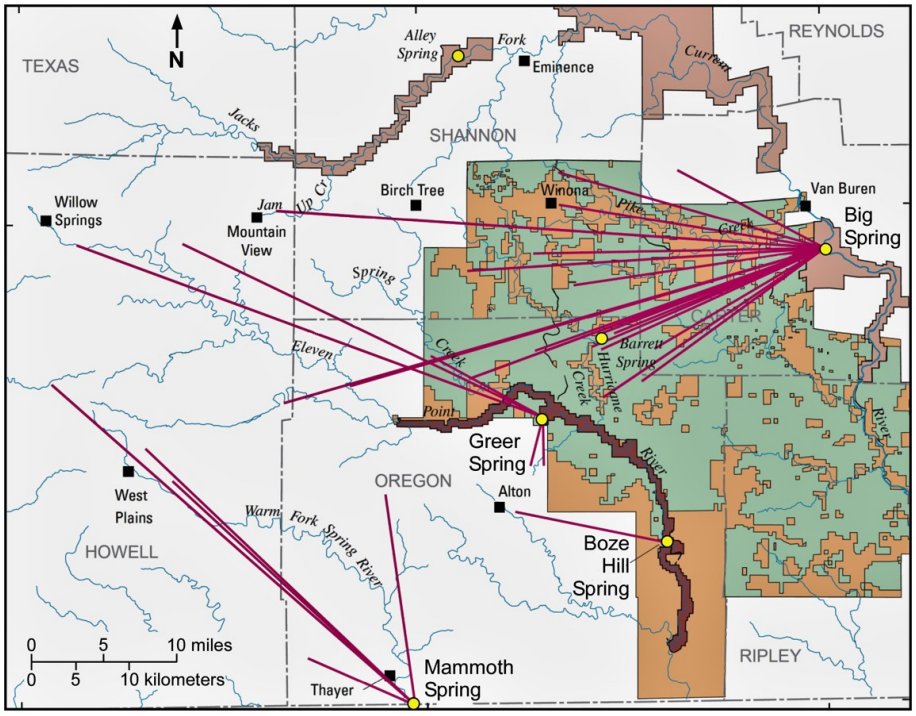


Figure 1.36 Results of dye-tracing investigations that successfully identified a hydrologic connection between a sinkhole or a losing stream reach and a major spring in south-central Missouri. Dye traces are in dark pink, different color polygons represent various land uses. Note how different dye traces cross different watersheds, sometimes intersect, and can be more than 30 miles long. Modified from Imes et al., 2007.

1.1.1 Sinkholes

Sinkholes, together with large springs and caves, are the most obvious signs that the underlying and host rocks are karstified. They can also reveal potential presence of preferential flowpaths in the aquifer below when occurring in linear patterns (see Fig. 1.37 and Fig. 1.1). Being closed depressions, sinkholes also present areas of focused, enhanced aquifer recharge as they interrupt overland precipitation runoff over larger areas and are internally drained downwards. This is one of the reasons why, compared to other aquifer types, karst aquifers generally have higher rates of recharge.

As discussed by Ann Tihansky of USGS (https://pubs.usgs.gov/circ/circ1182/pdf/15WCFlorida.pdf), new sinkholes have been correlated to land-use practices. Induced sinkholes are conceptually divided into two types: those resulting from groundwater pumping and those related to construction and development practices. Modified drainage and diverted surface water commonly accompany construction activities and can lead to focused infiltration of surface runoff, flooding, and erosion of sinkhole-prone earth materials. Manmade impoundments used to treat or store industrial- process water, sewage effluent, or runoff can also create a significant increase in the load bearing on the supporting geologic materials, causing sinkholes to form. Other construction activities that can induce sinkholes include the erection of structures, well drilling, dewatering foundations, and mining.

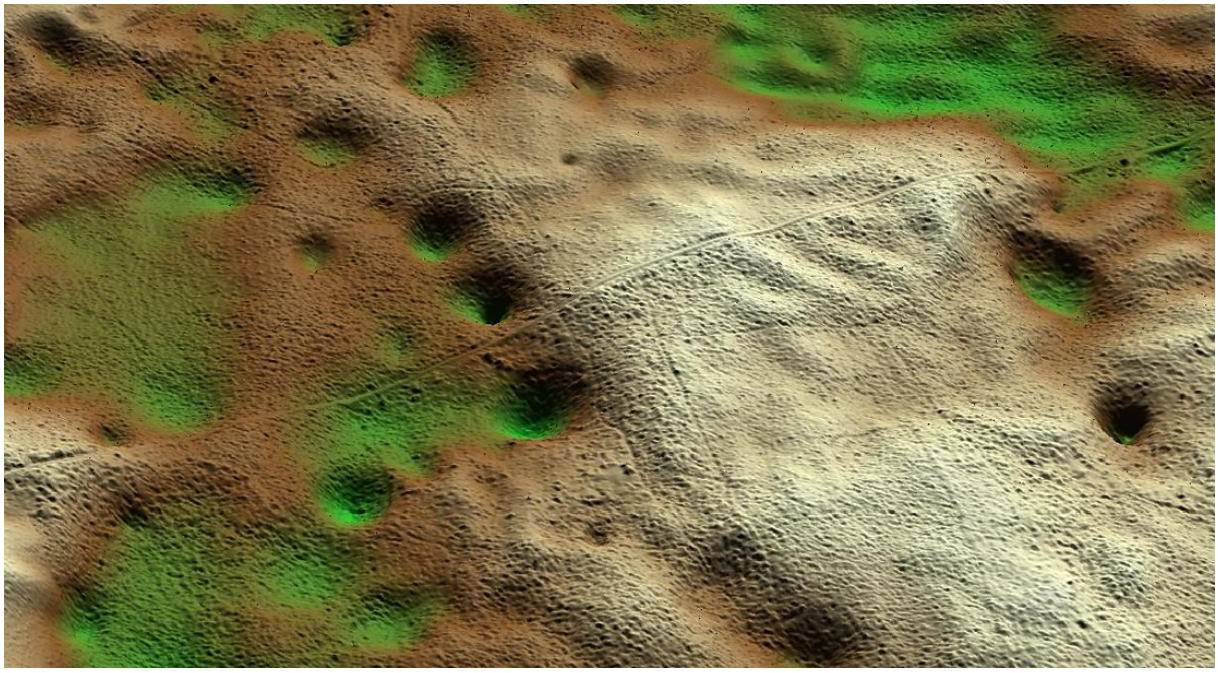


Figure 1.37 Digital elevation model created from high-resolution data collected by airborne LiDAR (Light Detection and Ranging) instrument. Lines of sinkholes like these near Ocala, Florida, developed in surficial sandy sediments, indicate possible preferential flow paths in the underlying karst aquifer. Note the extraordinary detail obtained by the LiDAR technology. Depth of the wider sinkhole by the road is about 20 ft (from Kresic, 2013).



Figure 1.38 Sinkholes in Monroe County, West Virginia. Photo courtesy of William Jones.

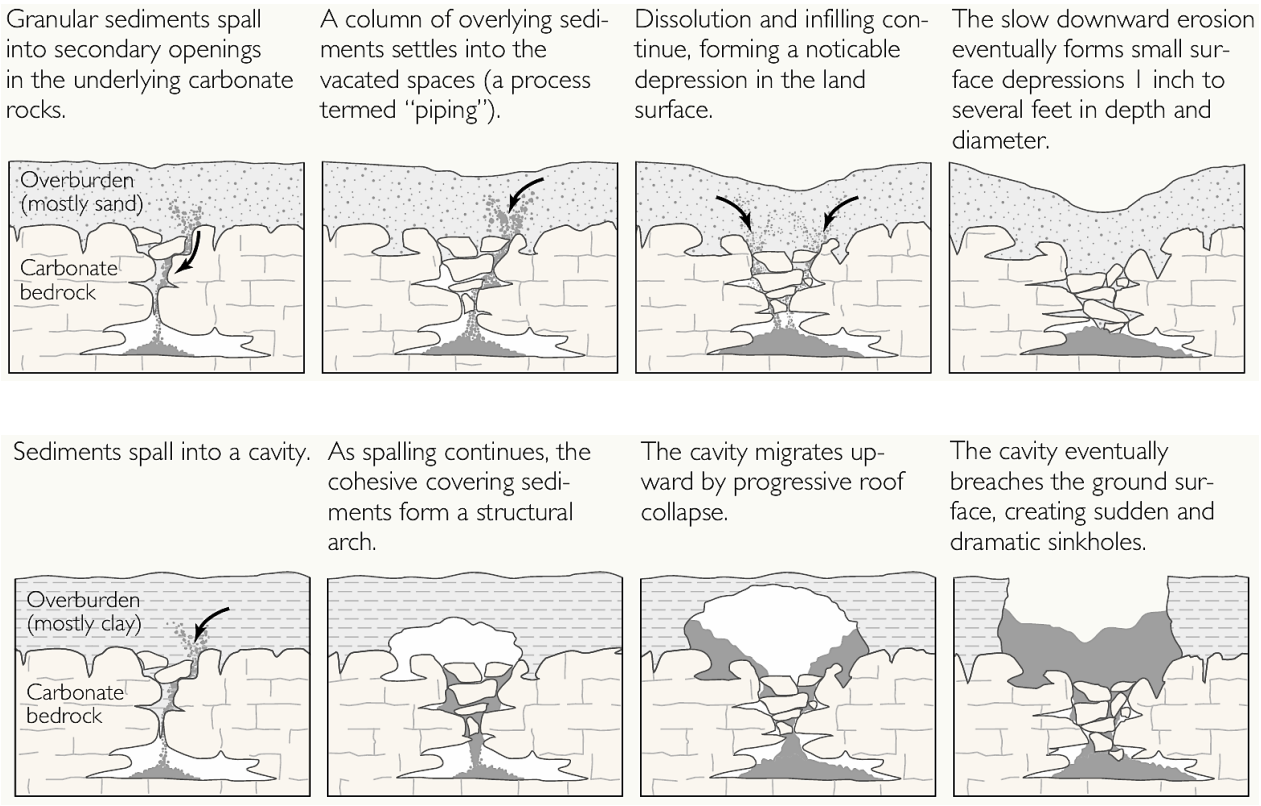


Figure 1.39 *Top*: Cover-subsidence sinkholes tend to develop gradually where the covering sediments are permeable and contain sand. In areas where cover material is thicker or sediments contain more clay, cover-subsidence sinkholes are relatively uncommon, are smaller, and may go undetected for long periods. *Bottom*: Cover-collapse sinkholes may develop abruptly (over a period of hours) and cause catastrophic damages. They occur where the covering sediments contain a significant amount of clay. Over time, surface drainage, erosion, and deposition of sediment transform the steep-walled sinkhole into a shallower bowl-shaped depression. From: *Sinkholes, West-Central Florida, A link between surface water and ground water* by Ann B. Tihansky, U.S. Geological Survey, Tampa, Florida https://pubs.usgs.gov/circ/circ1182/pdf/15WCFlorida.pdf

Excessive irrigation can also cause sinkhole development as the surficial sediments become oversaturated. The increased weight or load of the saturated sediments can contribute to water ponding by causing some subsidence. In turn, the increased load can trigger the development of cover-collapse sinkholes.

The overburden sediments that cover buried cavities in the aquifer systems are delicately balanced by groundwater fluid pressure. In sinkhole-prone areas, the lowering of groundwater levels, increasing the load at land surface, or some combination of the two, may contribute to structural failure and cause sinkholes.

Aggressive pumping can induce sinkholes by abruptly changing groundwater levels and disturbing the equilibrium between a buried cavity and the overlying earth materials. Rapid declines in water levels can cause a loss of fluid-pressure support, bringing more weight to bear on the soils and rocks spanning buried voids. As the stresses on these supporting materials increase, the roof may fail and the cavity may collapse, partially filling with the overburden material. Prior to water-level declines, incipient sinkholes are in a marginally stable stress equilibrium with the aquifer system. In addition to providing support, the presence of water increases the cohesion of sediments. When the water table is lowered, unconsolidated sediments may dry out and coarser-grained sediments, in particular, may move easily into openings (Tihansky, 1999).

Induced sinkholes are generally cover-collapse type sinkholes and tend to occur abruptly. They have been forming at increasing rates during the past several decades and pose potential hazards in developed and developing areas of west-central Florida. The increasing incidence of induced sinkholes is expected to continue as our demand for groundwater and land resources increases. Regional declines of ground-water levels increase sinkhole occurrence in sinkhole-prone regions. This becomes more apparent during the natural, recurring periods of low annual rainfall and drought (Tihansky, 1999).



Figure 1.40 A 40-foot sinkhole at the National Corvette Museum in Bowling Green, KY, swallowed eight of the sports cars on display inside the facility's iconic Sky Dome early Feb. 12, 2014. Photo courtesy of National Corvette Museum. https://www.corvettemuseum.org/sinkhole

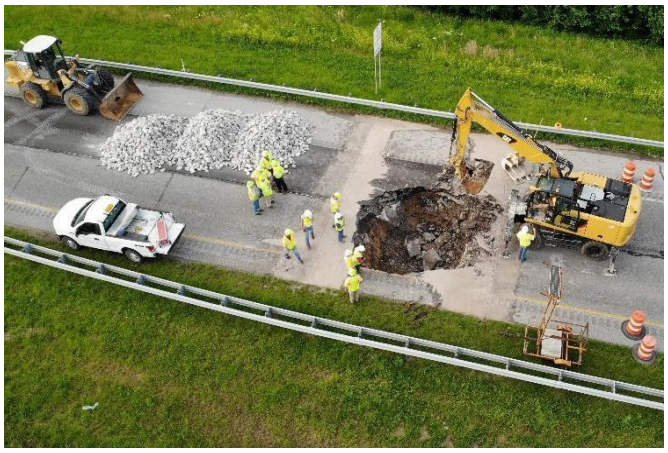


Figure 1.41 Sinkhole repair. From "Sinkhole closes I-265 East in southern Indiana for 12 hours" by Fallon Glick: *A sinkhole opened up on I-265 East near Charlestown Road….Two people were killed in the backup caused by the sinkhole*. Image credit: WDRB Sky Cam. (Sinkhole closes I-265 East in southern Indiana for 12 hours | Local News | wdrb.com)



Figure 1.42 Barry County sinkhole. Photo courtesy of Missouri Department of Natural Resources. Sinkholes | Missouri Department of Natural Resources

1.2 Types and Characteristics of Karst Springs

A spring is a location at the land surface where groundwater discharges from the aquifer, creating a visible flow. This discharge is caused by difference in the elevation of the hydraulic head ("groundwater level") in the aquifer and the elevation of the land surface where the discharge is taking place. The opening through which groundwater discharges is called spring orifice. Springs issuing from consolidated rocks usually have a well-defined orifice, as opposed to springs in unconsolidated sediments, although the latter ones may also have a clearly visible orifice.

A fracture (or fissure) spring refers to concentrated discharge of water from bedding planes, joints, cleavage, faults, and other breaks in the consolidated fractured rock. In karst, fracture springs are in many cases modified by dissolution and often referred to as cave springs (Fig. 1.43).

Secondary springs issue from locations located away from the primary spring discharge, which is covered by colluvium (rock fall fragments) or other natural debris and therefore not visible. Although karst is best known for its spectacular cave springs (Fig. 1.43-*Right*), the water seldom runs entirely from a single opening at any given location. Often near large cave springs, there are scattered smaller springs issuing from a variety of openings at different elevations, some of them active only after heavy rains.



Figure 1.43 *Left*: Fracture enlarged by dissolution at the Montezuma Well outlet spring in Arizona. *Right*: Rick's Springs in Wasatch-Cache National Forest, 15.7 miles from Logan, Utah, up Logan Canyon Scenic Byway (Utah 89). Photo courtesy of US Forest Service.

What is called a single spring in one locality may be equivalent to what in another locality is regarded as a group of springs, each of which has an individual name. Some springs are designated in the singular and some in the plural—for example, Silver Spring (such as main headspring of what is now called Silver Springs in Florida) and Comal Springs in Texas. The idea that underlies this usage is that if the water issues from a single opening or from several openings that are close together, it forms a spring, whereas if it issues from a number of openings that are farther apart, it forms springs. However, local terminology is so variable in this respect that there is no consistent distinction between "a spring" and "springs" and often there is no uniformity in usage of terms even for the same group of openings (Meinzer, 1927).

All springs (except some associated with young volcanism and hydrothermal activity where discharge is driven by gases and temperature gradients) ultimately discharge at the surface because of the force of gravity. Regardless of the rock type, they are divided into two main groups based on the nature of the hydraulic head ("aquifer water pressure") in the underlying aquifer at the point of discharge:

- **Gravity springs** emerge under unconfined conditions where the water table intersects the land surface. In the case of well-defined cave springs in karst, this is equivalent to a free flowing, predominantly horizontal or gently sloping cave, where the cross-sectional perimeter of the cave is not fully submerged most of the time. Such springs are also called descending springs (e.g., see Figs. 1.44 and 1.45).
- **Artesian springs** discharge under pressure due to confined conditions in the underlying aquifer. They are also called ascending or rising springs. The spring orifice is completely submerged, and so are the karst cavities (conduits) supplying water to the springs (Fig. 1.46). The main feeder conduit(s) of these springs is often vertical or quite steep and, if visible and large enough, presents a continuing challenge to brave cave divers who want to see where it goes. Ascending springs are also called **vauclusian springs**, named after Fontaine de Vaucluse in southern France (Fig. 1.47).

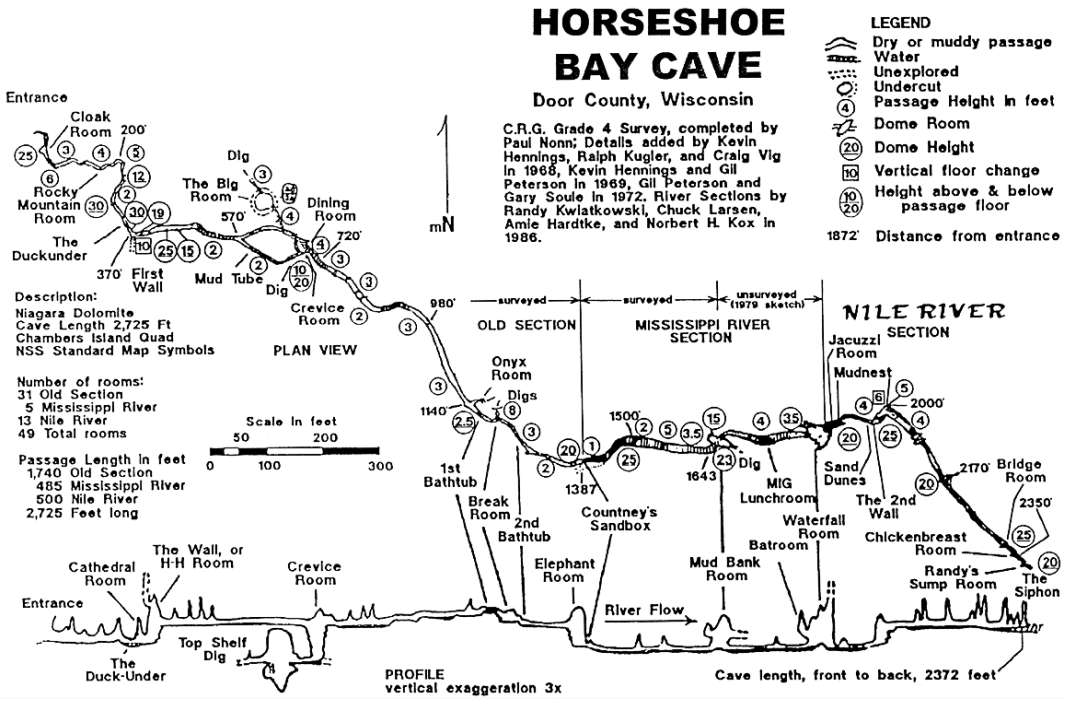


Figure 1.44 Map and profile (bottom) of Horseshoe Cave, a simple flow-through cave. There are both dry passages and passages with water flowing after heavy rain and snowmelt. Horseshoe Bay Cave is one of the longest caves in northeastern Wisconsin, located near the shore of Green Bay in Door County. Courtesy of Wisconsin Speleological Society.



Figure 1.45 Entrance to Horseshoe Bay Cave in Wisconsin. The cave's existence has been known since at least 1896, when two hunters noticed water emerging from the bluff. From 1959 to 1963, cavers explored and mapped 1,740 ft (530 m) of passage, much of it low, wet, and cold. In 1978 cavers dug through a sand and gravel filled crawlway at the end of the mapped passage and entered a watery stream crawlway leading to about another thousand feet of passage. Cave divers have gone even farther. The cave is unusual in Wisconsin for containing flowing water—most Wisconsin caves are high above the current water table and developed before valleys were formed by erosion. Many "rooms" in the cave are formed along the passage by solutionally enlarged joints. Occasionally water flows out of the cave, when snow melts rapidly enough. In September 2014 heavy rain caused the entrance to flood. Photo by Eric Aleson, from Zachariasen, 2016.

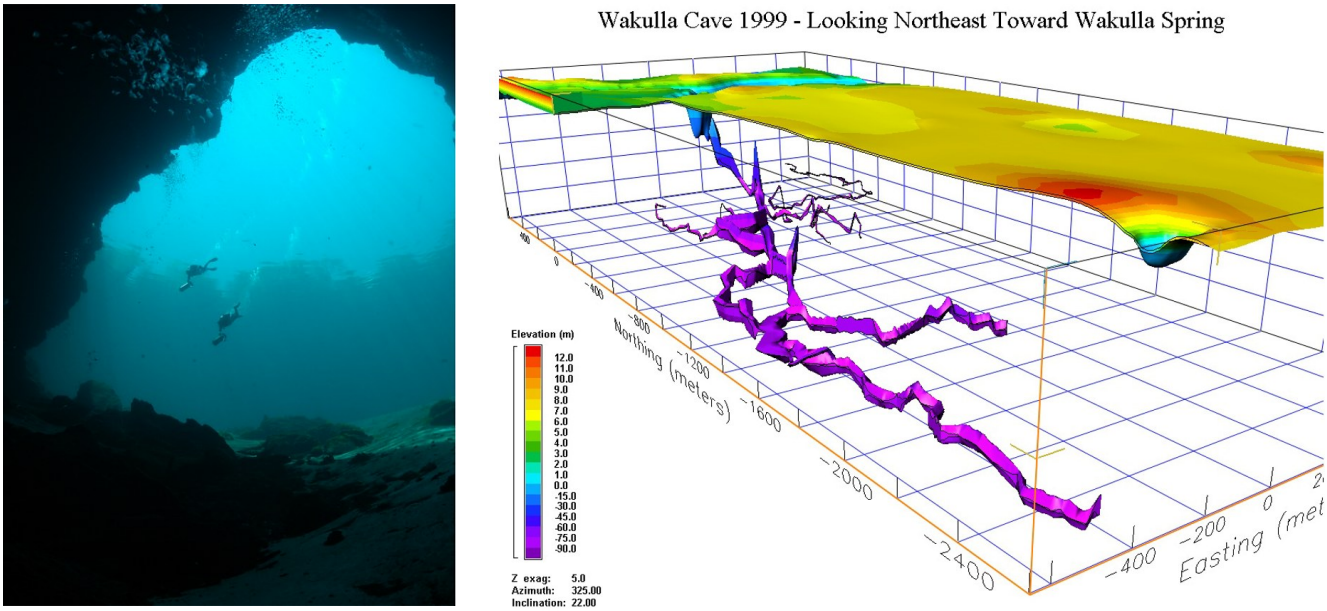


Figure 1.46 *Left*: View of the Wakulla Spring outlet from a cave diver's perspective. This first magnitude spring in Wakulla County, Florida, one of the two largest in the country (together with Big Spring in Missouri) has miles of explored submerged cave passages. The spring and the cave are formed in Oligocene-Miocene limestones with very high, primary intergranular porosity of up to 55% (e.g., see Brooks, 1967). Several of the early *Tarzan* movies starring Johnny Weissmuller were filmed in the Wakulla Springs State Park. Photo copyright David Rhea & Global Underwater Explorers 2006, printed with permission. *Right*: Computer-generated view of the submerged Wakulla Cave passages based on the cave diving surveys. The passages all converge toward the Wakulla Spring which is one of only three springs in the World included on the list of World Geoheritage Sites by the International Union of Geological Sciences The other two are also karst springs, Buna Spring in Bosnia and Herzegovina (Fig. 1.7), and Fontaine de Vaucluse in France (Fig. 1.47). 3D view courtesy of Dr. Todd Kincaid.



Figure 1.47 *Left*: Upper outlet of the Fontaine de Vaucluse during high discharge (64.5 m^3/s or 2278 cfs). Photo courtesy of E. Simon, available at https://iugs-geoheritage.org/geoheritage_sites/fontaine-de-vaucluse/. *Right*: The main outlet is dry when the spring discharges only at a lower level, through colluvium in a narrow valley downgradient. Photo available at https://uk.islesurlasorguetourisme.com/page/when-to-come-see-the-source+5638.html. The main steep/vertical feeder conduit (Fig. 1.49) is explored to depth of 315 meters (1033 ft) by *Spéléonaute*, a remotely operated vehicle (ROV). The spring is considered *locus typicus* (prototype) for all such springs worldwide ("vauclusian type spring"). The spring discharge has been recorded since 1878: the average is 17.3 m^3/s (611 cfs), the minimum is 3.1 m^3/s (109.5 cfs), while the maximum exceeds 80 m^3/s (2825 cfs). Photo courtesy of E. Simon, available at https://iugs-geoheritage.org/geoheritage_sites/fontaine-de-vaucluse/.

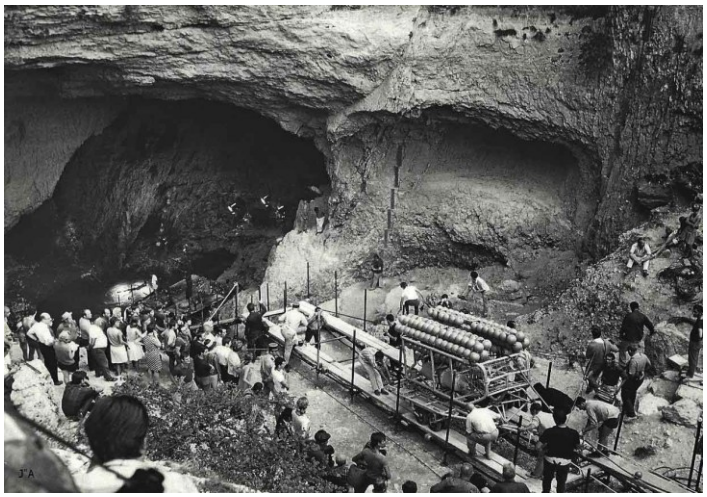


Figure 1.48 Launching of *Telenaute* ROV, 1967. Photo by Jacques-Yves Cousteau. Courtesy of Syndicat Mixte du Bassin des Sorgues.

Virtually all first magnitude karst springs in the United States (springs with average discharge rate higher than 100 cubic feet per second, cfs) and almost all of the largest karst springs in the world are vauclusian. Their drainage areas extend well beyond the immediate topographic divides, and the thickness and therefore the volume of the aquifers (saturated zone below water table) that supply water to these springs are very large. For example, the drainage area of Fontaine de Vaucluse is estimated at 1,160 km^2 (448 mi^2) while the saturated zone is up to 700 m (2297 ft) thick.

Many large and small deep vauclusian springs worldwide are called "Blue Spring", "Pozo Azul" (Spanish), or "Puits Bleu" (French). Their blue color is due to the selective absorption of light by deep, clear, calcium carbonate-rich water. As sunlight hits the water, dissolved microscopic mineral particles in the water absorb longer, warmer

wavelengths (reds, oranges, and yellows) and scatter shorter wavelengths (blues and greens), which are then reflected to our eyes (Figs. 1.50 and 1.51).

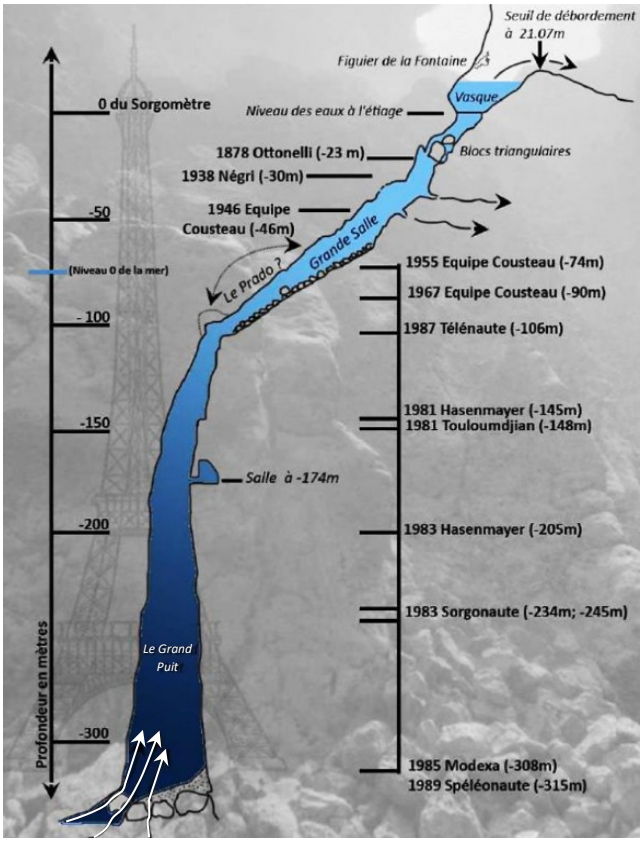


Figure 1.49 Vertical cross-section of Fontaine de Vaucluse, explored to depth of 315 m (1033 ft) in 1989 using *Spéléonaute,* a remotely operated vehicle (ROV*)*. Note the silhouette of Eiffel Tower on the left for scale. Courtesy of Direction Régionale de l'Environnement, de l'Aménagement et du Logement. https://www.fontainedevaucluse.fr/le-gouffre,-la-sorgue



Figure 1.50 Examples of "Blue Holes", ascending karst springs in the Valley and Ridge karst of the Appalachians. *Left*: Ellisons Blue Hole, Crockford-Pigeon Mountain Wildlife Management Area, Walker County, Georgia. *Right*: McBroom Branch Blue Hole, Putnam County, Tennessee. Photographs courtesy of Chuck Sutherland**.**

In many instances, a karst spring represents a combination of the two basic types because of the nature of karst: the karstification process constantly creates new solution cavities (conduits) both vertically and laterally as explained earlier. What ones used to be a "simple" gravity cave spring can evolve into a dry cave spring hanging above the incising erosional level (usually a major stream), while new, lower spring feeder conduits are being

developed trying to catch up with the stream incision. If geological and structural conditions permit, conduits may keep developing deeper below the stream level, and the spring may eventually turn into an ascending one, sometimes discharging directly into the stream without a visible orifice (Fig. 1.52; see also Fig. 1.2).



Figure 1.51 Round Spring in The Ozark National Scenic Riverways, Missouri.

Provided there is enough areal extent and thickness of soluble carbonates, the conduit network feeding the spring will keep expanding including possible underground piracy—the large expanding spring may divert water from the smaller ones which eventually may cease to flow altogether ("big fish eats little fish".)



Figure 1.52 Boiling Spring on Potts Creek, Alleghany County, Virginia. Photo courtesy of Phil Lucas.

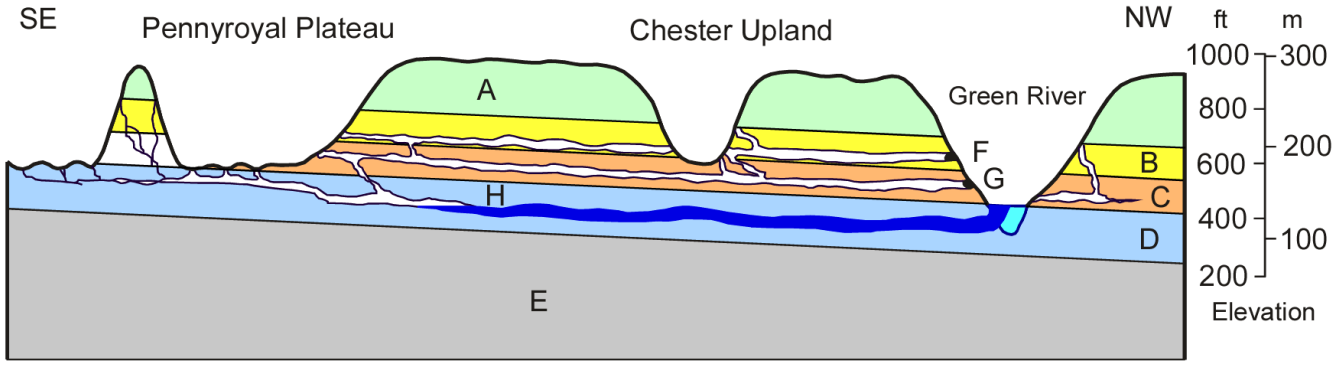


Figure 1.53 Generalized profile through Mammoth Cave (from Palmer, 1985). A=caprock of interbedded sandstone, shale, and limestone (Chesterian Series); B=Girkin Formation; C=Ste. Genevieve Limestone; D=St. Louis Limestone; E=impure limestone and detrital rocks; F=upper cave levels of late Tertiary age; G, H=typical levels of Quaternary age (partial flooding of the lowest level is due to late Pleistocene alleviation of the Green River).

The following points from an educational panel by the Big Spring in Missouri (Fig. 1.54) best illustrate the ever-expanding conduit networks of karst springs. During an average day, Big Spring carries in solution about 173 tons of dissolved dolomite rock. Therefore, in a year's time enough bedrock is removed to form a cave passage 11 feet high by 12 feet high and 1 mile long. Of course, this material is not removed as a unit but is distributed throughout the ramifying system of solution channels that feed the spring. The Big Spring system is continuously

getting larger simply because each year the feeder system grows larger by the removal of rock in groundwater solution and, each year, more rock is exposed to the dissolving action of groundwater.

One piece of practical advice for a novice karst hydrogeologist is that, if a spring is large, behaves like a karst spring (it has notable fluctuations), and appears to have a very significant deficit in its topographic (land surface) drainage area, then it is most likely a karst spring. In other words, even when such a spring discharges from a nonkarstic rock, but there are carbonates somewhere in the vicinity, one should always consider the possibility that the primary aquifer providing water to the spring is a karst aquifer. A very good example is Giant Spring in Great Falls, Montana. This first magnitude spring, one of the largest in the country, was once listed in the Guinness Book of World Records as the world's shortest river called the Roe River that flows into the Missouri River. The spring waters originate as precipitation that falls on the Madison Limestone of Little Belt Mountains over 4,000 ft above the Missouri River. The limestone has all the characteristics of karst, including losing streams and dry caves. At Giant Springs, the Madison Limestone is less than 400 ft below the surface and groundwater from this karstic aquifer escapes upward through a likely fault zone and fractures in the overlying Kootenai sandstone (Fig. 1.55).

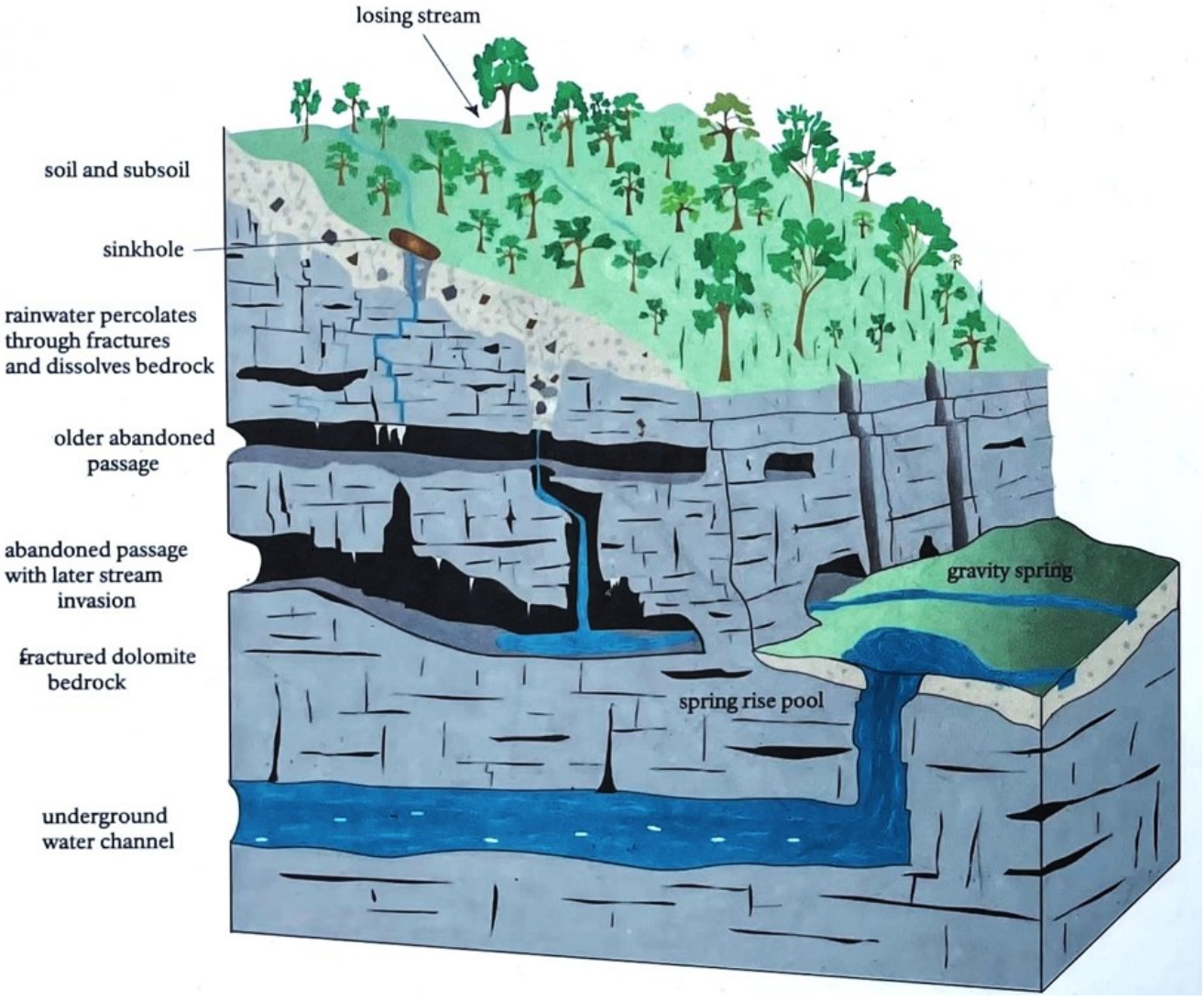
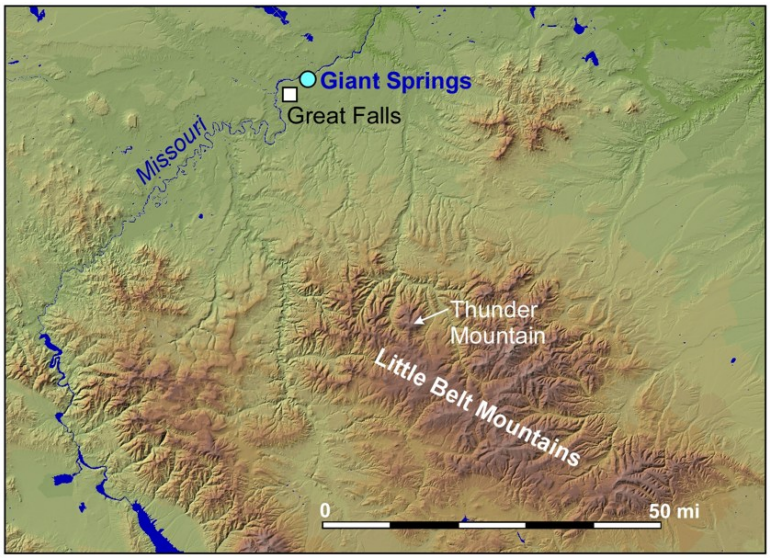
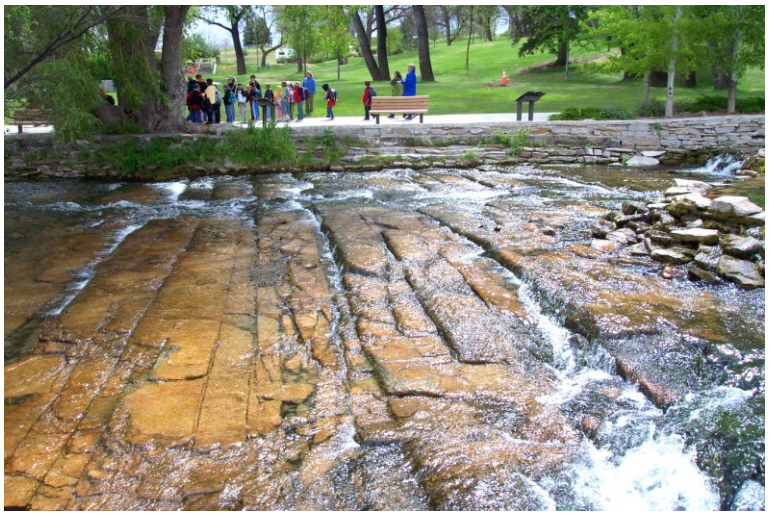


Figure 1.54 Part of a National Park Service informational panel by the Big Spring in Missouri, one of two largest individual karst springs in the country.





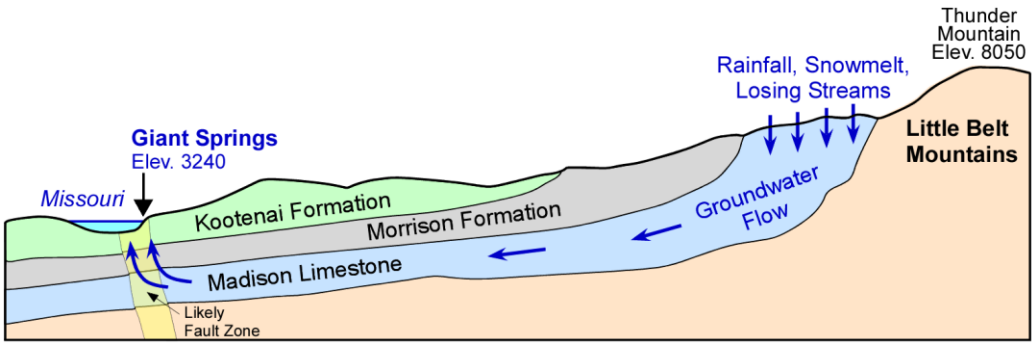


Figure 1.55 *Top*: Main recharge zone for the portion of karstic Madison Limestone Aquifer in Montana, drained by Giant Springs, is in its outcrop areas on Little Belt Mountains *Middle*: The vertical fractures in Kootenai Sandstone at Giant Springs State Park near Great Falls, Montana. Giant Springs is located on the crest of the Sweetgrass Arch—a gentle fold that was tectonically active during deposition of Paleozoic and Mesozoic sediments. Madison Limestone is only 400 feet below the surface. The fractures are extension fractures and are open. They provide an easy conduit for groundwater in the Madison aquifer to rise to the surface and be discharged in and next to the Missouri River. Text and photo courtesy of Dr. David Baker. *Bottom*: Schematic cross-section between Giant Springs and its recharge area in Little Belt Mountains. Modified from a schematic provided by Giant Springs Bottled Water Company.

Estavelle is a spring with a dual function: it acts as a spring during high hydraulic heads in the aquifer, and as a surface water sink during periods when the hydraulic head in the aquifer is lower than in the body of surface water (Fig.1.56). Estavelles are located within or adjacent to surface water features.

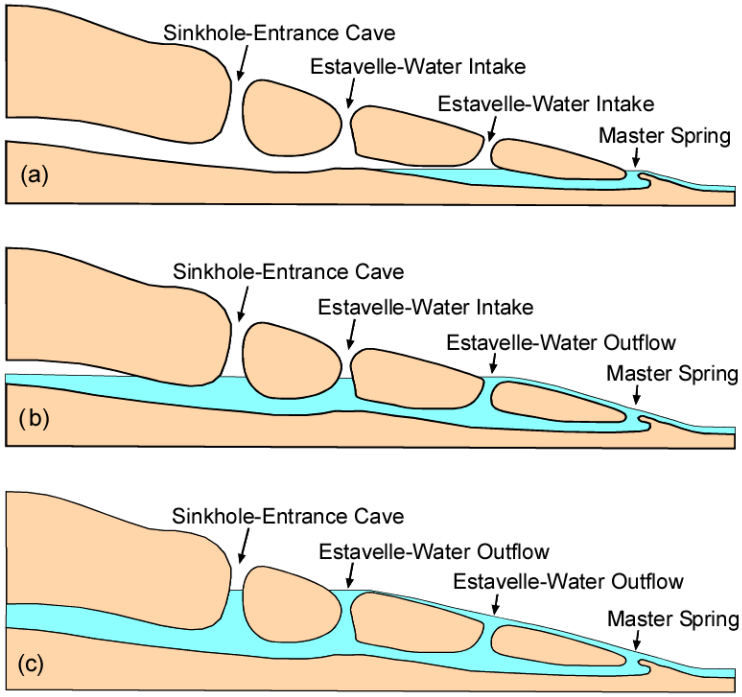


Figure 1.56 Hypothetical stream profile showing sequential reversal of flow in estavelles. (A) Low flow: only lower sections of karst drainage system flooded; estavelles are sinks (swallow holes); (B) medium flow: headward flooding of karst drainage system; lowest estavelle becomes spring (rising); and (C) High flow: storage capacity of karst drainage system exceeded; estavelles become springs, water backs up in headward caves. From Vineyard and Feder, 1974, 1982.

Discharge of *ebb-and-flow springs*, or *periodic springs*, occurs in relatively uniform time intervals (periods) and is explained by the existence of a siphon in the rock mass behind the spring (Fig. 1.57). The siphon fills up and empties with regularity, unrelated to the recharge (rainfall) pattern. The best-known example is Periodic Spring in the Bridger-Teton National Forest near Afton, Wyoming (see also Chapter 3.3 in Volume 2).

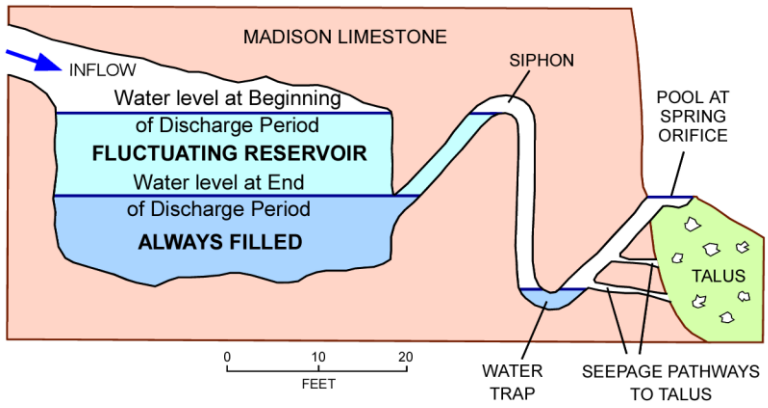


Figure 1.57 Siphon model of the Periodic Spring reservoir. When the reservoir water level reaches the siphon level, the flow commences. Flow continues until the reservoir level drops to base level. From Blanchard et al., 1990; modified from Huntoon and Coogan, 1987.

Karst springs typically have the highest amplitude (oscillation) of discharge rate compared to springs in other aquifer types. This is because of rapid aquifer recharge from precipitation and snowmelt episodes due to karstified rocks, and high transmissive rates of fractures and conduit networks (Fig. 1.58).

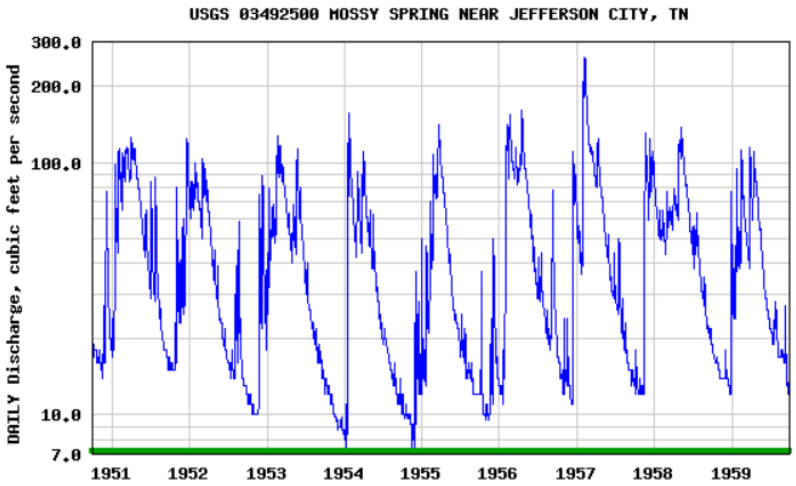


Figure 1.58 Daily discharge rate of Mossy Spring near Jefferson City, the largest spring in Tennessee, for the period of record. Average is 43.8 cfs, minimum is 7.4 cfs, maximum is 261 cfs. Index of Variability is 35.3.

Meinzer's classification of springs based on average discharge (Fig. 1.59) is widely used by the USGS and state agencies. Below are excerpts from the Meinzer publication illustrating the importance of evaluating and classifying springs based on their average discharge (on page 2):

Proposed classification of springs according to discharge

Magnitude	Average discharge
First	100 second-feet or more.
Second	10 to 100 second-feet.
Third	1 to 10 second-feet.
Fourth	100 gallons a minute to 1 second-foot (448 gallons a minute).
Fifth	10 to 100 gallons a minute.
Sixth	1 to 10 gallons a minute.
Seventh	1 pint to 1 gallon a minute. About 200 to 1,500 gallons, or 5 to 40 barrels, a day.
Eighth	Less than 1 pint a minute. Less than about 200 gallons, or 5 barrels, a day.

Figure 1.59 Photo of Oscar Meinzer's table on page 3 of the USGS Water Supply Paper 557 published in 1927. Note that 1 second-feet (cfs) = 449 gallons per minute = 646,000 gallons per day = 28.3 liters per second.

Thus the discharge of a spring can be determined with fair accuracy only by establishing a gaging station and obtaining a continuous record over a period of years. To compare a single measurement of one spring with a single measurement of another spring made at an entirely different time may give a result that is almost as incorrect as would be obtained by a similar comparison of surface streams. The question also arises as to whether a comparison is made according to the minimum, maximum, or average discharge. Thus, if the average discharge of a nearly constant spring is about the same as that of a spring which fluctuates greatly, the constant spring will rank higher with respect to minimum discharge and the fluctuating spring higher with respect to maximum discharge. There is some popular interest in the maximum discharge, but the value of a spring, whether it is used for a public supply, irrigation, power, or other purpose, generally depends more nearly on its minimum discharge, or on its discharge at the time when the most water is needed. In so far as comparisons are attempted in the following discussion, they are based on the average discharge.

As far as this author can tell, it appears that the Florida Geological Survey (FGS) is the only agency in the country that chose not to follow Meinzer's classification of springs based on their long-term average discharge (see Kresic, 2024 for a detailed analysis.) For example, FGS states that *One discharge measurement is enough to place a spring into one of the eight magnitude categories* (Scott et al., 2004. *Springs of Florida*, FGS Bulletin No. 66; emphasis added). This is just one of the reasons why the number of first magnitude springs in Florida grew from 11 (Meinzer's 1927 publication entitled Large Springs in the United States), to 17 in 1947, when Ferguson et al. published their Bulletin No. 31, also entitled *Springs of Florida,* and finally to 33 first magnitude springs in 2004, after various rules and practices in Florida changed.

As emphasized by Meinzer, the classification based solely on average spring discharge, without specifying other discharge parameters, is not very useful when evaluating the potential for spring utilization. For example, a spring may have a high average discharge, but it may be dry or just trickling most of the year. This discharge variability is typically higher in older carbonate rocks with low matrix porosity which cannot store significant volumes of groundwater that would provide relatively sustained flow between rainfall and snowmelt (recharge) episodes. The practice in most countries is that the springs are evaluated based on the minimum discharge recorded over a long period, typically longer than several hydrologic years (hydrologic year is defined as spanning all wet and dry seasons within a full annual cycle). The simplest measure of variability is the ratio of the maximum and minimum discharge, called Index of Variability:

$$I_v = \frac{Q_{max}}{Q_{min}}$$

Springs with the index of variability (I_v) greater than 10 are considered highly variable (see Fig. 1.56), and those with $I_v < 2$ are sometime called *constant* or *steady springs*. Meinzer proposed the following measure of variability expressed in percentage:

$$V = \frac{Q_{max} - Q_{min}}{Q_{av}} \times 100(\%)$$

where Q_{max}, Q_{min} and Q_{av} are maximum, minimum, and average discharge respectively. Based on this equation, a constant spring would have variability less than 25 percent, and a variable spring would have variability greater than 100 percent.

As discussed throughout this book and many other publications on karst, karst aquifers and springs are particularly vulnerable to both natural and anthropogenic contamination. The following discussion by Wolter et al. (2011) nicely echoes this common knowledge:

Losing streams occur where the local water table has dropped below the level of a stream bed, allowing water to flow downward. Karst areas are commonly typified by losing streams, as the development of conduit-flow systems tends to lower the water table in the aquifer, and the fractured and dissolved nature of the aquifer allows for ready downward leakage of surface water. In areas of karst development, some losing streams end in clearly visible sinkholes, while others tend to lose water more diffusely into the stream bed. Under relatively low flow conditions in many karst settings, total loss of stream flow occurs. The varying ways water enters and travels through karst groundwater systems has a profound effect on the quality of the recharge water, and hence on the quality of groundwater discharging back to the surface. Following rainfall or snowmelt, runoff to sinkholes and losing streams deliver recharge water with relatively high concentrations of sediment (see Fig. 1.56), *sediment-attached nutrients such as phosphorus and ammonia-nitrogen, herbicides, organic matter, and bacteria. In contrast, infiltration recharge to the aquifer, passing through the relatively thin cover of soil and surficial materials, delivers relatively high concentrations of soluble, non-adsorbing contaminants, in particular nitrate.*



Figure 1.60 Aqua Spring has the largest flow rate and the largest variation of flow of all springs in Bullpasture Gorge, Virginia. *Left*: Average flow conditions. *Right*: High flow rate after heavy rainfall carrying a heavy sediment load. The boils or mounds of water above the spring are more than 10 feet high. Photographs courtesy of Phil Lukas.

The following excerpts from a report prepared by the USGS in 2014, entitled *Water Quality in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge Regions, Eastern United States, 1993–2009* (Lindsey et al., 2014) illustrate well the general vulnerability of karst aquifers and springs to anthropogenic contamination, not just in the East.

Concentrations of nitrate in the carbonate-rock aquifers were among the highest in the Nation.

One of the reasons that the carbonate-rock aquifers are susceptible to nitrate contamination is that they have high-permeability karst features, such as sinkholes and conduits, which allow contaminants from the surface to easily enter the aquifer and to rapidly move through them. As a consequence, much of the water that reaches a well is very young. In addition, the presence of sinkholes favors oxic conditions, making denitrification unlikely. The combination of direct infiltration of contaminants into the aquifer, rapid movement through the aquifer, and oxic conditions within the aquifer, coupled with large nitrogen inputs, explains the high nitrate concentrations in samples from the carbonate-rock aquifers

In the Piedmont, Blue Ridge, and Valley and Ridge regions, total coliform bacteria were detected in all samples from springs and nearly 60 percent of samples from wells. E. coli, an indicator of fecal contamination, was detected in 91 percent of samples from springs and 17 percent of samples from wells. Although detections were frequent in all aquifers and settings, the carbonate-rock aquifers had a higher frequency of detection for E. coli and total coliform, as did areas overlain by agricultural land use.

At least one pesticide was detected in 55 percent of samples, and multiple pesticide compounds were commonly detected in a single sample. Median atrazine concentrations in domestic wells in the Piedmont and Blue Ridge carbonate-rock aquifers and the Valley and Ridge carbonate-rock aquifers were higher than those measured in domestic wells nationally.

Thirty-five of the 47 pesticide compounds measured were detected in at least one sample, and at least one pesticide was detected in 55 percent of samples. The most frequently detected pesticides were atrazine, deethylatrazine, metolachlor, simazine, prometon, tebuthiuron, and dieldrin.

Mixtures of pesticides (two or more pesticides detected in the same sample) also were detected more frequently in the carbonate-rock aquifers than in crystalline- and siliciclastic rock aquifers. In fact, mixtures of pesticides in the Piedmont and Blue Ridge and Valley and Ridge carbonate-rock aquifers were much more prevalent than in aquifers nationwide with five or more pesticides detected in more than 40 percent of wells in agricultural areas and more than 80 percent of the wells in urban areas.

Pesticides with highest use—atrazine and metolachlor—were among the most frequently detected pesticides in domestic and public-supply wells.

All seven of the most frequently detected pesticides were detected most often in samples of groundwater from domestic wells in the carbonate-rock aquifers. Many of these domestic wells are also in agricultural areas.



Figure 1.61 Weathered rocks that make up the carbonate-rock aquifer are exposed at the surface and provide direct pathways for water and contaminants to enter the aquifer without the filtering effects of soils. Voids, or enlarged holes in carbonate rocks, such as the ones shown here, are common in the aquifer. Water moves rapidly through these voids and remains oxygenated. Note geologic hammer for scale. Photograph by William Kochanov, Pennsylvania Geological Survey. Text from Lindsey et al., 2014.

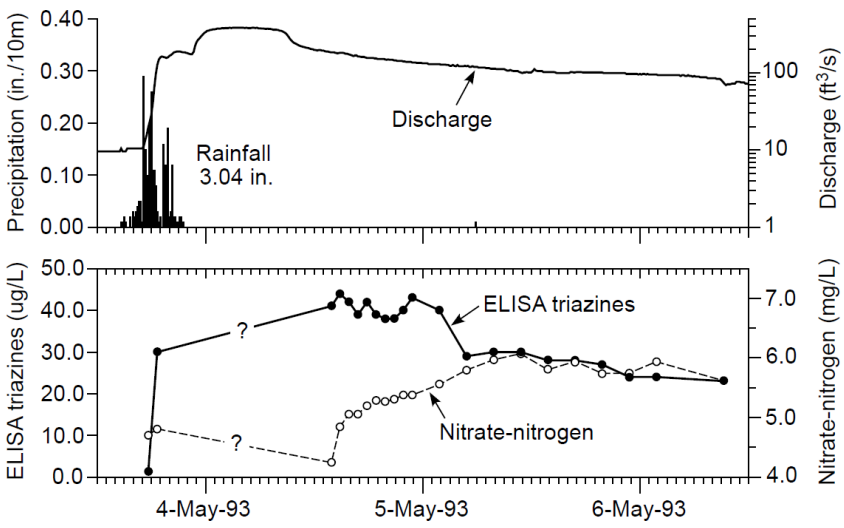


Figure 1.62 Chemographs and discharge hydrograph for a high-flow event at Pleasant Grove Springs in Logan County, Kentucky is an example of non-point source contamination from agricultural activities (Currens, 1999). Concentrations of triazines (including atrazine) and alachlor have exceeded drinking water MCLs during peak spring flows. Flow-weighted average concentrations for 1992–93 were 4.91 µg/L for atrazine-equivalent triazines and 5.0 mg/L for nitrate-nitrogen. In comparison, the maximum allowed concentration of any individual pesticide in drinking water in the European Union is 0.1 µg/L, and of all pesticides combined it is 0.5 µg/L.

In 2003, and again in 2020, the U. S. Environmental Protection Agency (U.S.EPA) allowed continuing use of atrazine. This herbicide has been banned for use in the European Union since 2004. In the U.S., it is one of the most commonly reported contaminants in groundwater and public drinking water. While atrazine is applied to a wide range of crops, it is primarily used on sugarcane, soy, sorghum, and corn; the U.S. Department of Agriculture notes that more than 65 percent of all corn crops in the U.S. have been treated with the herbicide. It is also a weed killer for golf courses, fields, and residential and commercial lawn spaces across the United States (https://usrtk.org/pesticides/atrazine/).

It is mystifying that in its evaluations of risks associated with the continuing use of atrazine and other harmful pesticides, the U.S. Environmental Protection Agency did not even survey or mention private wells and springs used for water supply. A significant body of scientific research suggests that atrazine is an endocrine disruptor and linked to various cancers, premature birth and birth defects (https://usrtk.org/pesticides/atrazine/).

1.2.1 Spring vs. River Rise

As stated repeatedly and shown with many photographs and schematics in this book, what sets karst aquifers apart from any other hydrogeologic environment is the nature and dynamics of surface water-groundwater interactions. This is also the focal point of ongoing polemics about what constitutes a true spring in karst. For most classically trained and professional, practicing hydrogeologists, the two key terms in this polemics, *aquifer* and *spring,* are inseparable. Equally important is the relation between *groundwater* and *aquifer*: groundwater resides within and moves (flows) though an aquifer. It then follows that a spring is a location at the land surface where groundwater discharges from an aquifer—a definition that is common to all textbooks on hydrogeology and scientific or general encyclopedias. However, when it comes to karst, these general definitions and relationships between aquifers, groundwater, surface water, and springs may be blurred ("all is not black and white"). The following points and discussion will, hopefully, shed some light on this sometimes-contentious polemics.

A casual observer or perhaps a karst geographer that describes what her or his eyes see will state that, if water comes out of a cave opening (however small or large), then this is undoubtedly a spring, no further discussion needed. A trained karst hydrogeologist would, in most cases, also ask himself or herself a much more important questions "What is the origin of that water"? before making any final judgment. This difference between the two approaches is embedded in the meaning of words **-graphy**, which refers to describing, drawing, or mapping a subject, and **-logy** which refers to the scientific study or theory of a subject. Put in a different way, a karst geographer sees water coming out of the cave and automatically describes it as a spring; a karst hydrogeologist wonders if at least some of that water comes from the karst aquifer before declaring it a spring, understanding fully that karst aquifers are unique when it comes to surface water–groundwater interactions.

Following are some examples illustrating the usage of terms *spring* and *river rise*, as well as the related hydrogeologic analyses.

The Santa Fe River in Florida flows west across the Northern Highlands to the Cody Scarp, an extensively karstified transition zone between the confined and unconfined parts of the Floridan aquifer (Scott, 1991) where it disappears into O'Leno sink. From O'Leno sink, the river flows underground for roughly three miles to its resurgence at the River Rise. From there, the river flows onto the lowland limestone plains of the Central Highlands and Gulf Coastal Lowlands where the Floridan aquifer is unconfined and precipitation infiltrates directly into the aquifer. Below the River Rise, the Santa Fe River is both a gaining and losing stream. It receives considerable water from several springs, however, less noticeable are the frequent "sucks" where part of the flow is diverted underground for some distance (Ellins et al., 1991; Kincaid, 1994).

Hisert (1994) conducted tracing experiments at O'Leno State Park which demonstrated that, after disappearing into O'Leno sink, the Santa Fe River flows at over 3 mi/day to its resurgence point at the River Rise. Hisert recorded the groundwater tracer at 8 intermediate sinkholes between O'Leno sink and the River Rise which are now known to be karst windows that intersect the underground flow path of the river. Furthermore, he found that over 40% of the resurgence at the River Rise is groundwater that augmented the river flow (Global Underwater Explorers, https://www.gue.com/hydrogeologic-setting.)

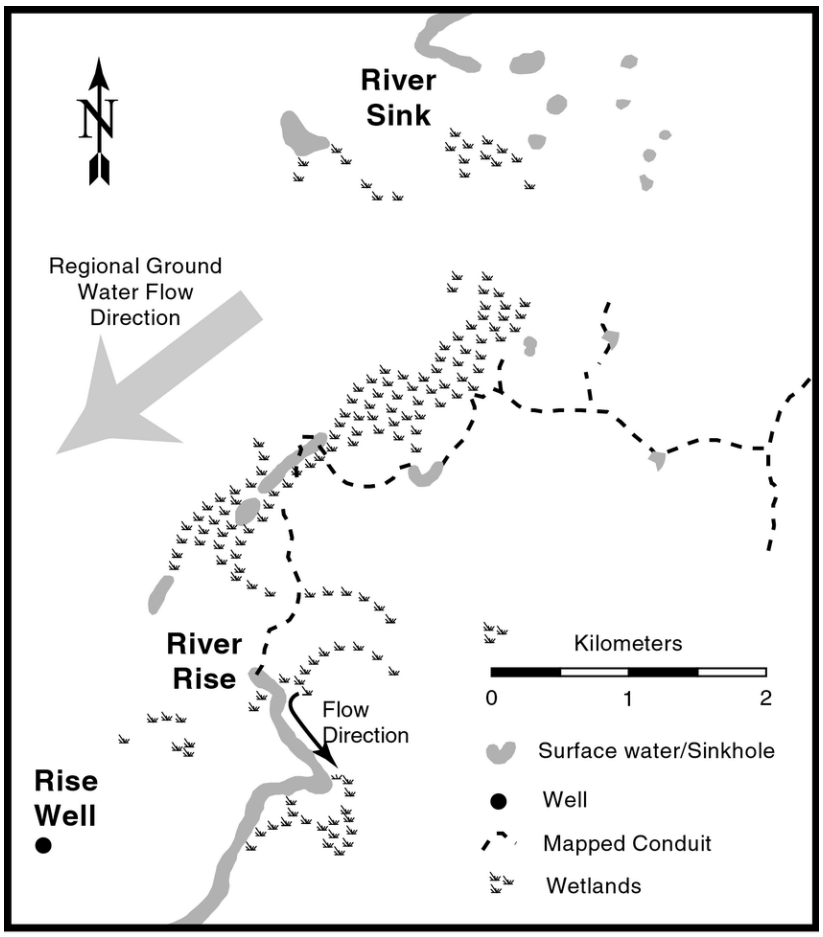


Figure 1.63 Sketch map showing the location of Santa Fe River at the sink/rise system, surface water bodies that commonly represent sinkholes, distribution of wetlands and the extent of the mapped conduit system. The river sinks into the subsurface at the location labeled River Sink, and re-emerges at the location labeled River Rise. Modified from Martin and Dean, 2001 in press; from Martin and Screaton, 2001.



Figure 1.64 The Santa Fe River goes underground in O'Leno State Park and reemerges 3 miles away in River Rise Preserve State Park as a circular pool before resuming its journey to the Suwannee River (https://www.floridastateparks.org/RiverRise). The water upwelling into the Rise pool is virtually always dark due to presence of naturally occurring substances in rivers called tannins, released during the decomposition of wood. Unlike this and other river rises, many true karst springs in Florida are famous for their clarity and near-constant water temperature of about 72 degrees Fahrenheit year-round. Photo courtesy of Suwanee River Water Management District (SRWMD). https://map.mysuwanneeriver.com/district-springs/santa-fe-river-rise-alachua-30/

The average flow rate of the Santa Fe River Rise, based on data made available by SRWMD, was 547.9 cfs as of 2014, the last year of data reporting (https://www.mysuwanneeriver.com/507/Water-Data-Portal). And yet, no government agency or anyone else has ever stated that the Santa Fe River Rise is a spring, or the largest spring in

Florida, even though its average flow rate was higher than that of any other true (hydrogeologically speaking) karst spring in Florida at the time, including Silver Springs and Wakulla Spring.



Figure 1.65 Holton Creek Rise with its characteristic dark color due to the presence of tannins. SRWMD does not consider it to be a true karst spring: *While it is connected to the Floridan Aquifer, Holton Creek Rise is also a resurgence of the Alapaha River. Most of its waters come from swallets in the Dead River Sink, where the Alapaha River disappears. Holton Creek Rise serves as an overflow for the Alapaha River, and when river levels are low or high, the spring flow fluctuates. This is a popular spot for fishing and hiking.* Photo and text courtesy of SRWMD (May 2026). https://map.mysuwanneeriver.com/district-springs/holton-creek-rise-25/

A similar example is described in detail by Intera Geosciences and Engineering (2021). The Alapaha River contains a series of swallets, natural openings in the riverbed, southeast of Jennings, Florida. This is approximately four miles south of the Florida state line. During periods of low flow, noted as below 350 to 500 cubic feet per second (cfs), surface water in the river is entirely captured by the swallets and enters limestone conduits. This water provides recharge to the Floridan aquifer (Upchurch, 2014). The water that enters the aquifer via the swallets at Dead River eventually discharges to the Suwannee River through two resurgences: the Alapaha Rise and Holton Creek Rise. This is about 19 miles away from the location of the sinks.

Ceryak (1977) describes groundwater level fluctuations of up to 20-feet between periods of low and high flow, where high flow is defined as flow greater than 786 cfs. During low flow, Holton Creek Rise discharges clear groundwater. During high flows when the river stage exceeds the elevation of the potentiometric surface of the Floridan aquifer, water from the river is forced into the Floridan aquifer. Discharge from the Alapaha Rise and Holton Creek Rise is typically discolored by organic material during such times. During low flows, discharge from Holton Creek Rise is entirely clear and will dry up during extreme low flows (Intera Geosciences and Engineering, 2021).



Figure 1.66 One of Alapaha River sinks. Courtesy of Suwannee Riverkeeper. https://wwals.net/2014/11/13/alapaha-river-sink/

The above analyses of surface water-groundwater interactions in karst are prime examples of quantitative hydrologic and hydrogeologic approaches to the evaluation of river rises which are discharging a mixture of surface water and groundwater (i.e. true aquifer water) in various proportions depending on surface water input conditions.

Table 1.1 Mean River Water Fractions at Alapaha Rise and Holton Rise based on Alapaha River flow conditions at Jennings. From Intera, 2021.

Flow Condition	Holton Rise River Water Fraction	Alapaha Rise River Water Fraction
< 400 cfs	0.3208	0.2414
400 – 1500 cfs	0.5931	0.5129
> 1500 cfs	0.8157	0.6907

An example of surface water-groundwater interactions in the case of true karst springs, where aquifer water is the most important component of spring discharge, is provided by Kincaid (1994).

The Devil's Ear Spring cave system in Florida is an extensive network of phreatic karst conduits that are directly overlain by the 1.5 km reach of the Santa Fe River between Rum Island and July springs. The cave and the river are situated on a karst limestone plain where the Ocala Limestone is exposed at the surface leaving the Floridan aquifer unconfined. Fluctuations in the stage of the Santa Fe River and the hydraulic head in the Floridan aquifer drive dynamic interactions between the surface water in the river and groundwater in the network of submerged cave conduits. Natural tracers Radon-222 (222Rn) and δ18O and the artificial tracer Sulfur hexafluoride (SF6) were used to quantify these interactions and describe their hydrogeological implications.

The Devil's Ear Spring cave system is comprised of the network of underwater cave passages that proceed upstream from Devil's Ear Spring. Devil's Ear Spring is a second magnitude spring that has gone mostly unnoticed in the scientific community because it is located in the Santa Fe River channel and is not visible from the surface throughout much of the year. Devil's Ear Spring is physically connected to two other springs, Devil's Eye and July where the combined discharge raises the group to first order status. All three springs are considered part of the Ginnie springs group (Wilson and Skiles, 1988). This spring system is famed for its water clarity, achieving an unrivaled fame among scuba divers of all skill levels when Jacques Cousteau dove here in 1974 and praised the crystal-clear water as "visibility forever." It is the international hotspot for scuba diving.

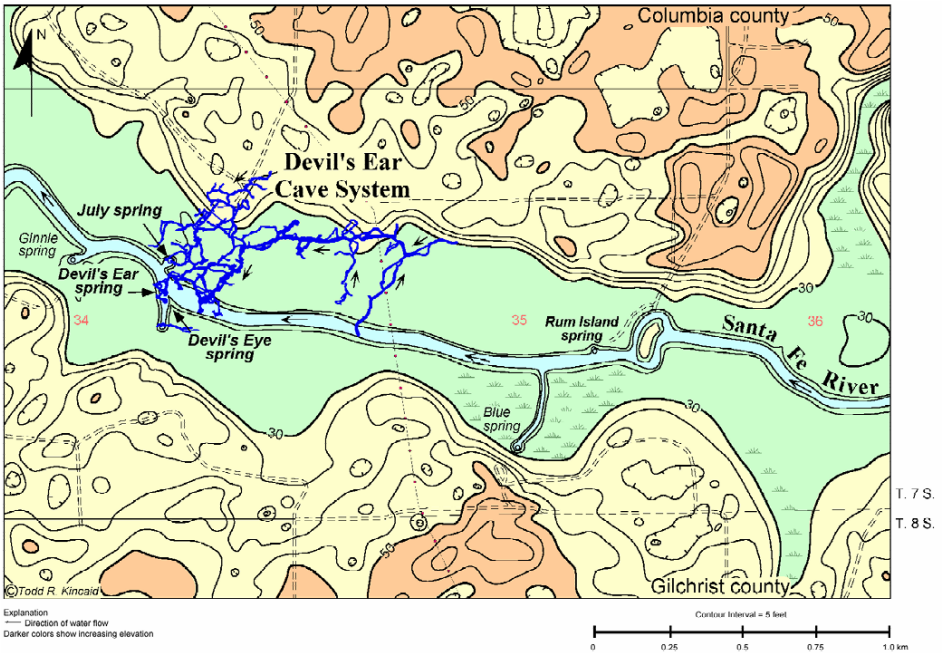


Figure 1.67 Section of the USGS High Springs S.W. topographic quadrangle, 7.5-minute series, showing the drainage features and karst landscape in the field area between Rum Island and July spring on the Santa Fe River near High Springs, north-central Florida. From Kincaid, 1994.



Figure 1.68 Drone photo of The Devil's Eye Spring by Frank Moore. Note the contrast between the crystal-clear spring water and dark tannic water of the Santa Fe River. Available at https://firstmagflorida.com/2020/10/10/devils-spring-system-ginnie-springs/

Fig. 1.69 shows groundwater percentage contour maps for the February 1992 and June 1993 comprehensive cave experiments which included cave diving and collection of water samples. The contour lines show the sources and distribution of pure groundwater and intruded river water throughout this section of the aquifer. Darker areas correspond to sections of the cave containing progressively greater amounts of intruded river water. Both maps show that surface water influx to the cave system originates from the passages on the south side of the system which trend toward and in some cases directly underlie the Santa Fe River.

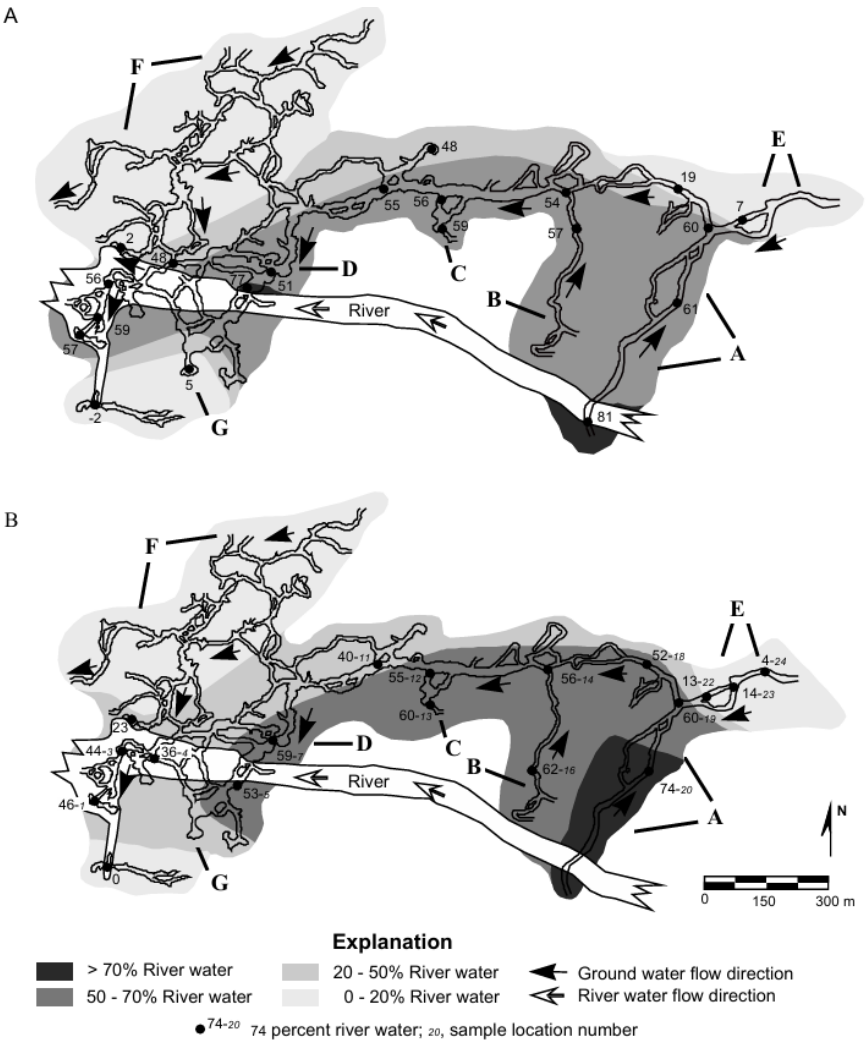


Figure 1.69 Contour maps showing the distribution of intruded river water in the Devil's Ear cave system on the Santa Fe River, north-central Florida during the (A) February, 1992 and (B) June, 1993 cave sampling experiments. Darker regions are the areas of greatest river water intrusion to the aquifer. From Kincaid, 1994.

The sections of the cave system contributing the most river water to the cave system are the: Mainlands region, Split Tunnel, River Intrusion Tunnel, and the Big Room (sections A, B, C, and D on Fig. 1.63). The contour maps indicate that the northern conduits are the major contributors of pure groundwater to the cave system (Kincaid, 1994).

The three presented examples of comprehensive scientific analyses of karst springs and river rises, as they relate to interactions between surface water and *aquifer water*, i.e., *groundwater,* are far from common as they are expensive, time-consuming, and are done by or with some help from experienced groundwater professionals. What they demonstrate is that, in karst, surface water including sinking streams, interacts with groundwater in different ways and to varying degrees, depending on specific circumstances.

However, when an entire surface stream disappears into the ground through a cave opening, and then reappears through a cave opening, after briefly (in terms of both time and length) flowing underground through a cave, the question of river rise vs. spring is not rhetorical anymore. This is illustrated with the schematics in Fig. 1.70. If during its underground journey, regardless of the time and distance involved, the underground portion of the surface stream does not interact with the aquifer surrounding the flow-through cave (conduit) in any appreciative fashion, then that cave outlet is not a spring. In other words, characteristics of the water input to the system (flow/quantity, temperature, concentration of constituents) are the same as of the water output from the system. The *aquifer water*, i.e., the *groundwater* is not involved, and the common hydrogeologic definition of a spring, including in karst, does not apply.

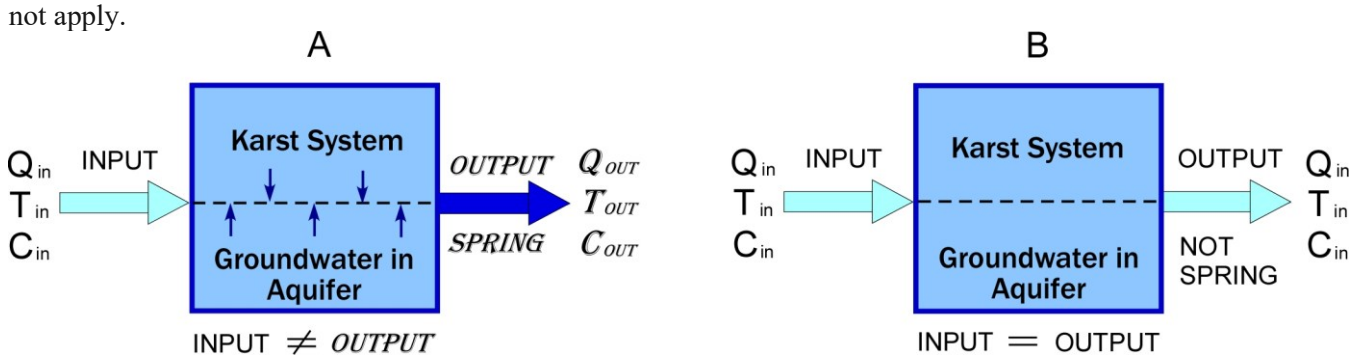


Figure 1.70 General schematic of a karst aquifer (system) which receives water input and has water output though a visible cave opening. A: If all or any of the characteristics of water, such as quantity (Q), temperature (T), or concentration of constituents (C) is transformed between the input and the output, then the output is a spring. B: When none of the characteristics is transformed, i.e. the water residing in the aquifer does not mix with the input water, then the output cannot be considered a spring. Note: There may be, and usually are, multiple water inputs such as sinking and losing streams (so-called *allogenic recharge*) and recharge from precipitation (so-called *autogenic recharge*).

In conclusion, when classifying or evaluating the emergence of water in karst, it is important to apply as many hydrogeologic principles as possible to avoid any misunderstandings. This includes a propagation of possible errors made because of generalizations based on insufficient information. The following excerpts from Gunn et al. (2025) illustrate this point. This paper explains the process of nominating springs to be included in the list of **M**ost **I**mportant **K**arst **A**quifer **S**prings in the world (project MIKAS of Karst Commission of the International Association of Hydrogeologists)

"Initially it was planned to have as much information about the proposed springs as possible. However, the PAB recognised that the amount of information available varies widely from country to country and decided to simplify the Survey Form to facilitate the work of national experts. One of the parameters that was initially thought of as being mandatory is the spring regime. However, it has become apparent that surprisingly few of the springs that meet other MIKAS and NIKAS criteria have their flow measured on a continuous basis and for some the flow

has only ever been estimated as opposed to being measured using recognised hydrometric techniques. A case in point is Tobio in Papua New Guinea which was listed in Ford & Williams (1989, Table 5.6 and 2007, Table 5.9) as being the world's largest karst spring with a mean discharge of 85 – 115m3s-1. The main reference given (Maire, 1981) states that "the huge Tobio emergence has been reckoned by Beck to [sic] 85 – 115 cubic metres per second". No reference is given but the actual source is thought to be Beck (1975) who states that "at Tobiu something like 3000 – 4000 cusecs (85 – 113 cumecs) was thundering from an entrance 55m high by at least 24m in width". The lead author of the present paper was able to contact Beck (pers. comm., 8 January 2025) who provided the following information: "On route to Pulupare the Iaro River which emerges from Tobio is crossed on a bridge about 16 km upstream… our estimate of water flow at the cave had no scientific basis, other than attempting to gauge volume from the banking at this crossing. I would think this would be the only safe place where a proper measurement might be attempted, but it was beyond our remit and abilities at the time. The river could well of course have picked up other unknown tributaries between bridge and resurgence". This is entirely reasonable and Beck is to be commended from at least making an estimate but it illustrates the problems of assembling data on world karst spring regime."

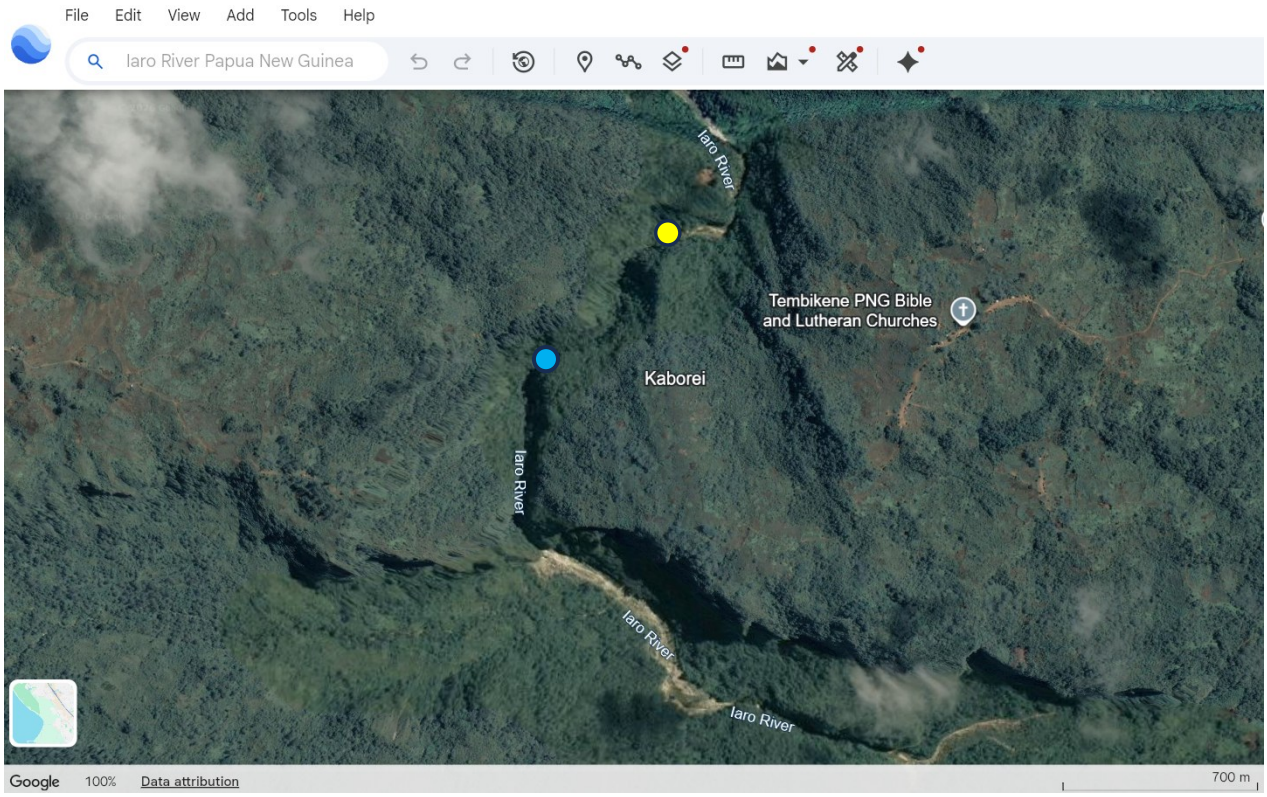


Figure 1.71 Google Erath image of the Iaro River section near Kaborei, Papua New Guinea. Added yellow dot denotes the Iaro River sink, added blue dot denotes the Iaro River resurgence locally called *Tobio*. A curved depression in the relief between the river sink and the river resurgence is an abandoned (former) canyon of the river, now hanging above the underground section of the river; it is about 670 meters (2,200 feet or 0.4 miles) long. Note metric scale in the bottom right. White labels are original to Google Earth Map. Image from Maxar Technologies CNES/Airbus, 4/20/2014 and newer.

By looking at a satellite image (Fig. 1.71) of the general area of Tobio, which is how the feature is called locally (it is not referred to as a spring), it is also entirely reasonable to conclude, without having any other information, that Tobio ("Spring") may be just an exit point of the underground section of the Iaro River which starts at its

upgradient entrance to a flow-through cave, roughly 670 meters long. It is also possible that the percentage of karst aquifer (groundwater) contribution to the flow of this short underground section of the Iaro River may be minimal or even non-existent. Without any such information, it would be impossible to state that Tobio is a spring, let alone that it is *the world's largest karst spring*. Interestingly, the Google Earth Map layer, if chosen for a background map in Fig. 1.65, shows no break of the Iaro River between its sink and its resurgence called Tobio.

A Google inquiry about the Iaro River Cave yielded the following response (no answer was returned for "Tobio Spring" or any spring near Kaborei):

The large subterranean feature is officially documented in speleological records as the **Iaro River Cave**, located right in the Southern Highlands Province of Papua New Guinea.

First explored and mapped extensively by international caving expeditions in the mid-1970s, it is recognized as a **massive, high-volume river cave** Descent (31) Second-hand - Wild Places Publishing.

Hydrology and Scale of the Cave

- **The Underground River:** The cave serves as a dramatic underground conduit for the Iaro River. The river plunges into the limestone bedrock, carving out enormous chambers and roaring through subterranean channels before reaching its resurgence point Index to Niugini Caver - ANU Open Research.
- **Extreme Water Volume:** Because the Southern Highlands receives intense tropical rainfall, the Iaro River Cave carries immense amounts of water. It is considered a highly active and dangerous environment due to the risk of flash flooding inside the chambers.
- **Unique Ecosystem:** Early collections of cave fauna from the expedition teams documented unique, light-deprived wildlife thriving inside the cave, including specialized cave crickets and unique bat populations NEWSLETTER OF THE TASMANIAN ... - ASF Library.

The Caving History

- Detailed mapping and descriptions of this specific cave were published in early editions of *Niugini Caver*, a historical journal dedicated to documenting the incredible karst systems of Papua New Guinea. A prominent report on this exact system was written by explorer H. Beck in 1975, titled *"Iaro River Cave, Southern Highlands District."* NEWSLETTER OF THE TASMANIAN ... - ASF Library.

Below are excerpts from an article by Rolan Eberhard in the January/February 1990 issue of Newsletter of the Tasmanian Caverneering Club.

A SEASON IN THE HIGHLANDS Part 2: Iaro River

In October I made the long drive from Goroka to Kagua in the Southern Highlands. With me was Tony Wrightson, an expatriate kiwi who is a keen bushwalker but whom I'd managed to get interested in seeing a big river cave. This particular cave - formed where the Iaro River travels underground for some distance - was apparently first seen by white man around 1969 when Neil Ryan was kiap in the area. He returned to the location in 1974 accompanied by Howard Beck and others, and they briefly explored a section of fossil upper level inside the entrance. Some years later Neil Hickson also made short visit to the cave. From all accounts it was a very spectacular feature, with the flow rate of the emerging Iaro River being estimated at circa 100 cumecs.

After an overnight stay at Kagua, Tony and I drove along a steadily deteriorating road towards the village of Pulpare. It was decided to leave the vehicle at a pint where a small landslip had demolished part of the road and walk the final 5km. Our reception at Pulpare was rather cool. The local 'big man' said that the cave was taboo and

that we were not to go there. Long discussions ensued without getting us anywhere. At this point a younger man turned up and declared himself to be 'papa bilong graun' (ie. owner of the cave), and told us that we could go right ahead and have a look at it. Having come so far we decided to take his word for it and so we followed him down the track leading to the cave. On the way another man blocked the path saying that he was 'papa bilong gram true'. It was all getting rather tedious.

Eventually, after more haggling and a descent of several hundred metres down the precipitous sides of the Iaro gorge, we reached the efflux. Locally the feature is known as Tobio. From a gaping cavern in the rock face the Iaro River thundered out into daylight. The speed and force of water were quite awesome and downstream the river could be seen plunging through a narrow ravine reminiscent of the Gordon Splits. Like earlier visitors, we found that it was not possible to proceed upstream for any great distance inside the cave. The walls narrowed to a width of perhaps 12m and through this canyon pulsed the foaming Iaro. The upper level passage that had been explored in 1974 was clearly visible on the left side of the entrance, though we had no time for a proper look ourselves. Various 'papa bilong graunas' had subsequently arrived on the scene and were looking rather annoyed. This fact, combined with the long walk back, ensured that our visit was only brief.

Despite the hassle of local politics I am hoping to get back to the Southern Highlands for a closer look at Tobio. Howard noted the existence of numerous additional entrances in the dry canyon above the efflux and it is quite feasible that fossil upper levels meander over much of the length of the river on its underground course. A large log jammed in the river just inside the efflux indicates a fairly direct route from sink to resurgence, though exploring this at a safe distance above the raging water via upper levels sounds the most sensible option. As far as I am aware the point where the water goes underground - estimated to be about 1.5km away (Ryan, 1974) - has not been seen by anyone other than the locals, though they report that it is not hard to get to.



Figure 1.72 The Nostrils Cave in Sohodol Gorge, Carpathian karst of Romania. This is a textbook example of a flow-through cave with the outlet no one refers to as a "spring". This is simply because both the entrance of the surface stream into the underground ("input"; see Fig. 1.70) and its outlet ("output") can be clearly seen at the same time, by anyone. The cave is also readily accessible through its entire length. A potential argument may develop if the "input" (upper cave entrance) and the output are not both visible at the same time and are farther away from each other. In such case, a geographer or a casual observer may describe it as a karst spring (water is flowing out of a cave). A karst hydrogeologist will consider various elements discussed previously before making any final judgement if the feature is a karst spring, or a river rise, or just the end of an underground flow-through conduit that is not gaining water from the surrounding aquifer and is therefore not a karst spring. Photo courtesy of Zoran Stevanovic.

1.3 Web Resources

Most states with karst have recognized its importance in a variety of ways, commonly addressing its vulnerability and the need to protect the dependent ecological and human environments. This includes sustainability of groundwater withdrawals for public supply, agriculture, and industry, contamination of karst water resources, and threats to aquatic life and animals that depend on both karst groundwater and surface streams in karst. There are many examples of state and local parks established because of notable karst springs, and there are karst drainage areas protected from unchecked development by local and state regulations. Some state agencies have attractive karst-specific educational and outreach programs, while others still lack behind. Most importantly, there are numerous non-profit organizations throughout the country that advocate for karst protection, often including lawsuits against special interests and government entities that choose to ignore the specifics of karst and its water resources.

Examples of recognition of karst as unique and valuable natural environment include Missouri Department of Natural Resources, Ashley Karst National Recreation and Geologic Area in Utah, Mitchell Karst Plains Nature Preserve in Indiana, Virginia Natural Heritage Karst Program, Indiana Geological & Water Survey (Karst Outreach), The Nature Conservancy (Ozark Highlands Karst Program), The Watershed Association in Texas, Minnesota Pollution Control Agency, Minnesota Department of Natural Resources, Florida Department of Environmental Protection (Florida Karst Resources), Wisconsin Geological and Natural History Survey, Iowa Department of Natural Resources (Karst Bedrock & Well Contamination), The Edwards Aquifer Website, Florida Springs Institute, Florida Springs Council, Ohio Department of Natural Resources, Karst Waters Institute, United States Geological Survey, and National Caves Association, to name a few. Their respective web sites are provided below.

https://dnr.mo.gov/land-geology/geology/karst-missouri
https://www.in.gov/dnr/state-parks/parks-lakes/spring-mill-state-park/
https://www.uintah.gov/departments/f_-_p_departments/public_lands/index.php
https://www.dcr.virginia.gov/natural-heritage/karsthome
https://igws.iu.edu/outreach/karst
https://www.nature.org/en-us/get-involved/how-to-help/places-we-protect/ozark-karst-program/
https://watershedassociation.org/impactareas/education-and-outreach/karst/
https://www.pca.state.mn.us/air-water-land-climate/protecting-water-in-karst-regions
https://www.dnr.state.mn.us/waters/groundwater_section/mapping/springs.html
https://floridadep.gov/fgs/sinkholes/content/florida-karst-resources
https://home.wgnhs.wisc.edu/wisconsin-geology/karst-sinkholes/
https://www.iowadnr.gov/environmental-protection/water-quality/private-well-program/well-testing/karst-bedrock-well-contamination/
https://www.edwardsaquifer.net/
https://floridaspringsinstitute.org/
https://www.floridaspringscouncil.org/
https://ohiodnr.gov/discover-and-learn/safety-conservation/geologic-hazards/karst
https://karstwaters.org/about-kwi/mission-statement-governance-and-goals/
https://www.usgs.gov/mission-areas/water-resources/science/karst-aquifers
https://cavern.com/all-showcaves/

Chapter 2 Karst Aquifers of the United States: East

There are quite a few USGS maps and reports on principal aquifers, carbonate aquifers, karst aquifers, or areas with karst in the United States. Similarly, there are many reports and maps by the USGS and state geological surveys that feature karst areas and karst aquifers in individual states. However, they are not all necessarily consistent, not only because of the issues of scale. One difficulty when attempting to show the extent of major aquifers is that they may, and often do, extend both at the land surface (are outcropping), and deeper in the subsurface where they may be covered by other non-carbonate aquifers and rocks including aquitards (confining layers). There may also be multiple major karst aquifers below each other, separated by non-karst aquifers and aquitards which complicates attempts to create a single map of aquifers.

Major karst areas and karst aquifers in the eastern United States are shown on the map in Figure 2.1, with added annotation. This map is best viewed together with a map of all principal aquifers of the United States compiled by USGS (2003 revised version, The National Atlas of the United States of America, available at https://www.usgs.gov/mission-areas/water-resources/science/principal-aquifers-united-states). The two maps provide a solid overview of karst (carbonate) aquifers.

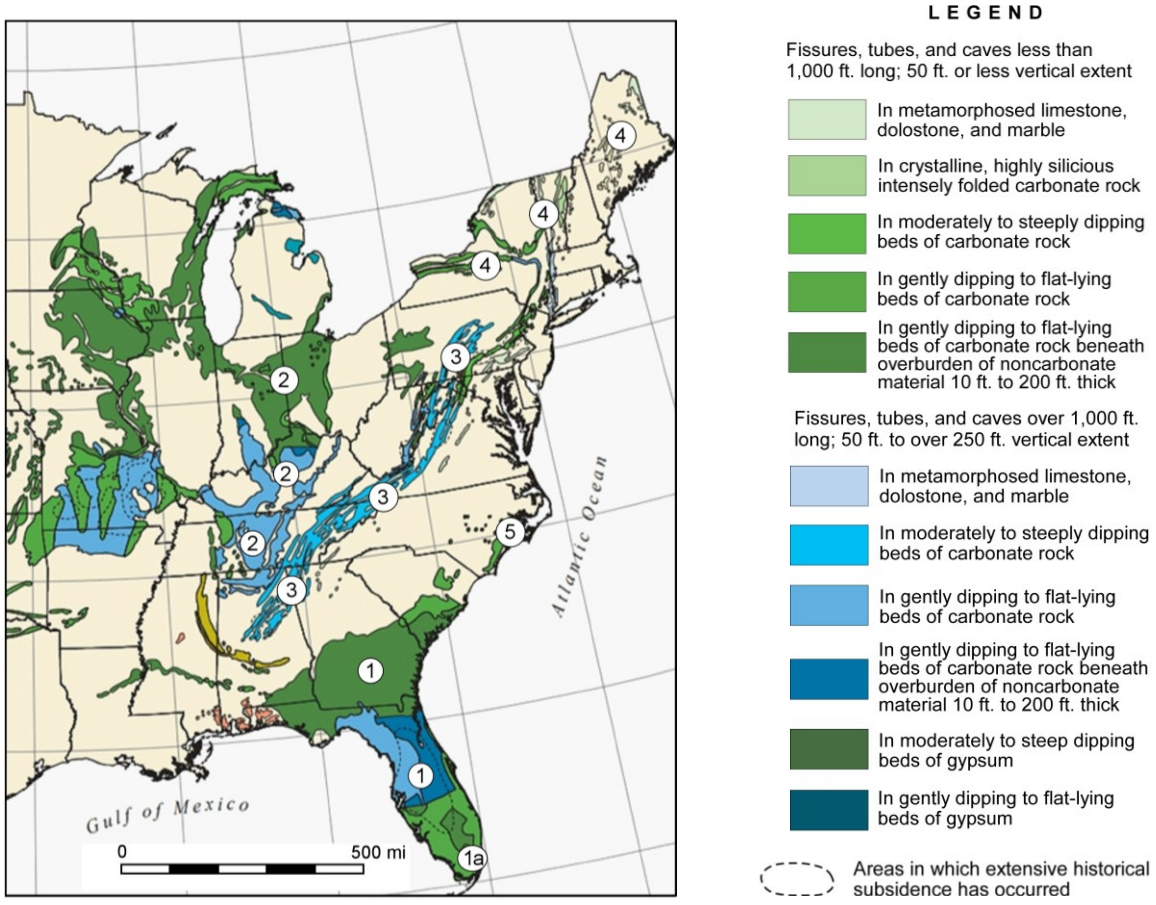


Figure 2.1 Karst map and principal karst aquifers of the eastern United States. From Tobin and Weary, 2004. Annotation with names of karst aquifers added. 1: Floridan aquifer (including where buried). 2: Appalachian and Interior Low Plateaus Karst Aquifers. 3: Appalachian and Interior Low Plateaus Karst Aquifers. 4: New York and New England Karst Aquifers. 5: Castle Hayne Aquifer (buried below non-carbonate sediments of the Atlantic coastal plain).

2.1 Floridan Aquifer

The Floridan aquifer system is one of the most productive aquifers in the world. It underlies an area of about 100,000 square miles in southern Alabama, southeastern Georgia, southern South Carolina, and all of Florida (Fig. 2.1) and provides water for numerous small and large cities, including Savannah and Brunswick in Georgia; and Jacksonville, Tallahassee, Orlando, and St. Petersburg in Florida, to name a few. In addition, the Floridan (often used synonym) provides water for many individual households, smaller communities, and rural areas. Locally, it is intensively pumped for industrial and irrigation supplies.

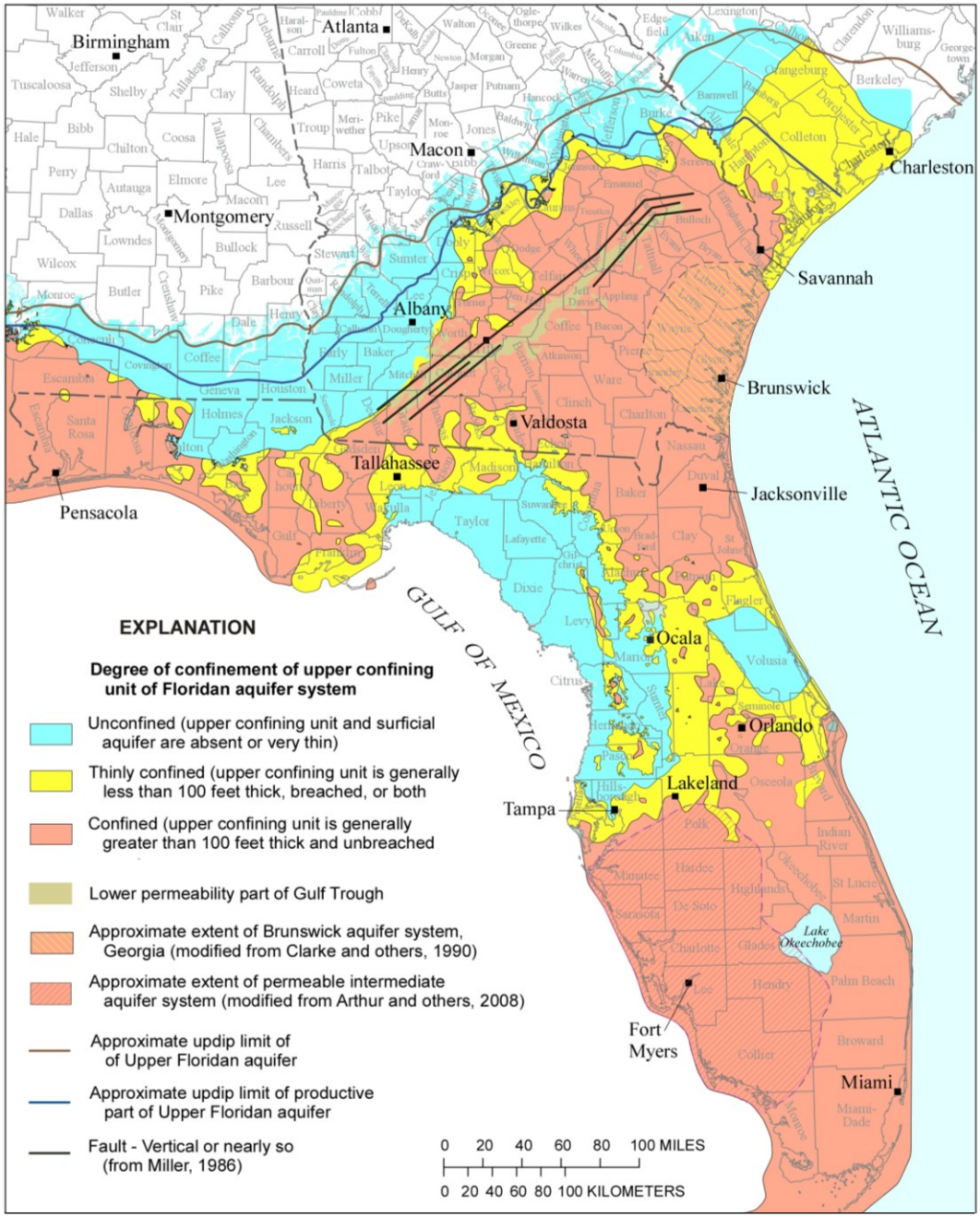


Figure 2.1.1 Relative degree of confinement of the upper confining unit of the Floridan aquifer system and approximate limit of the Upper Floridan Aquifer. Modified from Williams and Kuniansky, 2016.

A thick sequence of carbonate rocks (limestone and dolomite) of Tertiary age comprises the Floridan aquifer system. The thickest and most productive formations of the system are the Avon Park Formation and the Ocala Limestone of Eocene age. The Suwannee Limestone (Oligocene age) also is a principal source of water, but it is thinner and less extensive than the Eocene formations. The Tampa Limestone of Miocene age is part of the Floridan in only a few places where it is sufficiently permeable to be an aquifer. Both the Suwannee and the Tampa Limestones are discontinuous. The lower part of the Avon Park Formation, the Oldsmar Formation of early Eocene age, and the upper part of the Cedar Keys Formation of Paleocene age also are included in the Floridan where they are highly permeable. Limestone beds in the lower part of the Hawthorn Formation of Miocene age are considered part of the Floridan by some but are excluded from the USGS Groundwater Atlas because the permeability of these beds is thought to be minimal. The base of the aquifer system in much of Florida consists of nearly impermeable anhydrite beds in the Cedar Keys Formation.

Aquifers and Confining Units. The Floridan aquifer system is defined based on permeability. In general, the system is at least ten times more permeable than its bounding upper and lower confining units. In most places, as shown by the idealized layers in Figs. 2.1.2 and 2.1.4, the system can be divided into the Upper and Lower Floridan aquifers, separated by a less-permeable confining unit.

A detailed description of the hydrogeological units of Florida is provided in the Florida Geological Survey's Special Publication No. 28 (Copeland et al., 2009).

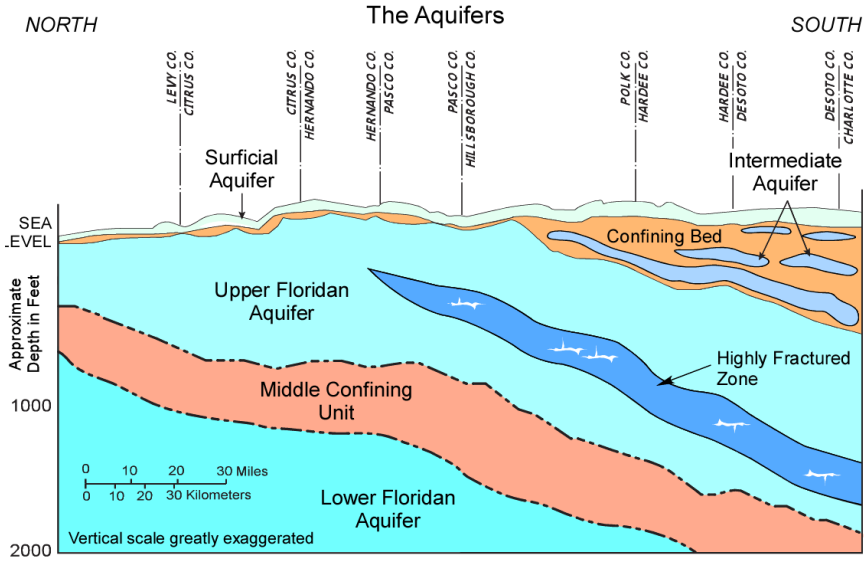


Figure 2.1.2 Generalized division of West-Central Florida's Aquifers. From SWFWMD, 2017.



Figure 2.1.3 New sinkholes frequently open in Florida, often triggered by anthropogenic factors such as groundwater pumping for irrigation (*this photo*) and water supply, modified surface drainage controls, failing/leaky water and sewer pipelines, mining, and other activities which interrupt a delicate balance between the surficial and Upper Floridan aquifers separated by a thin confining layer. Photo by Professor George Sowers, courtesy of Francis Sowers.

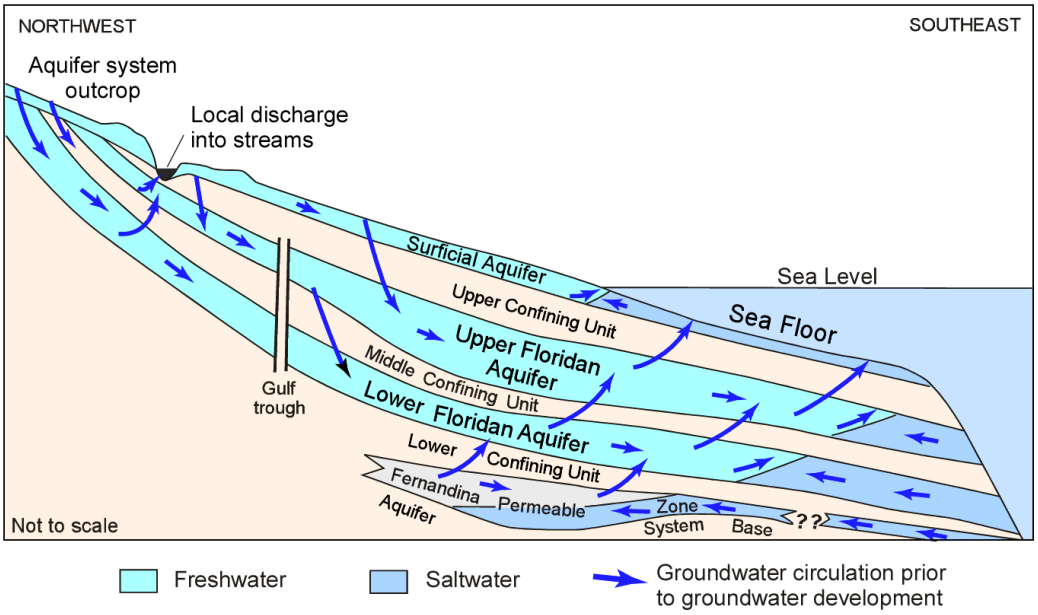


Figure 2.1.4 Schematic cross section of Floridan aquifer system from northwest to southeast Georgia. The Lower Floridan aquifer in this area includes a highly permeable unit called the Fernandina permeable zone. This zone is the source of a considerable volume of fresh to brackish water that leaks upward through the middle confining unit and ultimately reaches the Upper Floridan aquifer. From Barlow, 2003; modified from Krause and Randolph, 1989.

Despite the vast extent of the Floridan Aquifer and the volume of water stored in it, the Floridan's groundwater resources are in a free fall. Even national news media are now increasingly covering this catastrophe. Below excerpts are just one example among many (National Public Radio, January 17, 2025. Heard on Morning Edition, by Greg Allen; Development takes a toll on Florida's precious springs : NPR):

But development and pumping of groundwater are taking a toll. Some springs no longer bubble up from the aquifer and even the largest are now seeing their flow steadily reduced. State policymakers acknowledge the problem, but so far have been reluctant to do anything about it.

In some parts of Florida springs have stopped flowing or become choked by algae because of low flows and pollution caused by development.

But over the last two years, Orlando has been the nation's second-fastest growing region and new residential construction is booming. Jay Exum says that's why it's important for the state to adopt environmental protections for the springs that were ordered by lawmakers nearly a decade ago. Exum says there need to be changes in how Floridians use their precious groundwater.

There are many issues involving environmental degradation caused by the as yet unstoppable and exponential increase in the use of AI for just about every activity across the country. This includes competition for water resources that are needed for both humans and wildlife habitat. An inquiry into AI and its effects on sustainability of groundwater resources concluded the following (it is right on the money):

- **Over-allocation of Water Permits:** Regional water management districts have continued to issue permits for large-scale water consumption, with roughly 30,000 commercial permits operating in the springs region north of I-4. These permits often ignore the cumulative impact of withdrawals, leading to 26 of 30 designated "Outstanding Florida Springs" being classified as impaired.

- **Failed Protection Laws:** The Florida Springs and Aquifer Protection Act of 2016, which requires rules to protect springs from "harmful" withdrawals, has faced legal challenges due to regulatory failure to define and implement these rules efficiently.
- **Lack of Control on Private Wells:** Florida residents can often install private wells with minimal regulation, allowing for potential uncontrolled cumulative pumping.
- **Inexpensive Groundwater Rates:** Groundwater is often perceived as free or extremely cheap, with water bottlers paying very little for, or even less than $1 per 1,000 gallons to pump, removing incentives for conservation.
- **Reduced Spring Flows**: Most Florida springs flow at 30% to 50% less than their historical average, with some stopping entirely, destroying ecosystems and damaging tourism.
- **Saltwater Intrusion**: In coastal areas, removing freshwater lowers the water table, allowing saltwater to enter the aquifer, which contaminates drinking water supplies (e.g., in Jacksonville).
- **Land Subsidence/Sinkholes**: When aquifer levels drop, the reduced hydraulic pressure fails to support the limestone land above, causing sinkholes.
- **Algal Blooms and Habitat Loss**: Lower water levels and increased pollution result in "brown-outs" and excessive algae growth, destroying submerged vegetation that manatees and other animals rely on.
- **Environmental Degradation**: The connection between groundwater and surface water means over-pumping causes wetlands to dry up and reduces the flow of rivers, such as the Santa Fe and Ichetucknee rivers.
- **Population Growth**: With Florida's population expected to grow by millions, the demand for water will rise, further straining the aquifer.
- **Climate Change**: Rising sea levels increase saltwater intrusion, while unpredictable precipitation and higher temperatures (causing more evapotranspiration) reduce the ability of rain to replenish the aquifer.

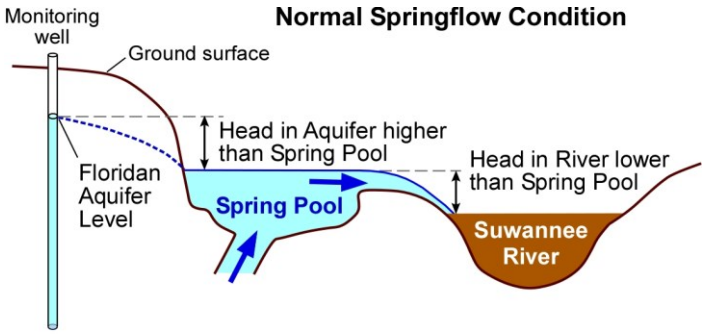
In the absence of any desire of the regulators and various Florida state agencies to enforce their own regulations and laws and fight special interests, there is not much left other than filing lawsuits on behalf of the concerned citizens of Florida, as illustrated by the following excerpts (from Florida Spring Council (FSC), https://www.floridaspringscouncil.org/springsharmrule):

> *Going to court was, in this case, our only option to protect springs and ensure the Florida Department of Environmental Protection (FDEP) follows the law.*
>
> *This is the next step in a multi-year effort to hold FDEP accountable to safeguard Florida's springs from harmful water withdrawals.*
>
> *FDEP's proposed Springs Harm Rule is circular, vague, and essentially the same as the consumptive use permitting rules already in place. After eight years of delay and inaction, to propose essentially the same permitting rules in 2025 that have been in effect since 2014 is an insult to the people of Florida and the Legislators who worked for years to put this provision in law.*
>
> *The Administrative Law Judge sided with FDEP, finding that the proposed rules:*
>
> - *did not need to be more protective than existing water use permitting rules*
> - *did not need to comply with the requirements of the Florida Springs and Aquifer Protection Act*
> - *did not need to prevent harm to Outstanding Florida Springs.*

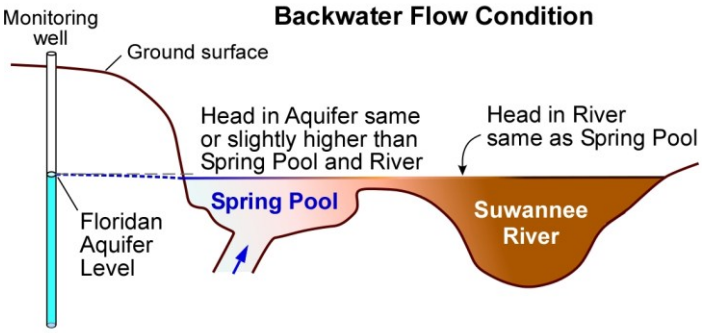
On Aug. 13, 2025, FSC filed an appeal with the 1st District Court of Appeals to overturn the decision made by the Administrative Law Judge in our legal challenge against FDEP's water use permitting rules proposed for Outstanding Florida Springs.

Our mission is to be a unified voice for the springs in the courts and in the Capitol. FSC's attorneys successfully defeated the Florida Department of Environmental Protection in Court in the past over the FDEP's failed Springs Basin Management Action Plans. We are determined to continue holding FDEP accountable to protect Florida's springs.

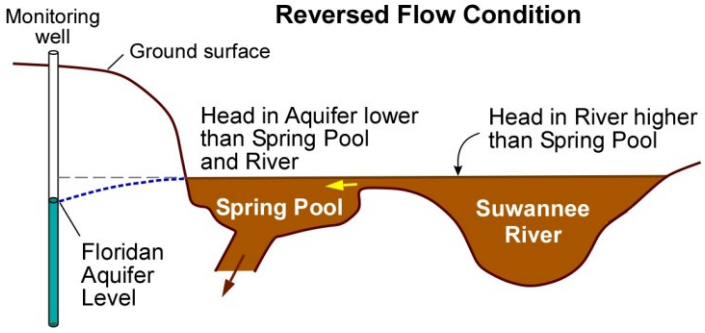
The figures and text that follow illustrate just a few examples of the catastrophic demise of Florida springs and groundwater resources in general.



Typically, groundwater levels are higher than river levels and the flow is out of a spring, down a spring run, into a river, and eventually ends up in the ocean.



When the river stage is equal to groundwater level, the river will act like a temporary "dam," slowing or stopping a spring's flow.



When the river stage becomes higher than groundwater levels, a reversing of a spring's flow can occur. Reversals result in the river water flowing back into the spring and aquifer (see Figure 2.1.6 for an example).

Figure 2.1.5 Sketches illustrating what happens to a spring near a river when there is over-pumping of groundwater in the adjacent aquifer. All captions are by Suwannee River Water Management District (SRWMD). Sketches and annotations are modified by the author for clarity and accuracy. From https://www.mysuwanneeriver.com/418/Discharge

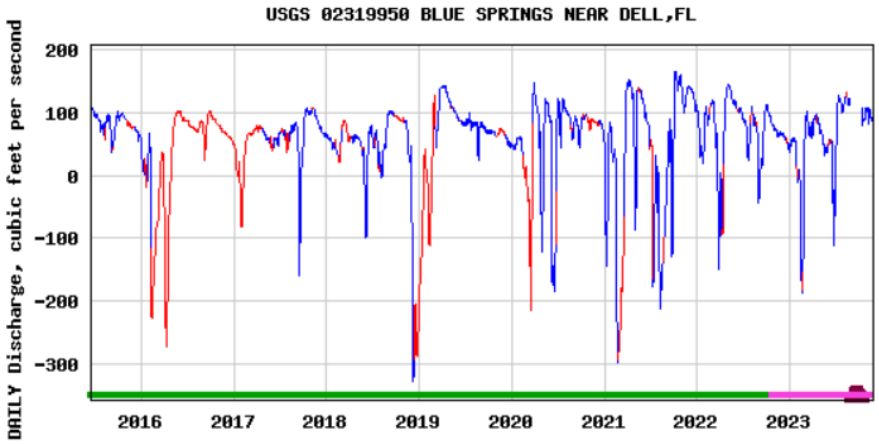


Figure 2.1.6 Hydrograph of Lafayette Blue Spring near Dell, Lafayette County. For the last 8 years the discharge rate rarely exceeded 100 cfs (the average is 52.2 cfs). Spring acted as a sink 14% of time—negative discharge value means that the flow is from the Suwannee River into the spring. Florida Geological Survey (FGS) still lists Lafayette Blue Springs as a first magnitude spring.

North of Gainesville, a church camp once attracted thousands of visitors because it was built around the gushing waters of Hornsby Springs. Then the spring stopped flowing and the camp had to spend more than $1 million to build a water park to replace it. The old spring site is now so stagnant that it's frequently declared unfit for humans to swim in.

From Florida's vanishing springs by Craig Pittman

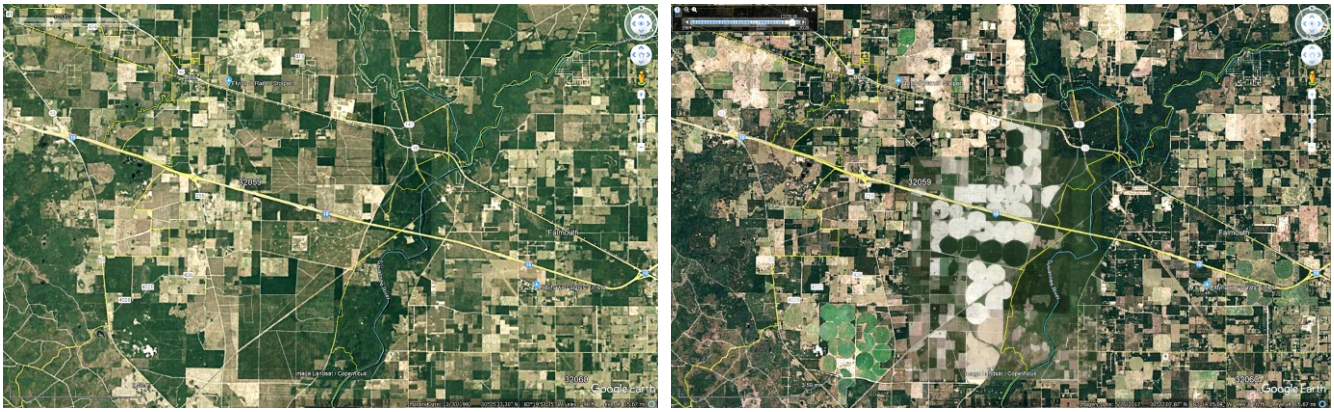


Figure 2.1.7 Google Map showing general area of the confluence of the Suwannee and Withlacoochee Rivers in north Florida. Satellite images by Landsat/Copernicus. *Left*: Image acquired on 12/30/1993; virtually no center-pivots ("large circles") are present. *Right*: Image acquired on 5/26/2018. Center-pivots are visible throughout, not only in the center of the image where they are most obvious.

According to the Southwest Florida Water Management District (SWFWMD), a steady decrease in rainfall since the 1960s is solely to blame for the reduction in discharge of their springs because all other factors are under control and are not responsible for this reduction (Fig. 2.1.8; https://www.swfwmd.state.fl.us/projects/springs/how-are-floridas-springs-threatened accessed on March 16, 2026). However, a long-term record of rainfall at the two closest major rain gaging stations, Ocala and Tampa, between which the springsheds of the SWFWMD's springs

are located, shows that this statement is far from the truth. This rainfall record is publicly available, and anyone can see the graphs of long-term rainfall for Ocala and Tampa on their computer screens when they visit Climate Data & Visualization web page of Florida Climate Center at Florida State University. Anyone can also download the data to create their own graphs (e.g., Figs. 2.1.9 and 2.1.10).

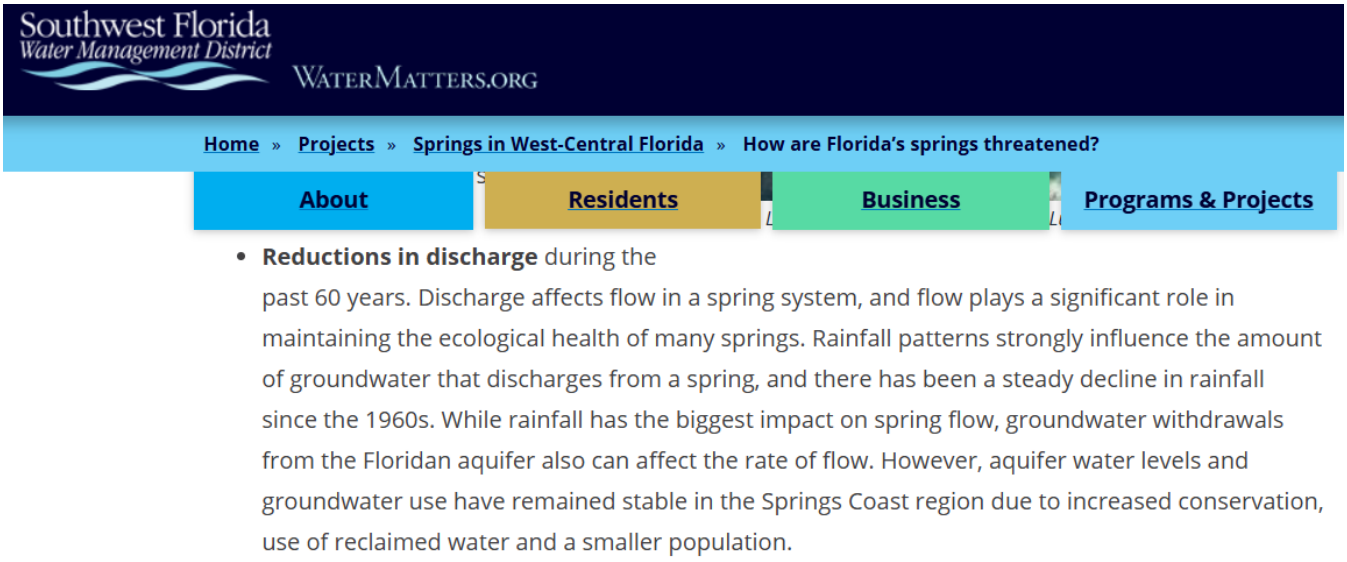


Figure 2.1.8 Screenshot of the SWFWMD web page accessed March 16, 2026. https://www.swfwmd.state.fl.us/projects/springs/how-are-floridas-springs-threatened

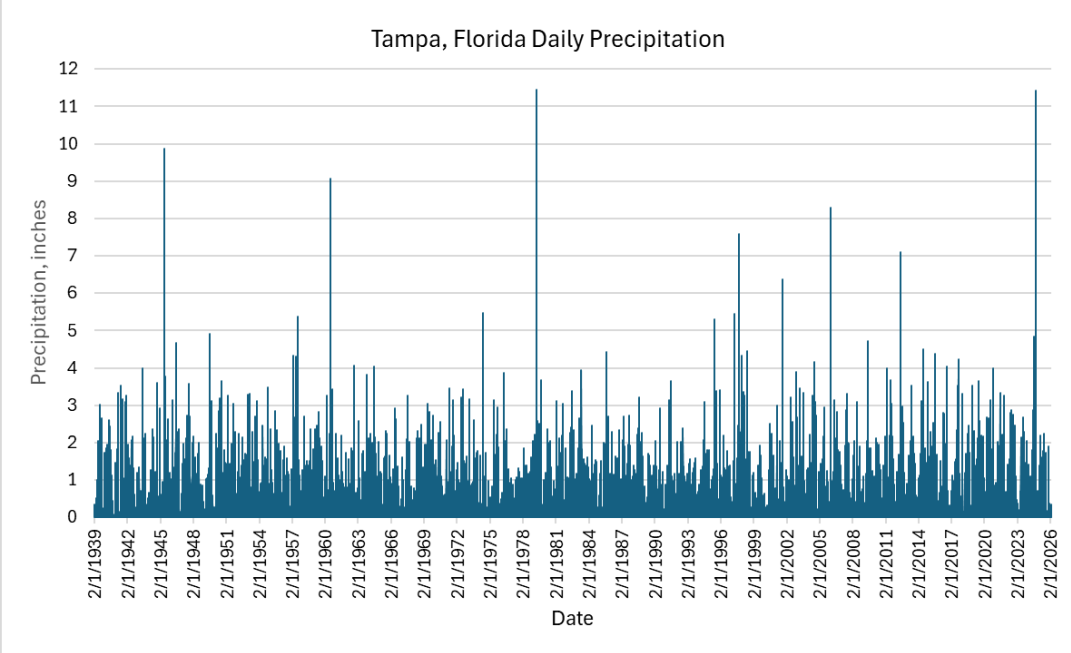


Figure 2.1.9 Daily rainfall recorded at Tampa Airport since 1939. Data from Climate Data & Visualization web page of Florida Climate Center at Florida State University https://climatecenter.fsu.edu/climate-data-access-tools/climate-data-visualization

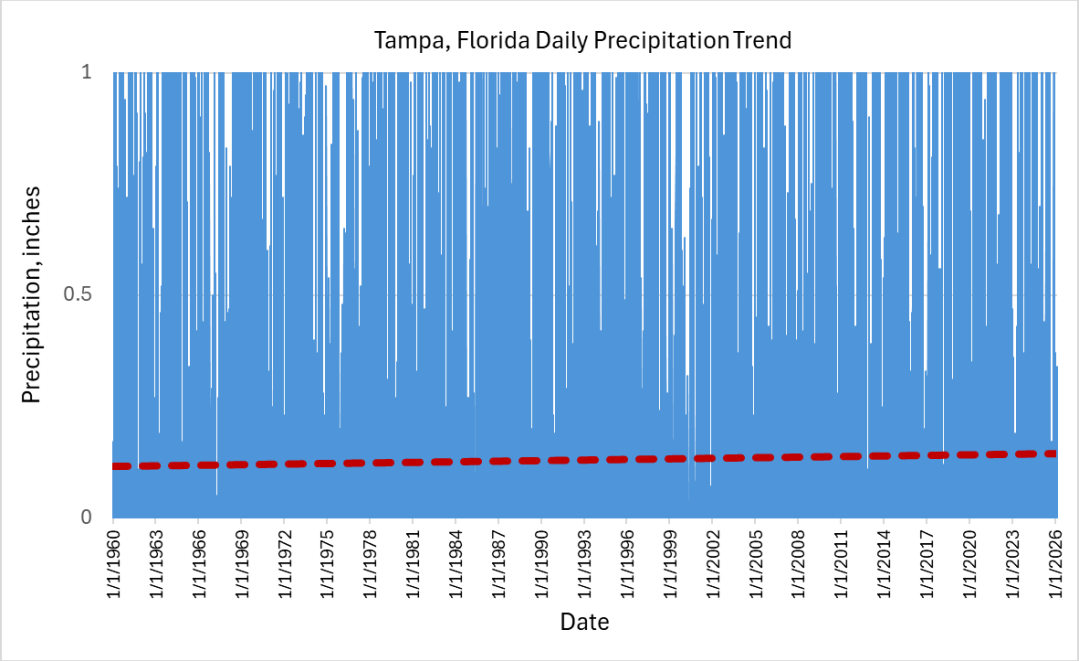


Figure 2.1.10 Trend in daily rainfall recorded at Tampa Airport since 1960. Vertical scale truncated at 1 in. to better show the slope of the linear trend line generated in Microsoft Excell. Data from Climate Data & Visualization web page of Florida Climate Center at Florida State University. https://climatecenter.fsu.edu/climate-data-access-tools/climate-data-visualization.

Contrary to the statement by SWFWMD that there has been a steady decline in rainfall since the 1960s, the main reason for the decline of springs' discharge rates as alleged by SWFWMD, Fig. 2.18 clearly shows that, in fact, there has been a **steady increase in rainfall** since 1960s. The linear trend line is from Microsoft Excel.



Figure 2.1.11 White Sulphur Springs in Hamilton County, once popular tourist destination. Copyright John Moran, all rights reserved. Printed with permission.



Figure 2.1.12 Poe Springs in Alachua County, once popular tourist destination. Copyright John Moran, all rights reserved. Printed with permission.

2.1.1 Biscayne Aquifer, Florida

The Biscayne aquifer underlies an area of about 4,000 square miles and is the principal source of water for all of Dade and Broward Counties and the southeastern part of Palm Beach County in southern Florida. About 70 percent of the water is withdrawn for public supply. Major population centers that depend on the Biscayne aquifer for water supply include Boca Raton, Pompano Beach, Fort Lauderdale, Hollywood, Hialeah, Miami, Miami Beach, and Homestead. The Florida Keys also are supplied primarily by water from the Biscayne aquifer that is transported from the mainland by pipeline. The only source of drinking water for more than 4 million people (USGS, 2020), the Biscayne aquifer was designated a *Sole Source Aquifer* by the United States Environmental Protection Agency in 1979, which restricts federally funded projects that could contaminate it.

The Biscayne aquifer is an unconfined, surficial aquifer made up of shallow, highly permeable Pleistocene limestone as well as some less-permeable sandstone and sand (Miller, 1990). Because of the shallow depth of the units that make up this aquifer, the connection to surface water is an important aspect of the hydrogeology of the Biscayne aquifer (Miller, 1990). Perhaps the most prominent example of the use of artificial recharge to control saltwater intrusion on the east coast of the United States is the Biscayne Aquifer. An extensive network of surface-water canals is used to convey freshwater from inland water conservation (storage) areas during the dry season to

coastal areas, where the water is recharged through the canals to the underlying Biscayne aquifer to slow salt water intrusion in the aquifer (Barlow, 2003).

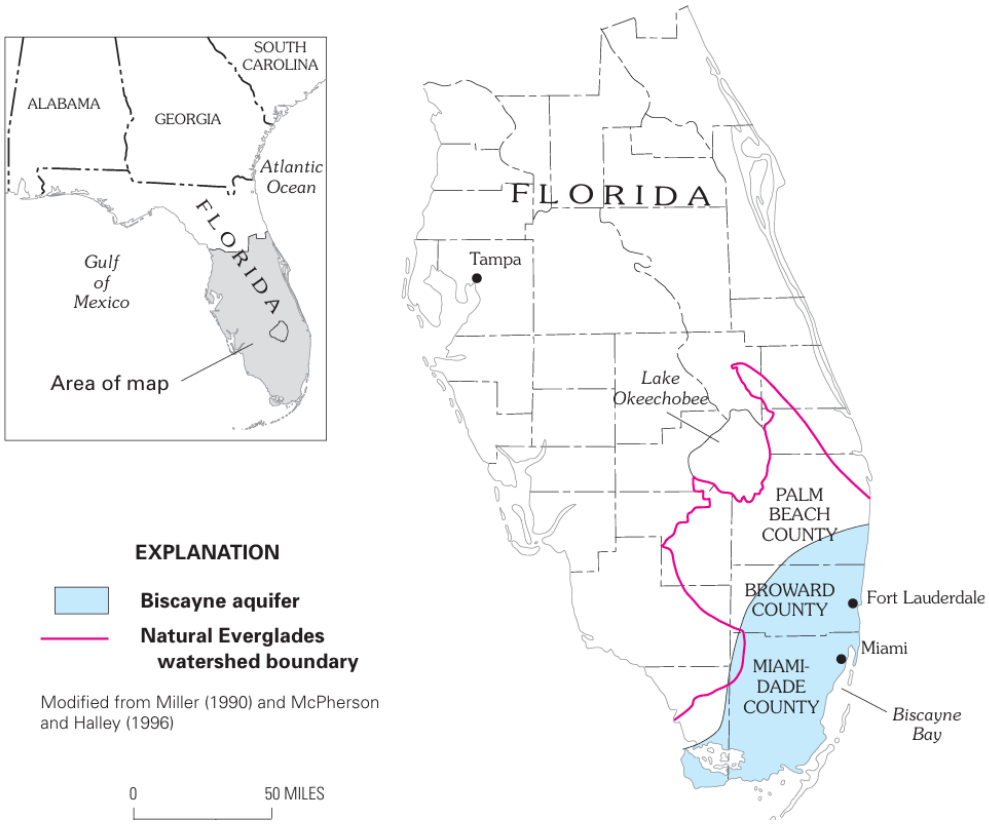


Figure 2.1.13 The Biscayne aquifer underlies southeastern Florida and is within the boundary of the natural watershed of the Everglades. From

2.2 Appalachian Plateaus, and Interior Low Plateaus Karst Aquifers

The Appalachian Basin of the eastern United States consists of the Appalachian Plateaus, Interior Low Plateaus, and the Valley and Ridge physiographic provinces which are often grouped together into the so-called “Inland Basin”. The Inland Basin occupies the landscape west of the Appalachian Blue Ridge to the Mississippi Embayment and north of the Gulf Coastal Plain and can be thought of as the Southeast's geologically stable, ancient topographic nucleus. It is composed of a thick sequence of Paleozoic-aged carbonate sedimentary rock deposited during multiple ocean incursions into the continent's interior, punctuated by blankets of siliciclastic sediment from the erosion of newly uplifted mountains. This alternating stratigraphy of carbonates and clastics underlies the entire region, and it is dominated by nearly horizontal or gently sloping sediment layers (Paleontological Research Institution, 2021).

The easternmost part of the Inland Basin, the Valley and Ridge, is a strip of linear geologic folds ("wrinkles") that create ridges and valleys running northeast to southwest, adjacent to the Blue Ridge of the Appalachians in the east. The Valley and Ridge province hosts numerous karst aquifers and springs as explained in more detail in Chapter 2.3.

The southern portion of **the Appalachian Plateau**, stretching from Kentucky and Tennessee to Alabama, is called the Cumberland Plateau. In Kentucky, the Cumberland Plateau is dominated by forested hills and dissected by V-shaped valleys. A 125-mile-long thrusted ridge, Pine Mountain, extends across the area. In the northern part of the Tennessee Plateau, an unusual pattern of late Paleozoic thrust faults has created a raised and tilted uplift called the Wartburg Basin, deforming the strata into the topographically higher Cumberland Mountains—a mountain range that lies on top of the plateau. In southern Tennessee, the Cumberland Plateau is bisected by a breached anticline, the Sequatchie Anticline, that later eroded to form Sequatchie Valley—also an example of topographic inversion. This northeast-trending valley resembles a deep knife slice into the southern Cumberland Plateau extending into Alabama.

The eastern side of the Appalachian Plateau is a major southeast-facing escarpment called the Appalachian Structural Front. It was formed in part by northeast- to southwest-trending thrust faults. The relief along this structure is steep, and rockfalls and landslides are common environmental hazards. In West Virginia, the escarpment is called the Allegheny Front, and its highest point is Mt. Porte Crayon (4700 feet). In Kentucky, it is the Pottsville Escarpment, a rugged sandstone belt of cliffs and valleys. In Tennessee, it is called the Cumberland Escarpment, and rises over 980 feet, with grand vistas of the Valley and Ridge to the east (Paleontological Research Institution, 2021).



Appalachian Plateaus aquifers occupy approximately 86,000 mi^2 in portions of Alabama, Kentucky, Maryland, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia (Fig. 2.2.1). Appalachian Plateaus aquifers are comprised of alternating sequences of fractured sandstone, siltstone, shale, limestone, and coal in Permian-, Pennsylvanian-, and Mississippian-age rock formations. Erosion of the rock formations has produced characteristic steep hills, rugged topography, and deeply incised valleys (USGS, 2014).

Figure 2.2.1 Location of Permian-age, Pennsylvanian-age, and Mississippian-age aquifers of the Appalachian Plateaus, eastern United States. USGS, 2014.

Groundwater flow in Appalachian Plateaus aquifers is characterized by short flow paths, typically extending no more than tens of miles. Groundwater flow is controlled both by the regional dip of bedrock, local topography, and distal hydrologic boundaries coincident with large river valleys.

Mississippian-age aquifers consist of sandstone, limestone, and fractured chert. Limestone content increases to the south where in Kentucky, Virginia, and West Virginia, the Greenbrier Limestone and Slade Formation discharge 1,000 gal/m or more to springs. Large spring discharges from the Mississippian-age carbonate aquifers along the sides of major incised valleys such as the Sequatchie Valley in Tennessee yield as much as 4,000 gpm from the Bangor and Tuscumbia Limestones (Miller, 1990).

Dissolution of Mississippian-age aquifers has resulted in the development of locally permeable karst features (Seaber et al., 1988). Caves, sinkholes, and sinking streams are prevalent in the extensive Mississippian-age karst aquifers of southeastern West Virginia and eastern Kentucky. In West Virginia alone, there are over 3,000 documented caves in Mississippian-age units (Dasher, 2012). Cave passages tend to be constrained by stress-relief fracturing within valley walls in “Cumberland Style” karst, indicating coincident groundwater and surface-water drainages on the Cumberland Plateau (Simpson and Florea, 2009; Sasowsky and White, 1994; Crawford, 1984). Simpson and Florea (2009) have noted several exceptions where cave passages follow fracture swarms associated with regional structures, effectively routing groundwater through ridges and between adjacent valleys.



Figure 2.2.2 Lost Waterfall in the Monongahela National Forest, 6 miles west of Elkins, West Virginia. . It is in the Appalachian Plateau province, specifically within the Allegheny Mountains section (also known as the Allegheny Highlands) The Taggard shales separate the Greenbrier formation into an upper limestone unit and a lower limestone unit. Water issues from the ground as a spring, cascades over the vertical surface outcrop of the Taggard Formation and immediately sinks back into the ground as it reenters solution channels in the lower limestone units. The Greenbrier limestone contains the majority of West Virginia's 3,000 or so known caves. Many of these caves have entrances just above or just below the outcrop of the Taggard shales. Photograph and text courtesy of James Van Gundy, for Universities Space Research Association; available at http://epod.usra.edu/blog/2009/10/lost-waterfall.html.



Figure 2.2.3 Lee White and Mark Wingard in Mt. Stromboli, Gourdneck Cave, Gourdneck Cave Preserve, Marion County, Tennessee. The cave is in Cumberland Plateau physiographic province, specifically situated within the rugged terrain of the southern Cumberland Plateau region often associated with the TAG (Tennessee, Alabama, Georgia) caving area. The cave features Mississippian-aged Bangor Limestone and is managed by the Southeastern Cave Conservancy Photo courtesy of Chuck Sutherland.

The Interior Low Plateaus is one of the most well-developed karst landscapes in the world, consisting of almost completely horizontal beds of Paleozoic sandstone, shale, and limestone. It forms a continuous arc from southcentral Indiana, through Louisville, Kentucky, middle Tennessee (where it surrounds the Nashville Basin), and down south to Russellville, Alabama. Unlike the rugged Cumberland Plateau, the Interior Plateaus is characterized by rolling hills and vast "sinkhole plains" where surface water quickly disappears into underground karst networks. These include the Mitchell Plateau (sinkhole plain) in southern Indiana, the Pennyroyal Plateau in Central Kentucky, which is the geomorphic and stratigraphic equivalent of the Mitchell Plain, and the Illinois Sinkhole Plain in Monroe County (part of the Salem Plateau in Illinois) to name just the most famous.

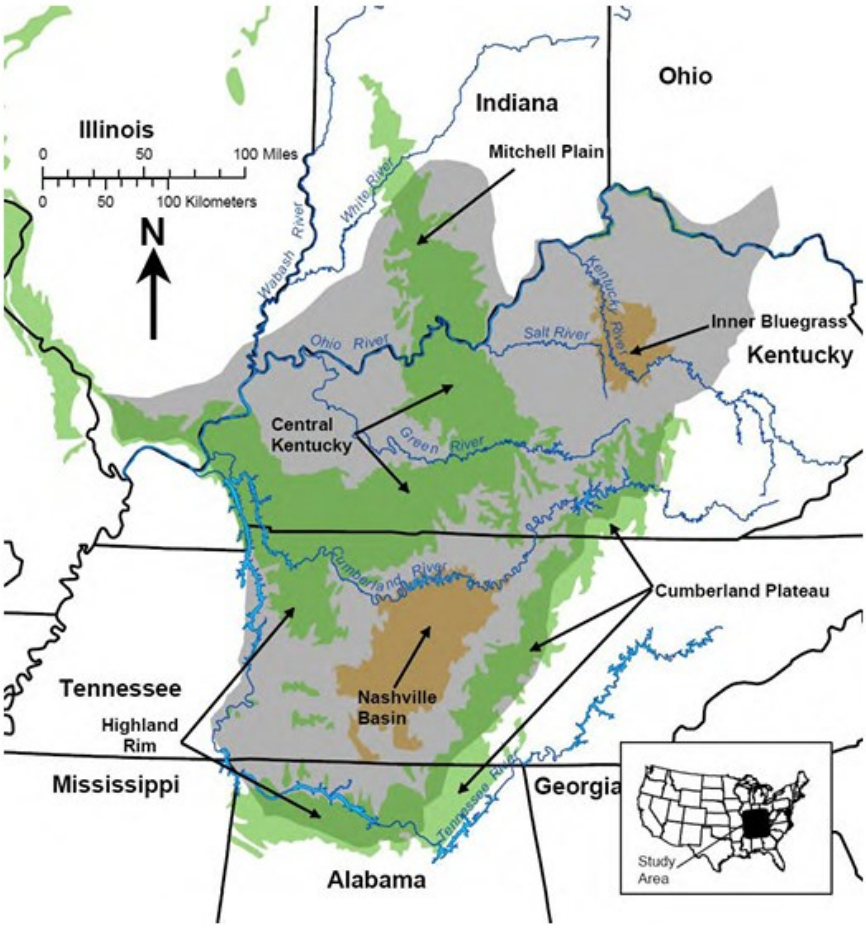


Figure 2.2.4 Geographic boundaries of the Interior Low Plateaus and major regional karst terranes. Explanation: tan areas underlain by Ordovician-age carbonates; green areas underlain by Mississippian-age carbonates; and grey areas underlain by relatively less karstified Ordovician-Mississippian carbonates, or non-karstic sedimentary rocks. From Taylor and Nelson, 2008.

The Mitchell Plateau, located in south-central Indiana, is one of the most iconic karst landscapes in the United States. The region is a low, broad plateau that is partially eroded by deeply incised stream systems. The plateau is developed on Mississippian-age carbonate bedrock and extends from the eastern part of Owen County southward to the Ohio River in Harrison County and into Kentucky. South of the East Fork White River, thousands of sinkholes transfer water to complex underground cave systems. The known maximum is 1,023 sinkholes in a square mile near the town of Mitchell, Lawrence County (Hasenmueller et al., 2003; see also https://igws.iu.edu/outreach/karst).

The Interior Low Plateaus contain numerous karst springs, sinking streams, and caves, including the longest cave in the world, the Mammoth Cave which is being continuously explored and surveyed. At the time of this writing (spring of 2026), the mapped length of the cave is 426 miles. (Exploring the World's Longest Known Cave (U.S. National Park Service)

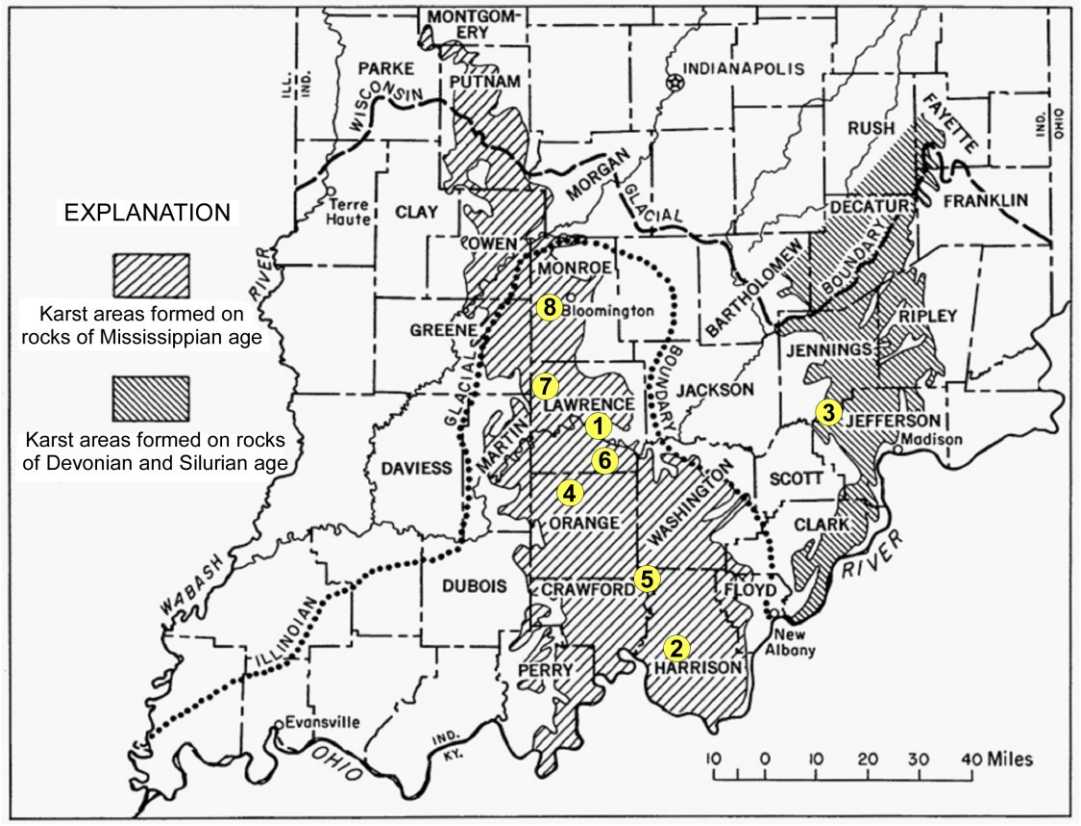


Figure 2.2.5 Karst areas in Indiana owned and protected by Indiana Karst Conservancy (https://ikc.caves.org/ikc-managed-nature-preserves). (1) Buddha Karst Preserve; (2) Indian Creek Sinks; (3) Lowry Karst Preserve; (4) Orangeville Rise; (5) Robinson Ladder Cave; (6) Shawnee Karst Preserve; (7) Sullivan Cave; and (8) Wayne Cave.



Figure 2.2.6 Sinkholes dot Pennyroyal Plateau in Central Kentucky. Photo courtesy of Annie Holt, American Cave Conservation Association Education Director. Available at https://www.facebook.com/HartCounty.



Figure 2.2.7 Showerbath Spring pours into the Mammoth Cave passage near formation named Frozen Niagara. NPS Photo by Ashley Decker. Mammoth Cave National Park is a designated UNESCO World Heritage Site as well as an International Biosphere Reserve. The park was established on July 1, 1941, and encompasses 52,830 acres of wilderness.

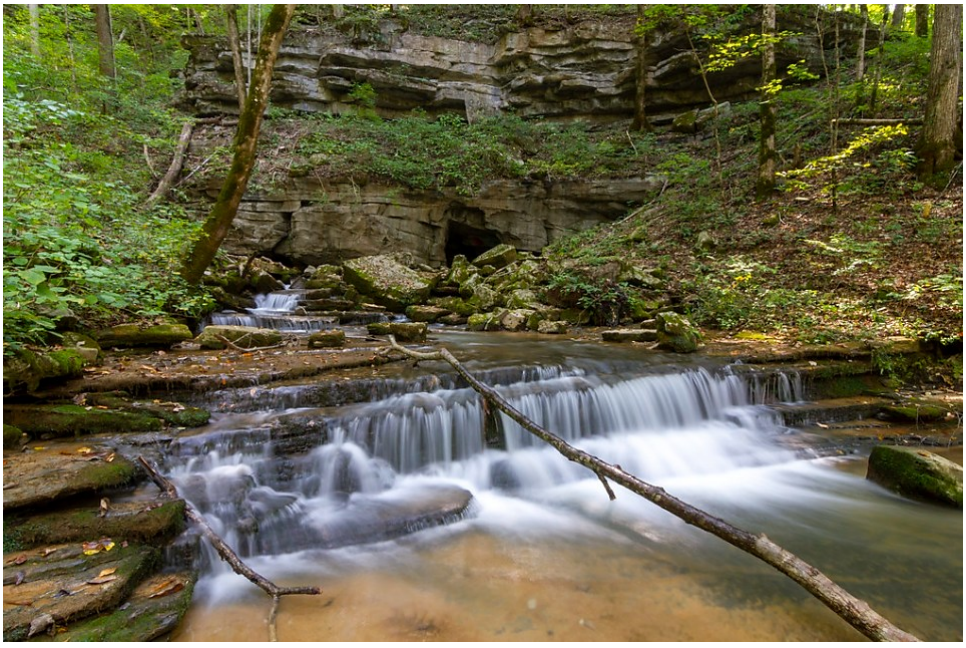


Figure 2.2.8 Garrett Mill Cave Spring in Overton County, Tennessee, on the Pennyroyal Plateau (also called the Highland Rim in Tennessee). The cave is a karst feature located at the contact points of Bangor Limestone and Monteagle Limestone. It is characterized by an active stream that powered an old grist mill, featuring both upper and lower passages and a second entrance. Photo courtesy of Chuck Sutherland. For more photographs illustrating many fascinating natural landforms in Tennessee, including caves, sinkholes, and springs, visit an excellent web page by Chuck Sutherland at https://www.tnlandforms.com/.



Figure 2.2.9 Cathedral Caverns in Cathedral Caverns State Park, Jackson County, Alabama.



Figure 2.2.10 Stephens Gap is one of the most beloved caves in the Southeast, with a beautiful 143-ft pit that cavers love and a huge walk-in entrance that draws hikers, photographers, and other outdoor enthusiasts. The view of the pit from the walk-in passage is one of the most photographed wild cave scenes in North America. Located in the heart of Jackson County, AL, Stephens Gap is Southern Cave Conservancy's (SCCi) 30th cave preserve. By acquiring this preserve, SCCi ensures that it is protected and preserved for future generations of cavers, hikers, and photographers. SCCIi is the largest land conservancy in the world solely focused on protecting caves. Photo by J. Silverman.
https://www.saveyourcaves.org/preserve?rowid=stephens-gap-callahan-cave-preserve

2.3 Valley and Ridge Karst Aquifers

The aptly named Valley and Ridge province, in the Appalachian Mountain region, is a series of northeast-southwest trending synclines and anticlines composed of Early Paleozoic sedimentary rocks. The province stretches approximately 1,200 miles from New York south to Alabama. It forms a broad arc west of the Blue Ridge Mountains, spanning Alabama, Georgia, Tennessee, Virginia, West Virginia, Maryland, Pennsylvania, New Jersey, and New York.

Limestones and shales are more susceptible to erosion and make up much of the valleys, whereas more resistant sandstones and conglomerates form the ridges. These folded strata are the result of the compression associated with the assembly of the supercontinent Pangea and the various mountain building events that produced the Appalachian Mountains. The elongate and folded sedimentary rocks of the Valley and Ridge were deformed by thrust faulting during the Alleghanian Orogeny, which created an accordion-like repetition of strata as sheets of rock folded and then broke to slide over adjacent areas (Paleontological Research Institution, 2021.)

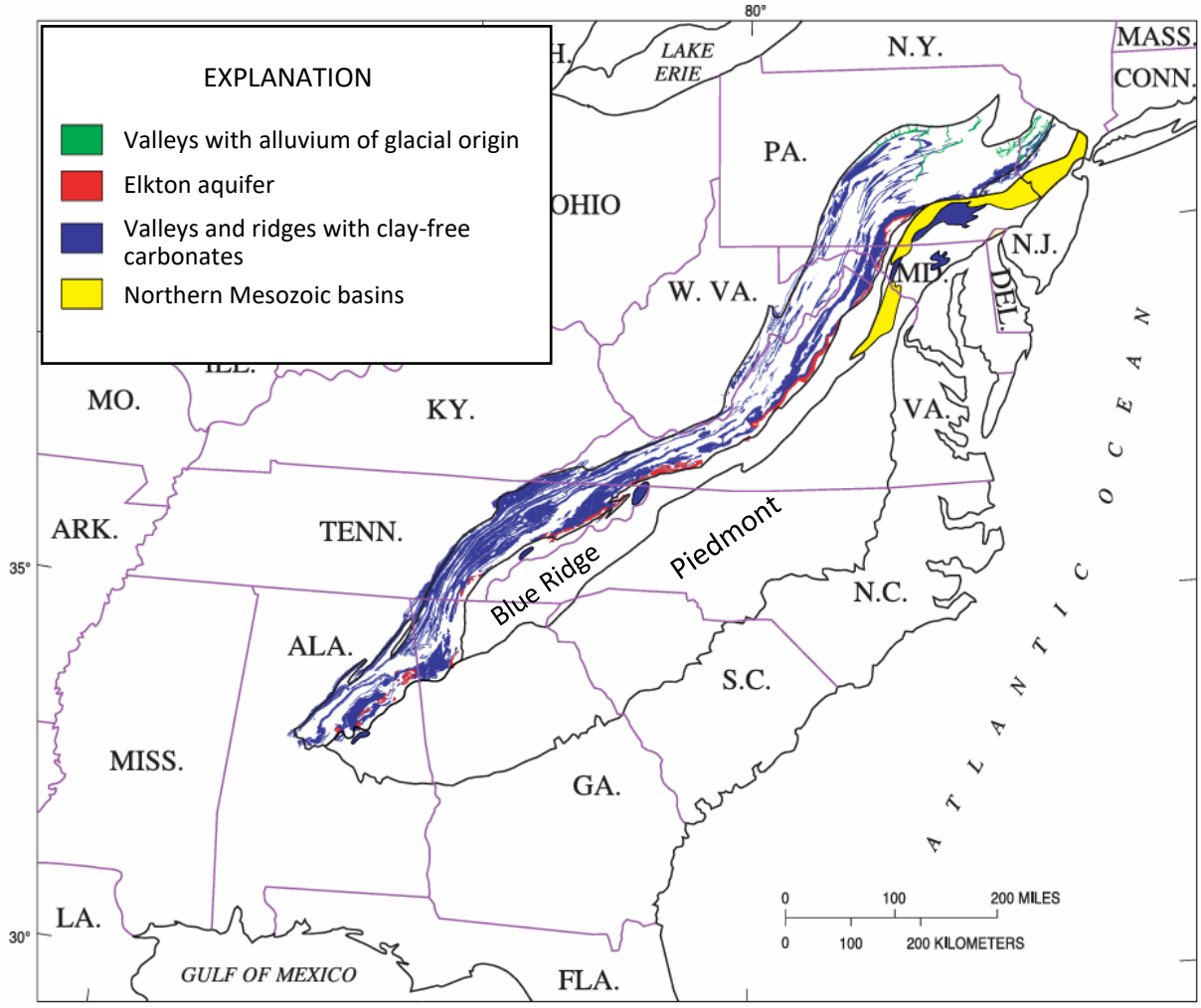


Figure 2.3.1 Areas where future development of municipal and industrial groundwater supplies from the Appalachian Valley and Ridge, and Piedmont Aquifer systems have good potential. Modified from Swain et al., 2004. Notes: Northern Mesozoic basins in the Piedmont Aquifer are mainly sandstones; Elkton Aquifer (also known as the Western-toe aquifer) along the northwestern margin of the Blue Ridge province is a highly productive Cambrian carbonate aquifer. It is named after the town of Elkton in the Virginia's Shenandoah Valley where it was first utilized for public water supply.

Many of the folds are plunging, meaning that the axes (fold creases) are not horizontal but are tilted to the northeast or southwest. At the southernmost extent, the Valley and Ridge province plunges beneath the Coastal Plain province. Erosion of this folded and tilted terrain has produced a trellis drainage pattern.

The Great Valley is a continuous basin spanning the eastern side of the Valley and Ridge province. It is known by different names in different states, and includes the Lebanon Valley (Pennsylvania), the Shenandoah Valley (Virginia), the Hagerstown Valley (Maryland), and the Great Valley of East Tennessee.

Drainage within the Valley and Ridge typically follows the orientation of valleys, with most rivers meandering back and forth across valley floors in a northeast to southwest direction. Short tributaries flowing down the ridge slopes feed the rivers. This distinctive drainage pattern, controlled by the Valley and Ridge topography, is referred to as trellis drainage. A few major rivers (including the Potomac and New Rivers) have cut narrow water gaps perpendicular to the ridges. Most notable of these include the Delaware and Susquehanna Rivers which are flanked in places by cliffs reaching 1,000 ft. (Paleontological Research Institution, 2021; National Park Service (NPS); https://www.nps.gov/articles/valleyandridgeprovince.htm.)

Karst processes in the carbonate beds have produced beautiful caves, well decorated with stalagmites and stalactites. These include the Skyline, Luray, Endless, and Shenandoah Caverns in Virginia. Skyline Caverns include unique white calcite growths called anthodites, after the Greek work for flowers. Natural Bridge, northeast of Roanoke, Virginia is large enough to support a major highway, spanning 90 ft and rising 215 ft above the Cedar Creek.

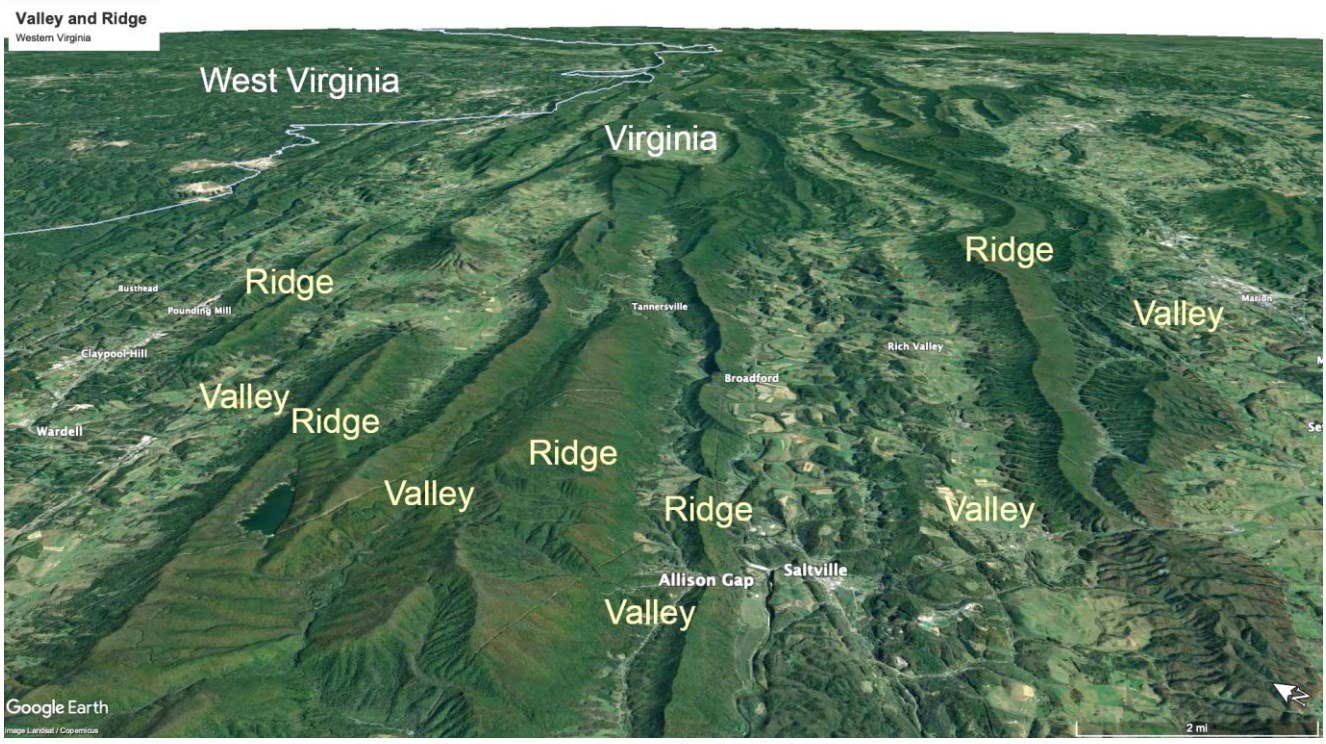


Figure 2.3.2 Northeast-facing satellite view of the Valley and Ridge system in western Virginia. Image © Google Earth, Landsat/Copernicus; labels added for the Earth@Home project. Available at https://earthathome.org/hoe/se/topography-ib/#valley-and-ridge

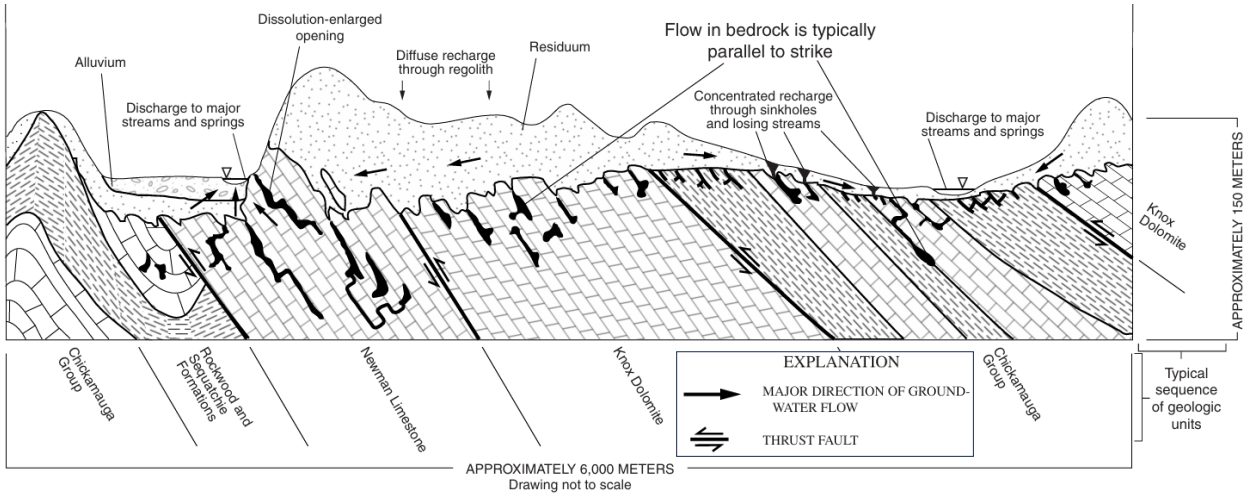


Figure 2.3.3 Generalized hydrogeologic section through the Valley and Ridge in Tennessee. From Wolfe et al., 1997.







Figure 2.3.4 *Top left*: sinks of Potts Creek in Alleghany County, Virginia. *Top right;* fossils of coral reef on ledge in Silurian limestone in a Highland County cave. *Bottom left*: "Really Big Rock" in a Highland County cave. Approximately 50% of the county's terrain is karst, which has led to the formation of over 220 reported caves. The Highlands underground is home to over 50 cave-dwelling invertebrate species, the Alleghany Woodrat and seven bat species, including the federally endangered Virginia Big-eared Bat and Indiana Bat. The majority of the invertebrate species are only known from a handful of caves in the region and nowhere else on Earth. Photographs courtesy of Phill Lucas.

The following excerpts and photographs in Figs. 2.3.5 and 2.3.6 are from a pamphlet "Karst Secrets of the Highland Region" produced by the Virginia Department of Conservation and Protection, the Virginia Natural Heritage Karst Program (https://www.dcr.virginia.gov/natural-heritage/karsthome), with support from the Cave Conservancy of the Virginias (https://caveconservancyofvirginia.org)

Although adapted for the challenges of living in caves without light and with limited food, cave species are extremely vulnerable to any changes in their environment, including disturbance to areas that overlie or drain to the caves. Such species can be protected with proper land management. Landowners can help these species by using best management practices when farming, and, in some cases, choose to pursue conservation easements designed to help protect the land into the future.



Figure 2.3.5 Federally endangered Virginia Big-eared Bats roosting in a Highlands cave.



The Virginia Cave Protection Act helps protect karst resources, which receive a few other protections under state or federal regulations. The identification and protection of sensitive karst areas through appropriate land use planning helps ensure a safe, clean water supply for everyone. These actions also protect rare species and natural communities. Therefore, do something for yourself and others — be aware of the karst that surrounds you, and help protect it.

Figure 2.3.6 Sediment spilled into the cave while drilling for a well.

2.4 New York, and New England Karst Aquifers

2.4.1 New York Karst Aquifers

Reddy et al. (2020) provide an extensive description of the New York State karst, the excerpt of which are provided throughout this chapter. Karst in New York is present in a number of bedrock lithologies (limestone, marble, dolostone, and shale with evaporite deposits; Fig. 2.4.1) and is also dependent on the structure of and within the rock (strike and dip of the rock and the presence of joints, fractures, faults, and bedding planes within the rock mass). Karst develops in either gently dipping west-to-east oriented bands in western and central New York or in steeply dipping beds or isolated exposures in southeastern New York. Weary (2008) characterizes New York's carbonate karst into two major groups, each with a subgroup based on glacial-cover thickness.

The first group of bedrock consists of gently folded and flat-lying carbonate rocks that have not been strongly deformed. One subclass of this group is thinly covered with glacial material and the other subclass has thick (more than 50-ft) unconsolidated glacial materials that tend to obscure karst land-surface features. In this group, where the carbonate rocks are thick and extensive, cave systems may be long and complex. Where the carbonates are thin and interbedded with noncarbonates, caves are small and short (Weary, 2008).

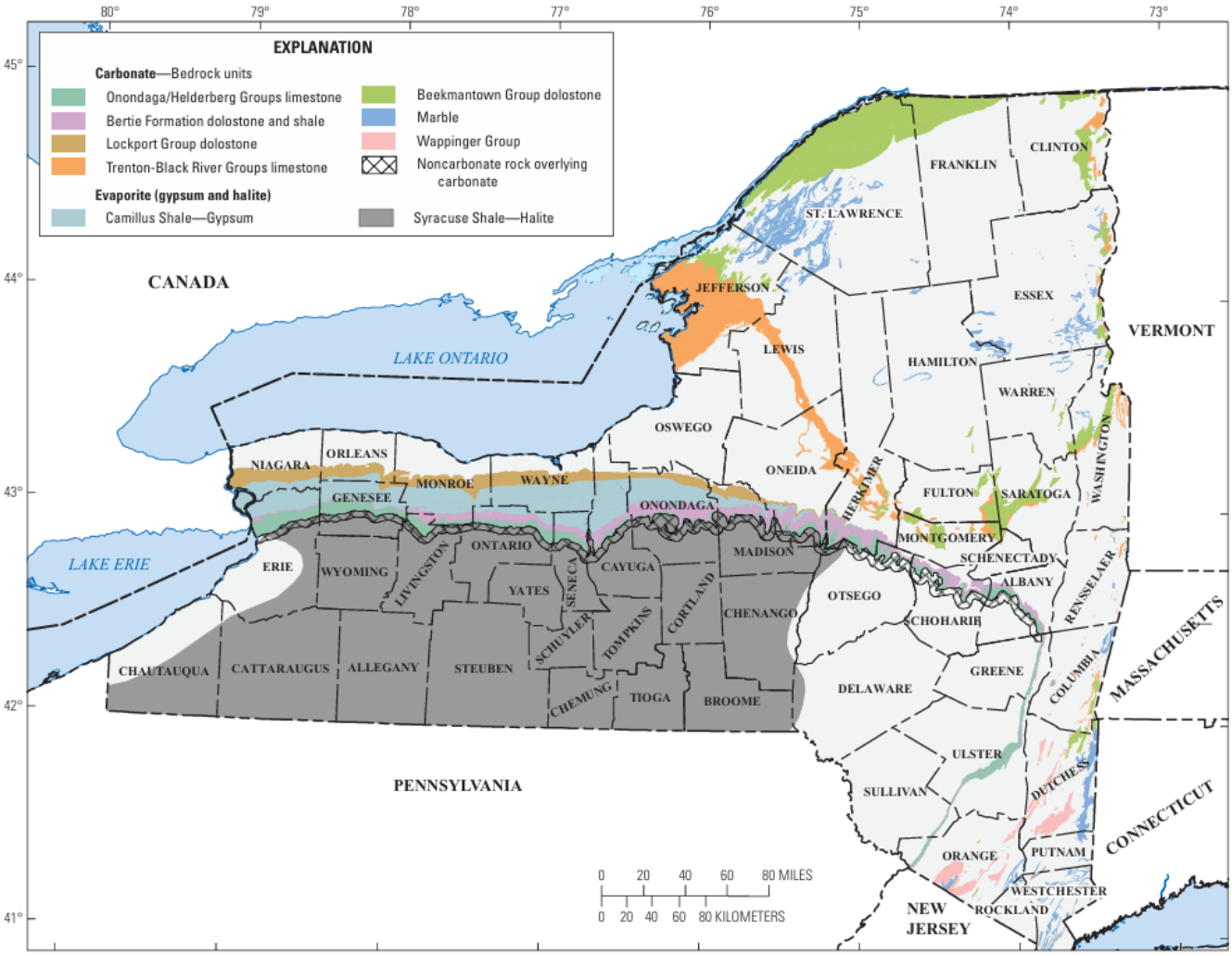


Figure 2.4.1 Major geologic units in which karst may be developed in New York State. From Reddy et al., 2020.

The second group of karst bedrock is composed of folded and faulted carbonate rocks flanking structural deformation zones that may be intensely folded, jointed, and faulted. Caves can be small and simple or long and complex (Weary, 2008). Palmer (1991) indicates that cave patterns in this group show structural control and form networked (angular grid- or road like) cave patterns as well as vertical connections to the land surface. Here, too, where the glacial deposits are thick (more than 50 ft), the karst features typically are not apparent at land surface.

Cooper and Mylroie (2015) described the geologic age and location of karst bedrock in New York as

- Precambrian Grenville Complex marble in the Adirondack Mountain region;
- Precambrian, Cambrian, and Ordovician marble in eastern New York (Wappinger and Chazy Groups);
- Cambrian and Ordovician limestone in northern New York lowlands and the Mohawk Valley (Trenton Group, Black River Group, and Beekmantown Group);
- Silurian and Devonian limestone and dolostone in nearly flat-lying beds from western to east-central New York (Onondaga Limestone, Helderberg Group, and Lockport Group), and within gypsum- and halite bearing shale (Salina Group) in western to central New York. Other carbonate beds are present in the Silurian and Devonian sequence and can be karstic locally (such as the Manlius, Coeymans, Rondout, and Tully Limestones and the Akron-Bertie Dolostone), but they are not highlighted here because they are generally associated with the previously mentioned bedrock units.
- Silurian and Devonian limestone and dolostone in structurally deformed and steeply dipping beds along the western side of the Hudson River Valley in eastern New York (Onondaga Limestone and Helderberg Group)



All bedrock in New York has been affected to various degrees through geologic time by continental movement (plate tectonics) and the associated structural deformation including folding, fracturing, and faulting. In an extreme case in the lower Hudson River Valley, bedrock strata have been deformed from a horizontal to a nearly vertical orientation (Reddy et al., 2020.)

Figure 2.4.2 Google Earth image of the karst bedrock in Madison County, New York, at a limestone quarry north of Perryville. Visible are major fracture networks enhanced by dissolution and marked by vegetation bands; quarry floor is in the shadow left of the fractured bedrock surface. From Reddy et al., 2020.

Because of glacial erosion and the dip of the regional bedrock, the Onondaga Limestone (Lower Devonian Limestones) is typically at or near land surface at its northern extent, creating a bedrock escarpment (cliff) also called the Helderberg Escarpment (Albany and Schoharie Counties). This area contains some of the most well-developed glaciated karst in the country. It is home to famous features like Howe Caverns and Secret Caverns. However, south of the escarpment the Onondaga Limestone is buried by progressively thicker glacial deposits—mostly till and glaciolacustrine fine sand, silt, and clay, but locally sand and gravel (Staubitz and Miller, 1987).

The Onondaga Limestone has been characterized as a principal aquifer in New York, which is defined as "an aquifer known to be highly productive or whose geology suggests abundant potential water supply, but which is not intensively used currently as a source of water supply by major municipal systems" (New York State Department of Environmental Conservation, 2020).

The dolostone of the Lockport Group (Silurian dolomite) at the Niagara escarpment is at land surface but further to the south, it is buried by thick glaciolacustrine silt and clay (Kappel and Jennings, 2012). Owing to fine-grained sediment cover and the fact that the dolostone is not as easily solutioned as limestone (because dolostone, which is calcium magnesium carbonate, has different mineral characteristics compared with limestone, which is calcium carbonate), the Lockport Group is less likely to develop karst features (Reddy et al., 2020). Regionally, the Lockport aquifer system is generally confined to these bedding-plane structures and the weathered bedrock surface and is not nearly as productive as the Onondaga Limestone.

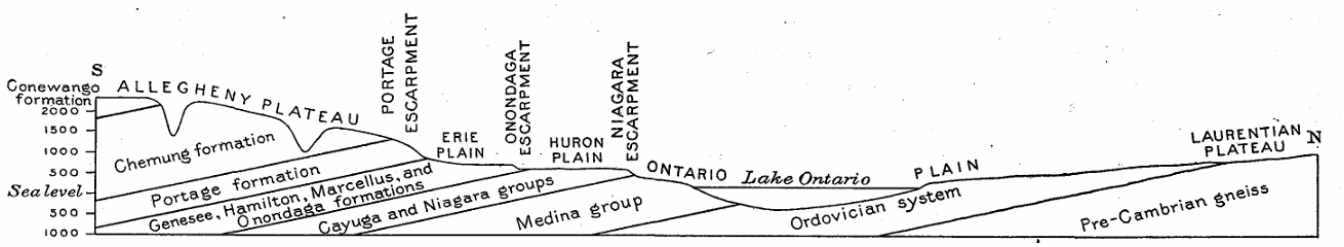
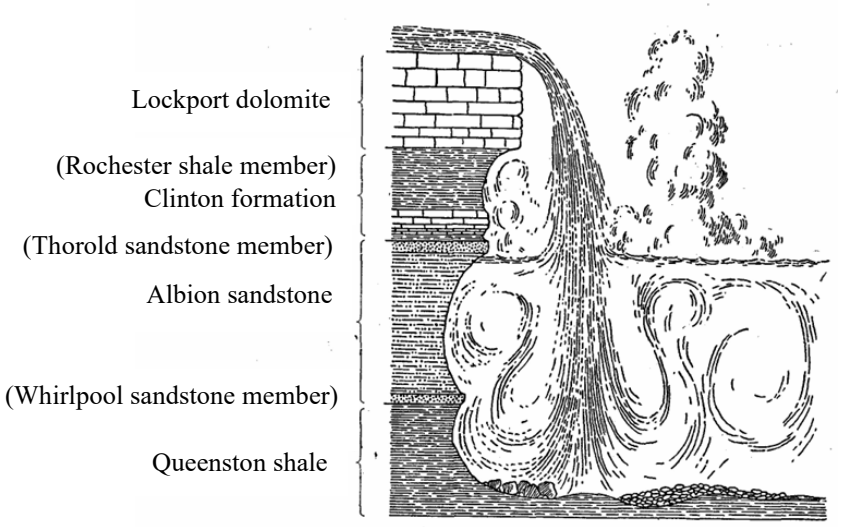


Figure 2.4.3 Diagrammatic south-north section through the center of the Niagara quadrangle from the Pennsylvania-New York State line to the Laurentian Plateau, Canada shows the physiographic divisions and the attitude of the underlying rocks. The steep inclination of the strata is the result of the exaggeration of the vertical scale. Niagara Escarpment is formed in Silurian Lockport Dolomite (Dolostone) of the Niagara Group, Onondaga (or Helderberg) Escarpment in Lower Devonian limestones, and Portage Escarpment (without dramatic cliffs) in Upper Devonian sandstone and shale. Cross-section from Kindle and Taylor, 1913.



The Beekmantown Group of northern New York unconformably (former overlying bedrock units are not present because of erosion millions of years ago) overlies the Precambrian Shield (Bernstein, 1992); the deep part of the Beekmantown Group is generally a sandstone, but the shallow units are dolostone.

Figure 2.4.4 Section of brink of Niagara Falls showing the arrangement of hard and soft strata and illustrating the process of erosion. From Kindle and Taylor, 1913.

The aquifer within the Beekmantown Group is generally present at the weathered bedrock surface and within the relatively shallow fractured bedrock resulting from glacial rebound of the land surface, and karst development is considered young and slowly developing (Cooper and Mylroie, 2015).

In the eastern part of New York, the strata of the Onondaga and Helderberg Groups have great thicknesses of carbonates and well-developed karst because of the extended period of time in which the bedrock has been exposed to repeated glaciation and interglacial erosion (Baker, 1976).

The Helderberg-Cobleskill Plateau region (Baker, 1976; Palmer et al., 2003; Cooper and Mylroie, 2015) is an incised carbonate terrain resulting from repeated periods of glaciation and erosion, which, over time, has created solution-derived fracture conduits and well-developed cave systems. The glacial and interglacial processes bisected the land surface to create a number of hydraulically isolated carbonate rock "islands" where vertical bedrock joints and sinkholes intersected south-dipping bedding planes to create a classic karst topography: upgradient losing streams and swallets flowing to downgradient springs, some of which might exhibit artesian flow where former, lower spring outlets were blocked by more recent glacial debris (Fig 2.4.5, Doc Shaul's Spring; Palmer, 2007). The area of Schoharie, Albany and Greene Counties on the Helderberg-Cobleskill plateau has the oldest known and largest number of well-developed, most-explored, and documented cave systems in New York.

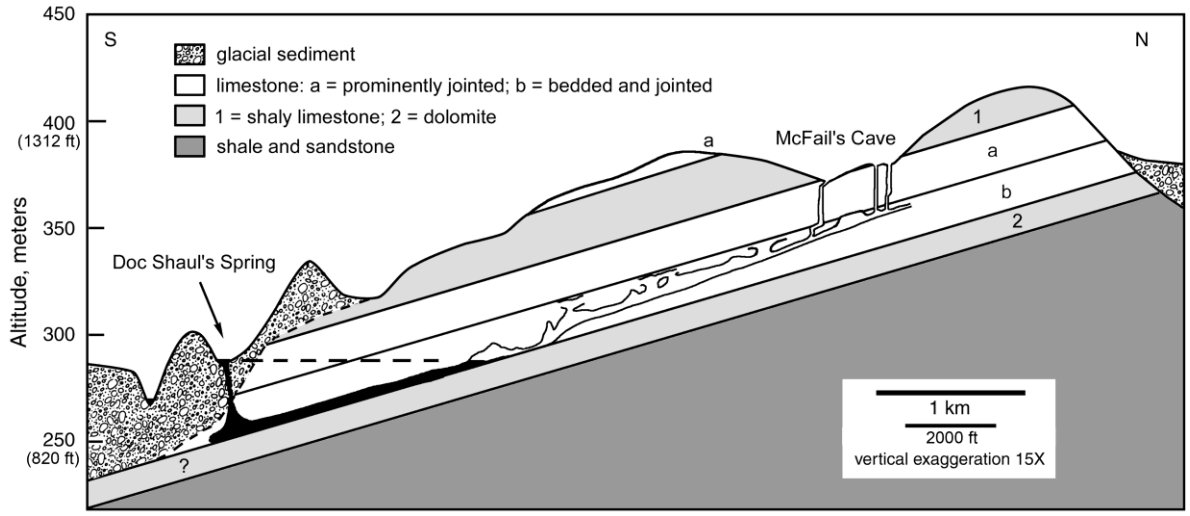


Figure 2.4.5 Profile through McFail's Cave, New York, the longest known cave in the northeast United States with more than 7.1 miles of mapped passage. The cave is named after Thomas Alfred McFail, a professor at the old Carlisle Seminary, who lost his life in the cave in 1853. The former spring outlet was buried by about 30 m of glacial and river deposits during the past 120,000 years, so that water is forced to rise through the sediment to an artesian spring named Doc Shaul's Spring. From Palmer, 2007; printed with permission.



Figure 2.4.6 McFail's Cave in Schoharie County is in the McFails Cave Nature Preserve, owned and managed by the National Speleological Society (NSS) since 1967. McFail's Cave is the longest known cave in the northeast United States with about 7.1 miles of mapped passages. It is developed in the Coeymans and Manlius limestones of Early Devonian age, and Cobleskill limestone of Late Silurian age. Photo courtesy of Dave Bunnell. https://caves.org/preserve/mcfails-cave-nature-preserve/



Figure 2.4.7 Example of focused recharge to karst aquifers. Swallet entrance to McFails Cave in Schoharie County, New York, during the dry season (*left photo*), and a 50-year flood discharge in January 1996 (*right photo*). Photographs courtesy of Art Palmer, professor emeritus, State University of New York at Oneonta. From Reddy et al., 2020.



Figure 2.4.8 Cave passages from the valley of the Cobleskill Creek, a tributary to Schoharie Creek, in Schoharie County. *Left*: Joint-controlled fissure passage in Coeymans Limestone. *Right*: downstream passage in McFails Cave in Manlius Limestone. Photographs courtesy of Art Palmer, professor emeritus, State University of New York at Oneonta. From Reddy et al., 2020.

In southeastern New York, the Inwood Marble exhibits some notable karst features (e.g., Surprise or Mystery Cave), although the amount of karst is limited by the small extent of the formation and the amount of urban development that has obscured the expression of karst features at land surface. Another well-known karst feature developed in the marbles near the Vermont border is Natural Stone Bridge and Cave. In general, however, marbles do not host productive aquifers in New York because of their limited extent and high degree of compartmentalization.



Figure 2.4.9 The massive Natural Stone Bridge is the largest marble cave entrance in the eastern United States and is still being carved by the sinking Trout Brook that disappears into the cave. It is located near Pottersville, in the northern part of Warren County, within the Adirondack Mountains. The entrance is about 180 feet wide and 62 feet high. Screenshot from a video produced by Natural Stone Bridge & Caves Park, available at https://stonebridgeandcaves.com/.



Figure 2.4.10 Secret Caverns in Cobleskill, Schoharie County is home to an impressive 100-foot underground waterfall. Photo courtesy of Kaitlyn Smith | @kaitlynlsmitty. The caverns are formed in Manlius Limestone (Upper Silurian age) and Coeymans Limestone (Lower Devonian age) rich with fossils of honeycomb coral, crinoids, and many brachiopods. The tour of the cave culminates with a view of the underground waterfall with plenty of photo ops. Pictures and touching the geological formations are allowed. More information is available at https://www.facebook.com/SecretCaverns.

2.4.2 New England Karst Aquifers

In the New England States, karst terrain is confined to metamorphosed limestones, dolomites, and marbles, that extend in a north-south band along the western boundary of Connecticut, Massachusetts, and Vermont, and similarly in the eastern-most portion of New York. This band constitutes the prominent Cambrian-Silurian carbonate platform where carbonate sediments were deposited on a passively subsiding continental shelf following late Precambrian rifting of the Rodinia supercontinent. These sediments accumulated along the Iapetus Ocean margin, evolving from tidal flats to shallow-water rimmed carbonate platforms that kept pace with tectonic subsidence, forming thick sequences of dolostone, limestone, and associated siliciclastics. The platform was part of an extensive passive margin along eastern Laurentia (North America), featuring a shallow-water shelf bordered to the east by a deeper basinal sequence of shales and breccias (Mehrtens, 1988). The sedimentary carbonates in New England were subsequently metamorphosed to varying degrees, creating areas with crystalline limestones and highly praised marbles, especially in Vermont.

In Maine, carbonate rocks are high in silica and other impurities, and solution features are generally absent; isolated pockets of these rocks include metamorphosed Silurian limestone and calcareous metasedimentary rocks in Aroostook County (northern Maine), Franklin and Somerset Counties (southern Maine), and Waldo and Knox Countries (eastern Maine). Devonian limestone with slate and phyllite beds of the Casco Bay Group is present in Cumberland County.



Figure 2.4.11 Although marble (left) and limestone (right) are both calcium carbonate, marble is often significantly less karstified than limestone because of its different physical properties as explained in the text. Photo courtesy of Stone Group. (https://stonegroup.gr/blog/marble-vs-limestone-how-to-choose/)

As opposed to sedimentary limestone and dolomite, karst in crystalline carbonates and marbles of New England is much less developed and limited to narrow fissures (fractures) and small solution cavities, which may be even absent altogether. This is because marble is a metamorphic rock that has been heated and deformed under high pressure, changing its physical properties to be less permeable to water than limestone. Intense heat and pressure cause the calcite grains to recrystallize, fusing into a dense, interlocking mosaic of crystals. This process destroys original sedimentary structures and fossils, producing a non-foliated, dense, and crystalline texture ("crystalline limestone" is term often used to describe limestone that has not been completely metamorphosed to marble).

While chemically the same (both are calcium carbonate), the harder and denser structure of marble makes it more resistant to the dissolution (karstification) process than the often softer and fossil-rich sedimentary limestone. In addition, brittle sedimentary limestone commonly features bedding planes and fractures that act as preferential pathways for water, allowing for widening into conduits and caves. Marble lacks these discontinuities as they were effectively sealed during metamorphosis and the rock mass converted into relatively homogeneous, massive, low-porosity medium.



Figure 2.4.12 Abandoned marble quarry in West Rutland, Vermont. The quarry is on the grounds of the Carving Studio & Sculpturer Center (CSSC) which offers unique sculpture and art education programs in a wide variety of media, and residences and exhibition opportunities to established and emerging artists.

In New Hampshire, carbonate rocks are rare and limited areas where they do occur include siliciclastic carbonates in Kinsman Notch (Grafton County), and in Coos County near the Quebec border. A stated by the New Hampshire Department of Environmental Services (2025):

"The New Hampshire Geological Survey (NHGS) regularly receives calls from landowners in New Hampshire who have experienced a sinkhole on their property and are seeking information about what may have caused it and what might be done about it. These holes in the ground are not really sinkholes in the true geologic sense of the term, though the occurrence of a hole forming in the lane of a highway or a property owner's backyard can be just as unsettling and disturbing when they occur. It is important to understand the distinction between true geologic sinkholes, and engineering and development related causes of ground sinking or holes that form in the ground.

New Hampshire is relatively immune to a classic geologic "true" sinkhole occurring because of the metamorphic and granitic nature of the rocks that underlie much of New Hampshire, and the notable lack of carbonate rocks, which makes the rocks of New Hampshire far less porous than in the states referenced previously. New Hampshire's rocks are the result of compressional forces and melting, which virtually eliminate the chances of carbonate rock occurrence in the state. Our metamorphic and granitic rocks will not dissolve because of groundwater and so do not form the traditional caves necessary for sinkholes."

Karst in New England is best developed in Vermont and consists primarily of small-scale features, such as narrow solutionally widened fissures, short, small caves, and limited marble dissolution, found mainly in the western part of the state, within the "Valley of Vermont" (between the Taconics and Green Mountains) and the Champlain Valley. A series of caverns and disappearing streams around the springs in Dorset are an example of local, active karst geology. Carbonate aquifers in Vermont are widely used for public and individual water supply utilizing wells which are also generally more productive compared to wells in other bedrock aquifers. For example, the carbonate platform karst aquifer in Bennington County has the most water supply wells with a reported yield between 100 and 600 gpm in the state (https://dec.vermont.gov/geological-survey/groundwater/statewide-gw).

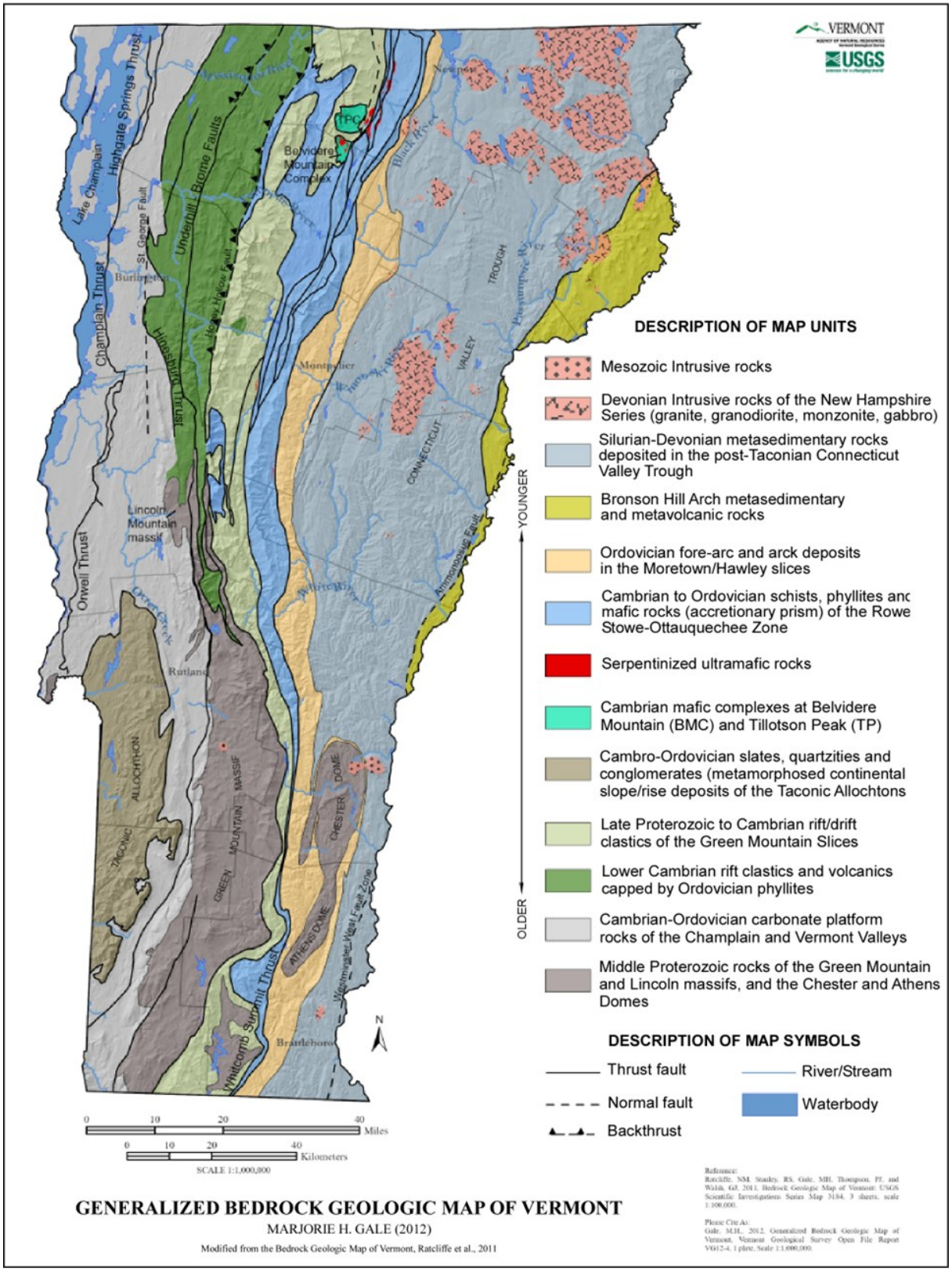


Figure 2.4.13 Generalized Geologic Map of Vermont by Marjorie H. Gale (2012), Vermont Geological Survey. Modified from the Bedrock Geologic Map of Vermont, Ratcliffe et al., 2011.



Figure 2.4.14 Dedicated by President Franklin Delano Roosevelt on April 13, 1943, the Thomas Jefferson Memorial in Washington, D.C. was designed by architect John Russell Pope, who echoed the classic style seen in Jefferson's two most famous buildings – Monticello and the University of Virginia Rotunda. The Memorial's exterior columns and walls are made of Vermont white marble. Photo courtesy of NPS.



Figure 2.4.15 "Julia Dorr," by sculptor Amanda Sisk, 2021. This marble sculpture is one of many in downtown Rutland, Vermont, honoring local artists and the marble artisan tradition that shaped the town. https://downtownrutland.com/sculptures

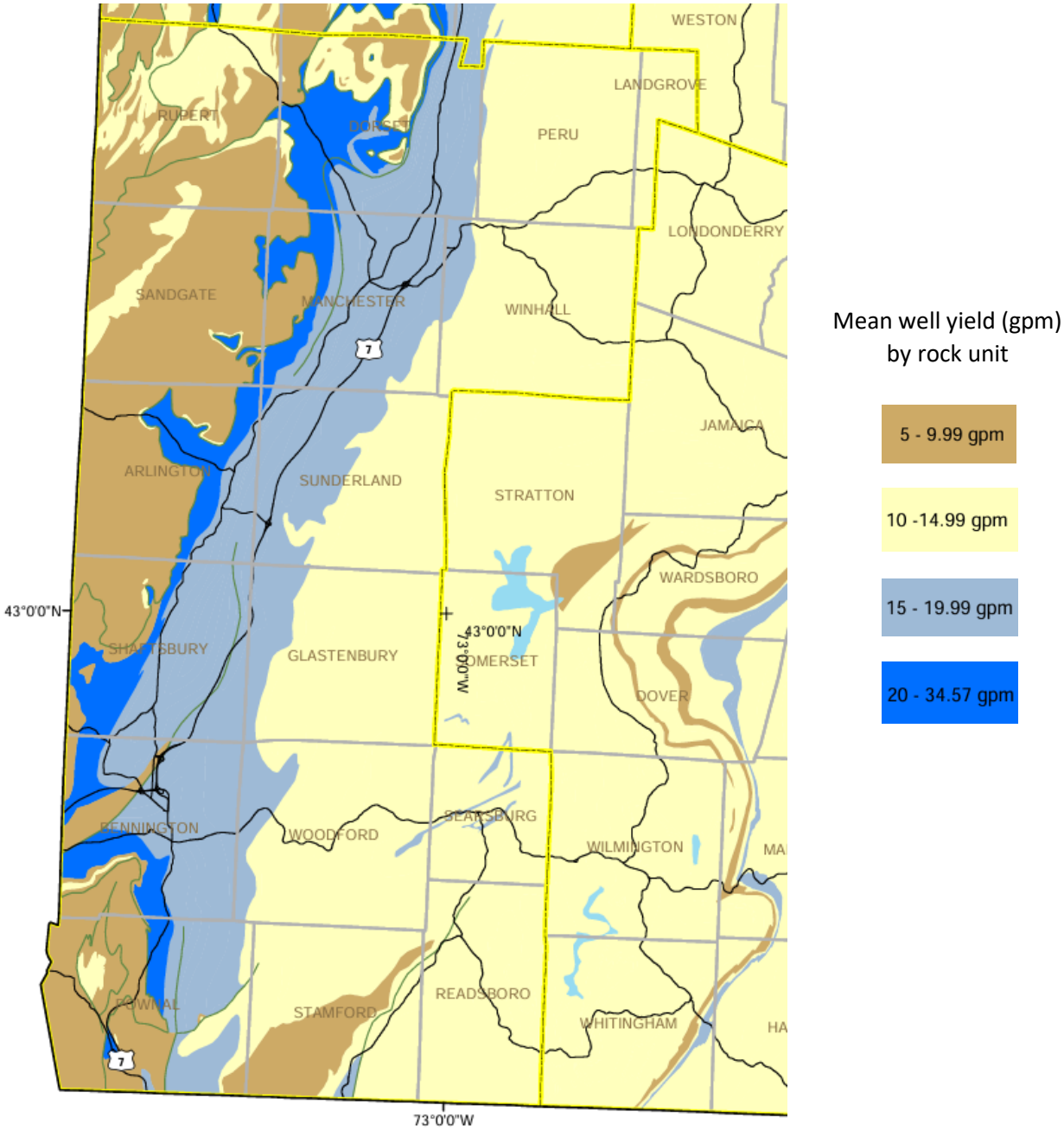


Figure 2.4.16 Part of Vermont state map entitled "Mean Yield (gpm) of Water Wells Compiled by Bedrock Unit". Bennington County in the southwestern corner of Vermont is outlined with yellow highlight. The highest mean well yield in the county, and the state, is in rocks of the Cambrian-Ordovician carbonate platform (see Fig. 2.96) including limestones, dolomites, marbles, and calcareous metamorphic rocks. These units also host the highest number of water supply wells with a reported yield between 100 gpm and 600 gpm. Modified from Gale et al., 2009a.

Carbonate rocks (mostly marble) in Massachusetts and Connecticut are primarily located in the western part of the two states, specifically within the Housatonic Valley (the "Marble Valley"). The Housatonic River begins its journey in Massachusetts, separating the Taconic Mountain and New England Upland sections of the New England Physiographic Province. The most significant concentration of carbonate bedrock (marble) and karst features includes areas surrounding Pittsfield, Cheshire, and Lanesborough.



Figure 2.4.17 McNamara Spring in Bennington County, Vermont issues from base of till slope underlined by a karst aquifer. Photo by D. DeSimone. Courtesy of Vermont Geological Survey. https://dec.vermont.gov/geological-urvey/photo-gallery/



Figure 2.4.18 Syncline in the Weybridge Member (limestone) of the Ordovician Chipman Formation near Middlebury, Adison County, Vermont. Courtesy of Vermont Geological Survey.

As it enters Connecticut's Western Uplands, the Housatonic River follows the Northern Marble Valley as far south as the Housatonic Highlands Plateau, two miles south of Falls Village. Here the river leaves the Marble Valley, flowing through the Housatonic Highlands until it rejoins the Northern Marble Valley at Cornwall Bridge, following it until it reaches Gaylordsville. The river then cuts a gorge through the Hudson Highlands Plateau until it reaches the Southern Marble Valley north of New Milford center. Two miles south of New Milford, the river crosses Cameron's Line and enters the Southwest Hills, flowing south easterly until it eventually reaches the Coastal Slope and discharges into Long Island Sound.

As discussed by Cooper and Mylroie (2015a), cave development in New England appears to have been mostly post-glacial, with a few relict (pre-glacial) large caves (e.g. Aeolus Bat Cave and Morris Cave in Vermont), and several large caves that are likely combination caves that, while active in the current deranged hydrology, have passages inherited from pre-glacial times (e.g. Vermonster and Carthusian caves in Vermont, and Merlins Cave in New York). Joint activation by isostatic rebound following ice withdrawal, coupled with large glacial lake discharges, are argued to be the prime initiator of cave development. The caves that result are commonly shallow, and vulnerable to removal by the next glaciation, indicating a cyclic nature to cave development and destruction, avoided only by the larger, deeper or fortuitously placed cave systems.

A general lack of glacial sediments in smaller caves is a good indicator that many caves are post-glacial, though some examples exist of pre-glacial caves containing sediment (e.g. Weybridge Cave in Vermont). Cave science has been sparse and sporadic in this region, but new discoveries of major caves indicates that this region will be a greater participant in speleology in the future (Cooper and Mylroie, 2015a).

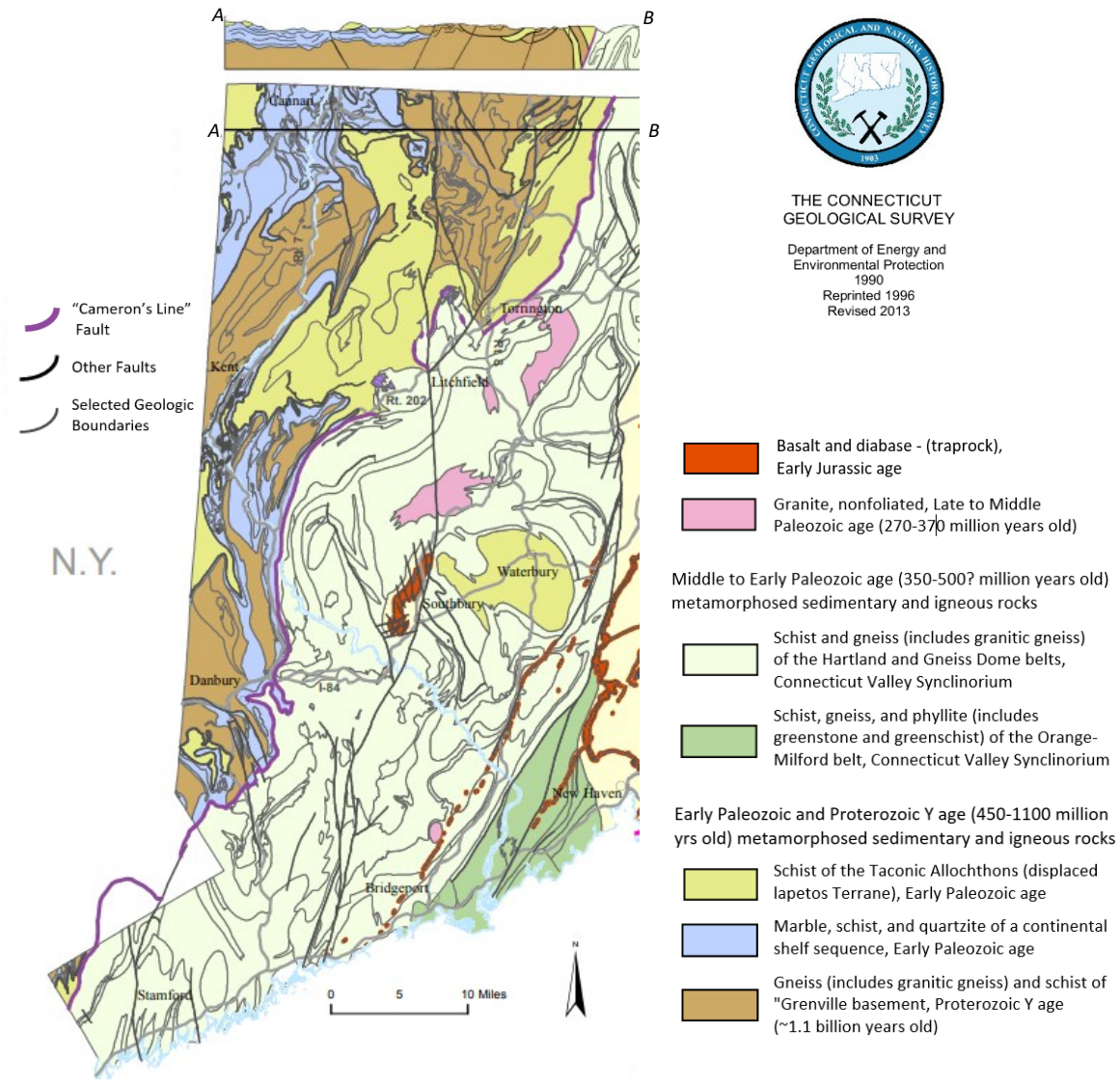


Figure 2.4.19 Western part of Generalized Bedrock Geological Map of Connecticut. From The Connecticut Geological Survey, 2013 (legend modified for better resolution/clarity). Available at https://portal.ct.gov/deep/geology/statewide-geologic-maps

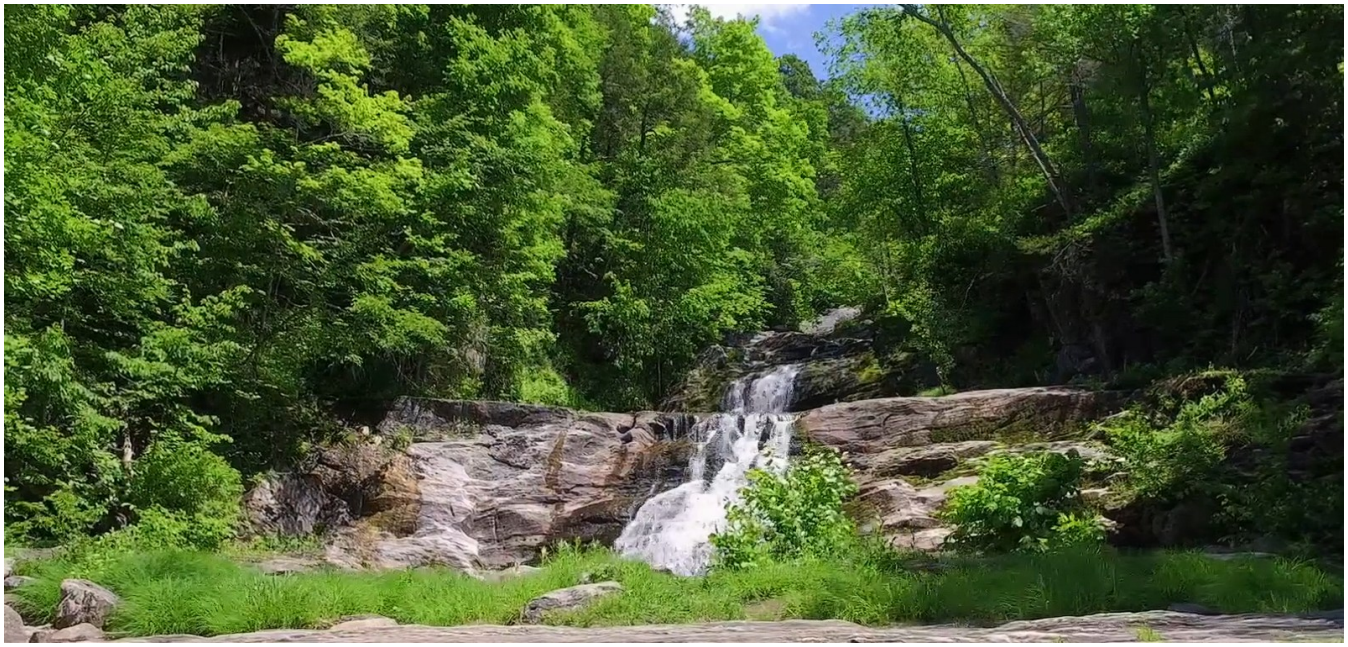


Figure 2.4.20 Kent Falls State Park is a public recreation area located in the town of Kent, Connecticut, within the Litchfield Hills region of the southern Berkshires. The state park is home to Kent Falls, a series of waterfalls on Falls Brook, a tributary of the Housatonic River. The falls drop 250 feet in under a quarter mile. The area around Kent features deep river gorges where the white and grey marble layers are clearly exposed by the Housatonic River. https://ctparks.com/parks/kent-falls-state-park

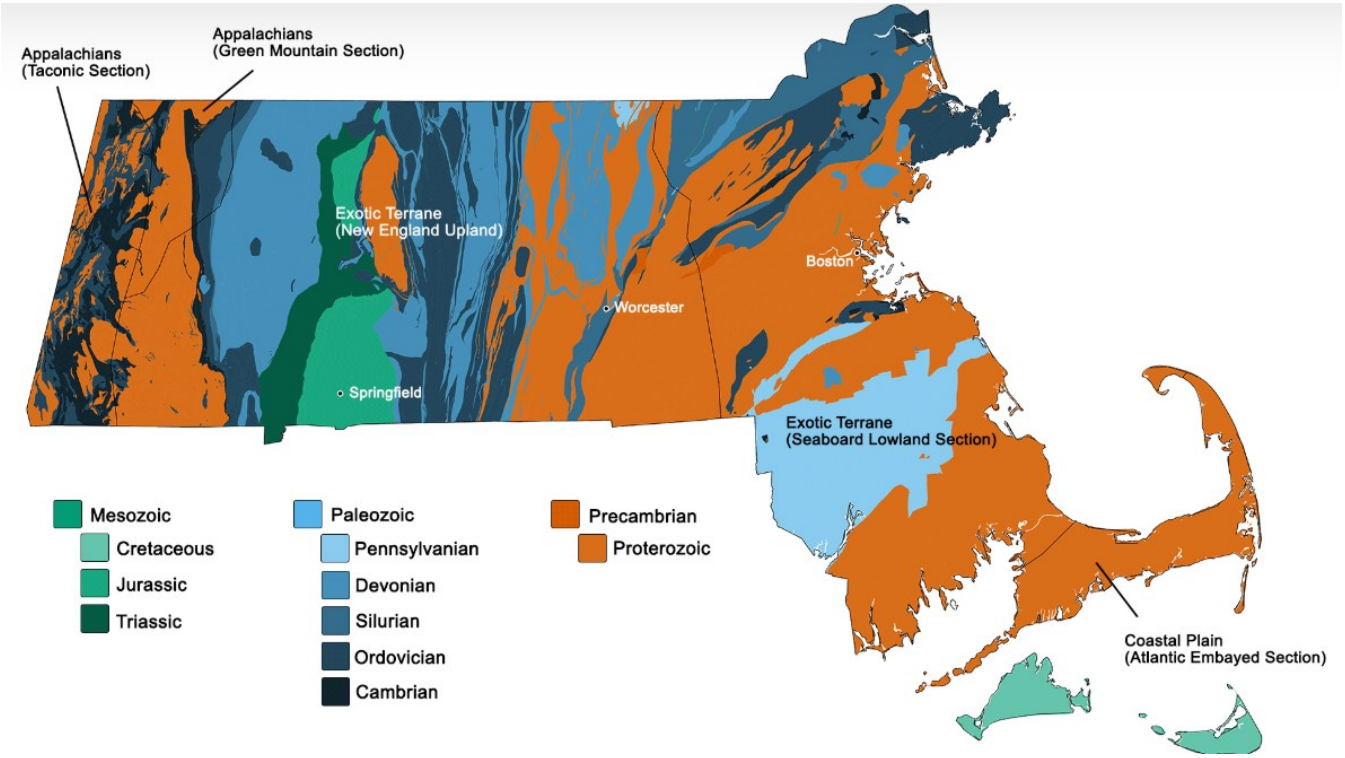


Figure 2.4.21 Geologic map of Massachusetts showing maximum ages of mappable units. Carbonate aquifers and karst terrains are in Cambrian-Ordovician bedrock units along the western edge of the state. Image by Kiera D. Crowley for the Earth@Home project developed using QGIS and USGS data (public domain). https://earthathome.org/hoe/us-earth-science-quick-facts/ma/ Map reproduced under Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International license.

2.5 Castle Hayne Aquifer

As described by Lautier (2009), Campbell et al. (2010), McSwain et al. (2014), and Lyke and Coble (1987), the Castle Hayne aquifer is the most prolific and high yielding aquifer in the North Carolina Coastal Plain where it covers approximately 12,500 square miles and serves as the primary source of fresh water for much of the coastal region. It is principally composed of the Eocene age Castle Hayne Formation, which consists of very permeable, gray to white molluscan moldic limestones and dolomites. It is interbedded and underlain by fine to medium grained calcareous sands and clays. The lower part of the Castle Hayne Aquifer in some areas includes highly glauconitic sands of the uppermost Beaufort Formation of Paleocene age.

The top of the aquifer is at the top of the Castle Hayne Limestone, as there are no apparent lower sand zones in the overlying Pungo River Formation that are hydraulically connected. The aquifer dips gently eastward at a rate of about 7 to 25 feet per mile, its top ranging in elevation from slightly above sea level in western Beaufort County, to greater than a thousand feet below sea level in Dare County. The aquifer is confined with the low permeable clastics of Quaternary age units that overly it. The base of the aquifer occurs at the top of the Beaufort confining unit.

Yields from the Castle Hayne Aquifer generally range between 50 and 500 gallons per minute (gpm), but in Pamlico, Beaufort and Washington Counties they can exceed 2,000 gpm. Many of the wells only partially penetrate the aquifer, since that is generally sufficient for adequate water supply. To the east of the intersection of the 250 mg/L chloride isochlor with the top of the aquifer, the Castle Hayne contains salt water in excess of the taste threshold and is not potable without treatment. Increased pumping has led to saltwater intrusion in some areas, with the 250 mg/L chloride line moving inland in parts of New Hanover and Brunswick counties.

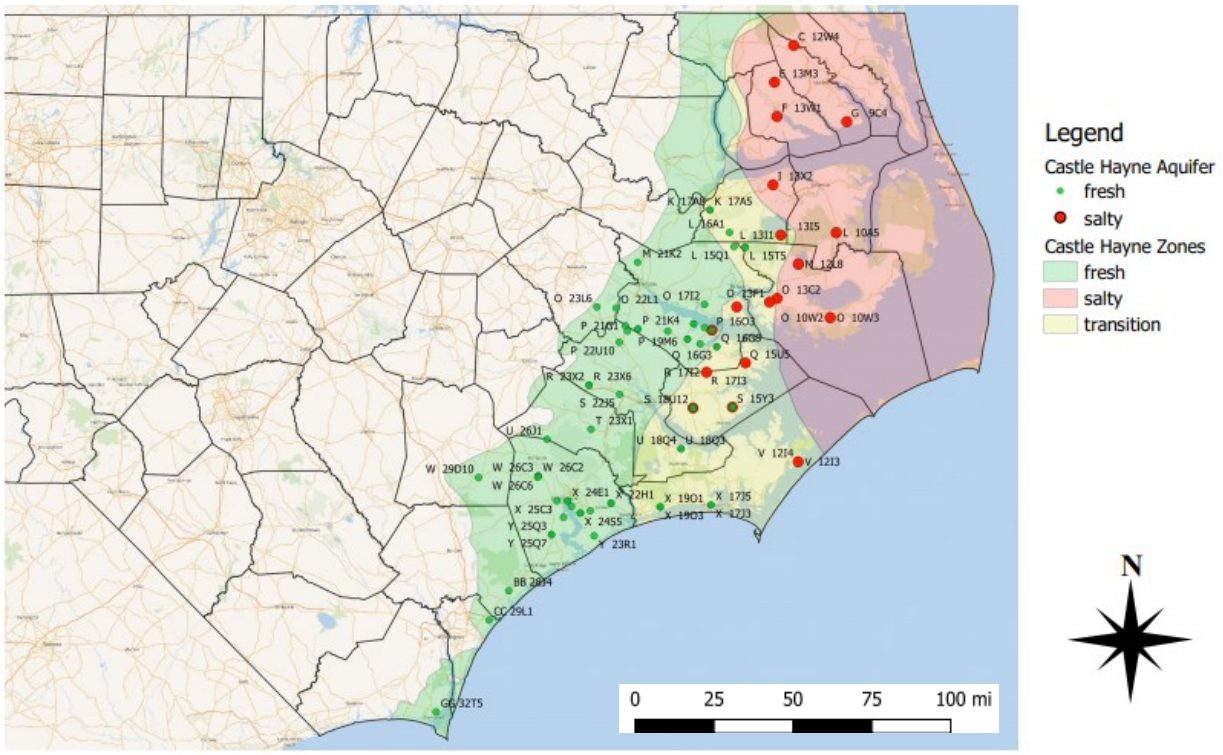


Figure 2.5.1 Chloride content within the Castle Hayne Aquifer as of August 2020. Courtesy of the North Carolina Department of Environmental Quality, Division of Water Resources. https://www.ncwater.org/?page=525

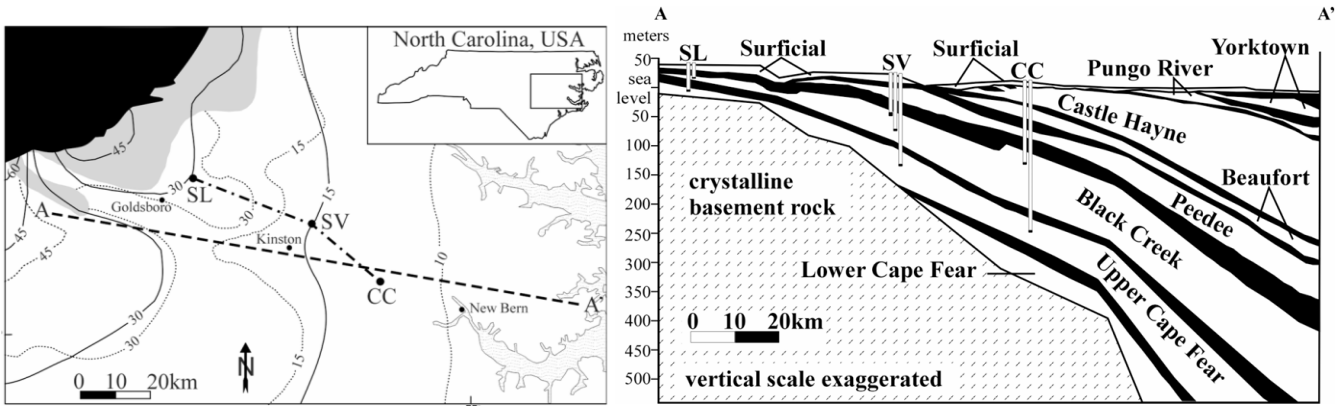


Figure 2.5.2 East-west hydrogeologic cross-section through the Coastal Plain of North Carolina along the line A-A' shown on the map on the left (Geise et al. 1997). On the map, the black and gray areas correspond to areas where the Upper Cape Fear and Black Creek aquifers, respectively, are absent (i.e. the eastern margin of the gray area represents the western margin of the Black Creek aquifer, and the eastern margin of the black area represents the western margin of the Upper Cape Fear aquifer). On the cross section on the right, aquifers are shown in white and aquitards in black. From left to right, the sites are Saulston (SL), Savannah (SV), and Cove City (CC). From Kennedy and Genereux, 2007.

Geologically, the Castle Hayne Aquifer is part of a larger, interconnected system referred to as the Castle Hayne-Aquia Aquifer by the USGS. While it behaves as a massive and productive limestone aquifer in North Carolina, the exact same geologic formation continues northward along the East Coast, transitioning into a glauconitic sand aquifer used heavily for water supplies in Virginia, Maryland, Delaware, and New Jersey.

Moving north into Virginia, the limestone pinches out and changes into the Aquia Aquifer. It serves as a vital source of drinking water for the Northern Neck and Middle Peninsula regions. It is intensely utilized by residential wells, small municipal water systems, and commercial agricultural operations spanning counties like Stafford, King George, and Westmoreland (Ground Water Atlas of the United States, Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia. HA 730-L, by Henry Trapp, Jr. and Marilee A. Horn (HA 730-L North Atlantic Coastal Plain aquifer system text).

Chapter 3 Important Karst Springs of the United States: East

3.1 Florida

As briefly described in Chapter 2.2, the State of Florida is rapidly destroying its two most valuable natural resources – the Floridan Aquifer and the karst springs. This was as painfully clear 10 years ago as it is now. In 2016, under relentless pressure from Florida citizens, activists, and many different organizations concerned with the catastrophes facing the beautiful Florida springs, the State Legislature enacted *Florida Springs and Aquifer Protection Act* which specifies 30 "Outstanding Florida Springs" (see Chapter 1).

At the time of this writing, exactly 10 years after the passage of Florida Springs and Aquifer Protection Act, it appears that the catastrophe for the outstanding and all other beautiful karst springs in Florida is a runaway train. Not only did the health and flow rates of the springs not improve, but the U.S. Geological Survey (USGS) terminated continuous nitrate monitoring at 13 Outstanding Florida Springs, shifting reliance to less frequent manual sampling by local water management districts and reducing real-time data visibility on nutrient pollution (https://www.wuft.org/environment/2025-07-17/usgs-to-remove-some-water-quality-monitors-from-outstanding-florida-springs). A similar end to continuous monitoring of water quality and discharge rates of other large springs has already occurred over the last 15 years. Two perfect examples are the headspring of Silver River (Silver Springs, once considered the largest in the country), and Wakulla Spring, currently considered to be the second largest individual karst spring in the country. USGS stopped reporting their discharge rates in 2010, and their respective Florida Water Management Districts are not reporting them publicly either. It is not clear if they are continuously monitoring them at all.



Figure 3.1.1 USGS map showing locations of their monitoring stations near Silver Springs. USGS stopped reporting the discharge rate of Silver Springs, the headspring of Silver River, in 2010, after 100 years. It is now reporting only the flow rate of the Silver River (red dot).

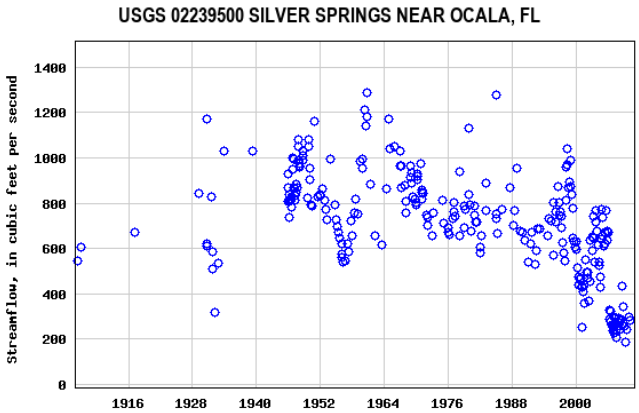


Figure 3.1.2 Graph of field-measured discharge rate of Silver Springs (headspring of the Silver River) as provided by the official USGS gaging station; available at https://nwis.waterdata.usgs.gov/

Instead of measuring and reporting the discharge rate of the headspring of Silver River, after doing it for hundred years, USGS is now monitoring only the Silver River flow rate more than four thousand feet downgradient of its source, after the river receives flow of the smaller springs and the diffuse groundwater inflow from the aquifer along the way. From the graph on Fig. 3.1.2 it is painfully obvious that something started to go terribly wrong with the headspring of Silver River in the mid-1960s. Coincidentally, this is when the population of Florida started skyrocketing from about 5 million to about 23.5 million today. To a bystander, this could look like a cover-up.

As noted in both editions of *Springs of Florida* (Ferguson et al., 1947; Rosenau et al., 1977) by the Florida Geological Survey, only about half of the total flow of Silver River is from the headspring. Various smaller vents downgradient of the headspring have water with different temperatures, which means the waters come from different depths or directions and are, in essence, different springs (Rosenau et al., 1977).

Follman and Buchanan (2023) argue that individual springs within spring groups should be measured separately. Doing so will give a clearer picture of the flow of individual springs of Florida, their fluctuations, sources, flow patterns, chemical components, and impacts on them.

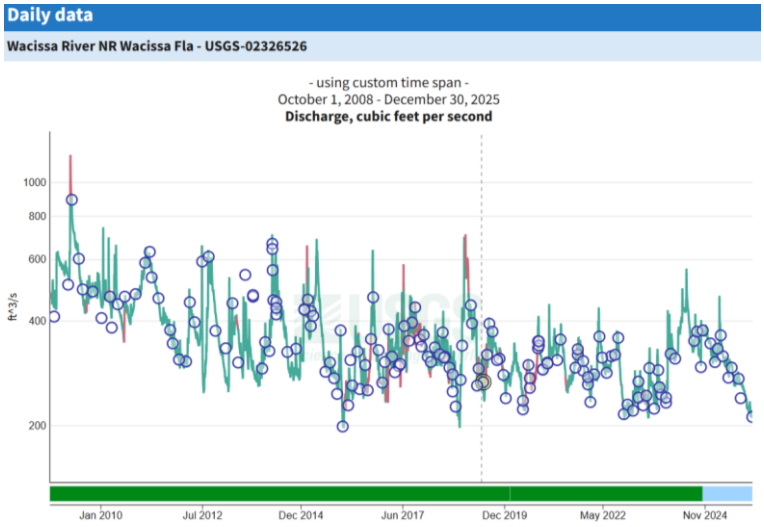


Figure 3.1.3 Combined flow from at least 20 springs which discharge to the Wacissa River, together with the diffuse aquifer discharge, is measured daily by USGS. Several springs are located at the head of the river near the county park. The rest are scattered along the upper 2 miles of the river. *All of the Wacissa River flow is grouped together as one first-magnitude spring group by FGS*. The hydrograph shows a dramatic decline in discharge rate of the river since 2008 when the monitoring started (note the semi-log scale of the vertical axis).

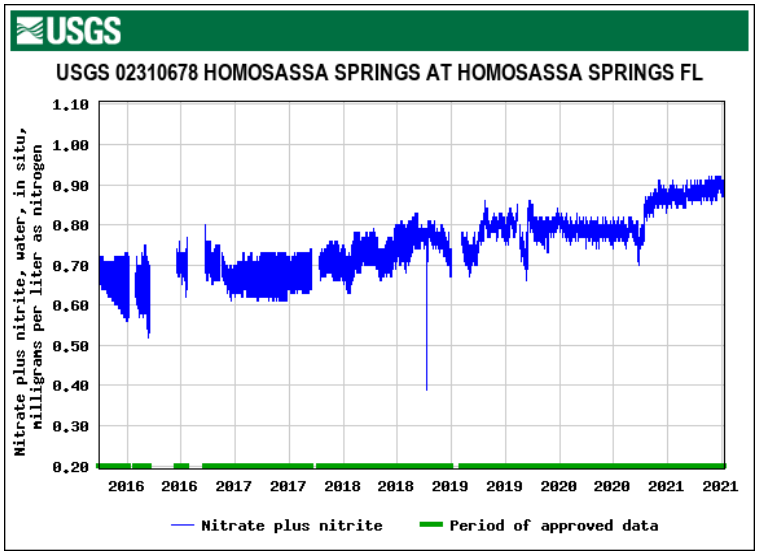


Figure 3.1.4 USGS stopped reporting (and analyzing?) water quality parameters it previously monitored at quite a few Florida Springs and "Spring Groups". This is an example for Homosassa Springs, one of the 30 Outstanding Florida Springs. USGS stopped reporting nitrate concentrations in July 2021. During the six years of monitoring (2015-2021), the nitrate concentrations dramatically increased from about 0.65 mg/l to 0.90 mg/l, greatly exceeding the regulatory ("safe") limit of 0.35 mg/L.

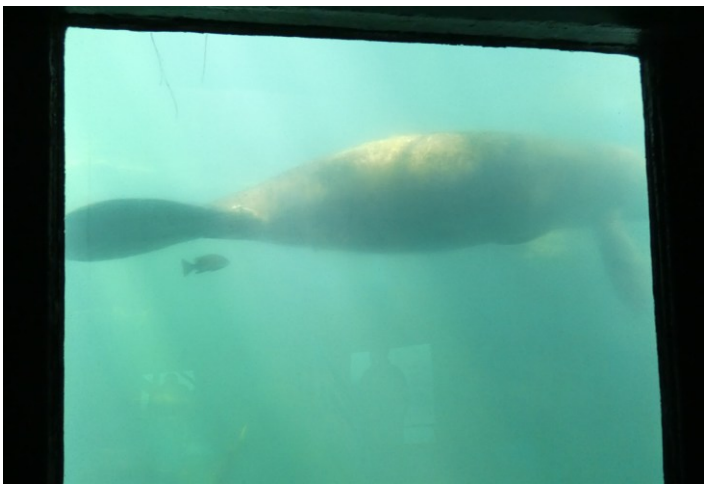


Figure 3.1.5 *Left*: The view through windows of Underwater Observatory at Homosassa Springs, December 2023. Visitors patiently waiting to spot a manatee are rewarded only if the gentle creature swims within a few feet of the glass.



Figure 3.1.6 Homosassa Springs – glory days of the past. Left: *Visitors in the underwater observatory, "The Fish Bowl"*; photo by Division of Tourism, circa 1964. Right*: Bluegill fish in Homosassa Spring*, photo by Dr. David E. LaHart, circa 1969. Courtesy of State Archives of Florida, Florida Memory.



Figure 3.1.7 Photo taken at Homosassa Springs State Park in December 2023. Dense mat of green algae completely covered the water surface at one of the springs.

Outstanding Florida Springs (OFS) are defined by statute and include all *historic* (emphasis added) first magnitude springs, including their associated spring runs, as determined by DEP using the most recent Florida Geological Survey (FGS) springs bulletin (#66), and the following additional springs, including their associated spring runs: De Leon Springs; Peacock Springs; Poe Springs; Rock Springs; Wekiwa Springs; and Gemini Springs. The term does not include submarine springs or river rises. (emphasis added; Section 373.802(4), F.S.)

The Act requires Florida Department of Environmental Protection (DEP) to assess the water quality in the OFSs. Based on these assessments, DEP determined that most of these springs are impaired. For these impaired springs, DEP must adopt (or re-adopt) a basin management action plan (BMAP) to implement all the protections of the Act, including:

- Prioritized lists of restoration projects along with planning level estimates for cost, schedule, and nutrient load reduction;
- Phased milestones (5-year, 10-year, and 15-year) to achieve water quality restoration targets in 20 years;
- Estimated nutrient pollutant loads, allocated to each source or category of sources;
- Completed remediation plans for onsite sewage treatment and disposal systems (OSTDS), commonly referred to as "septic systems," where septic loading accounts for at least 20 percent of the estimated nutrient input; and
- Delineated "priority focus areas" where certain activities are prohibited.

Since the enactment of the Act, BMAPs for the thirty OFSs were developed by various agencies including water management districts. These reports can be found on websites of the districts.

There are at least several puzzling things about the regulatory actions related to the protection of the OFSs, as well as the Florida springs in general:

- The use of the word "*historic*" first magnitude springs. All listed first-magnitude OFSs in the FGS Survey Bulletin #66 are still shown today as first magnitude springs, not "historic" first magnitude springs, on various webpages of the Florida agencies, including https://floridadep.gov/fgs/fgs/content/springs (the webpage of FGS.)
- One spring designated as a first magnitude spring by FGS was not included on the list of OFS—*Lime Run Sink Spring*. It is likely that the main reason for not including it is that this feature is a karst window, not a spring.
- Two "springs" that were previously not even included in the first two editions of *Springs of Florida* (Ferguson et al., 1947; Rosenau et al., 1977), are classified as such by FGS in its Bulletin No.66 published in 2004—Columbia Spring and Treehouse Spring. Interestingly, in December 2023, when this author again visited some springs in Florida, these two "springs" were shown as river rises on an information panel at the Santa Fe River Rise in the River Rise State Park.
- Are hundreds of springs that did not make it to the OFSs list doomed? Or, to put it more bluntly, are we all going to be complicit in watching the ongoing, slow-motion, mass murder of Florida springs

The story of how Florida gained 16 more first magnitude springs between year 1947, when Ferguson et al. published a table on page 37 of their Bulletin No. 31 entitled *Springs of Florida* (see Figure 3.1.11 in this book), and 2004 when FGS published its Bulletin No.66, also entitled *Springs of Florida*, is quite interesting. Kresic (*Notable Springs of the United States*, 2024) provides a related detailed analysis including publicly available information and discharge rate hydrographs for almost all alleged first magnitude springs.

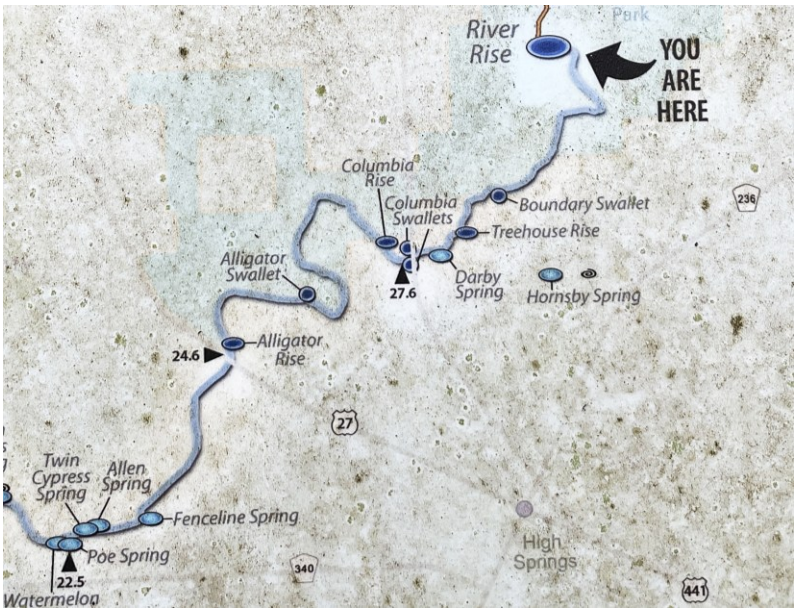


Figure 3.1.8 Part of an information panel at the Santa Fe River Rise in River Rise State Park near High Springs, Florida. Photographed in December 2023. The panel clearly indicates that Columbia Rise and Treehouse Rise are Santa Fe River rises and not springs as listed in the FGS Bulletin No. 66. They both have their swallets upstream where waters of the Santa Fe River sink ("Columbia Swallets", and "Boundary Swallet") and then reappear downstream at these two river rises.

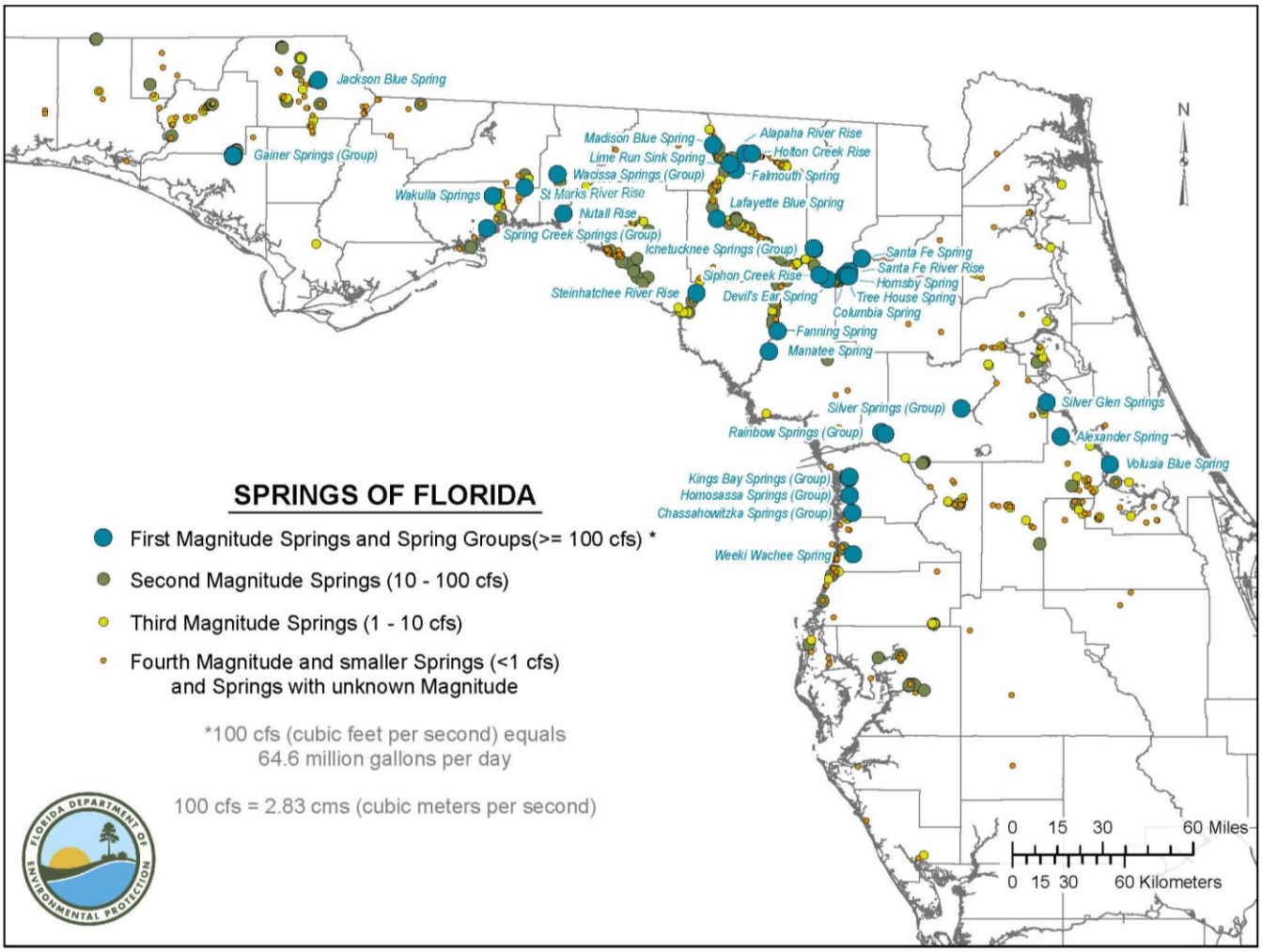


Figure 3.1.9 Map of springs of Florida, by Florida Geological Survey, accessed on July 27, 2026, at https://floridadep.gov/fgs/fgs/content/springs

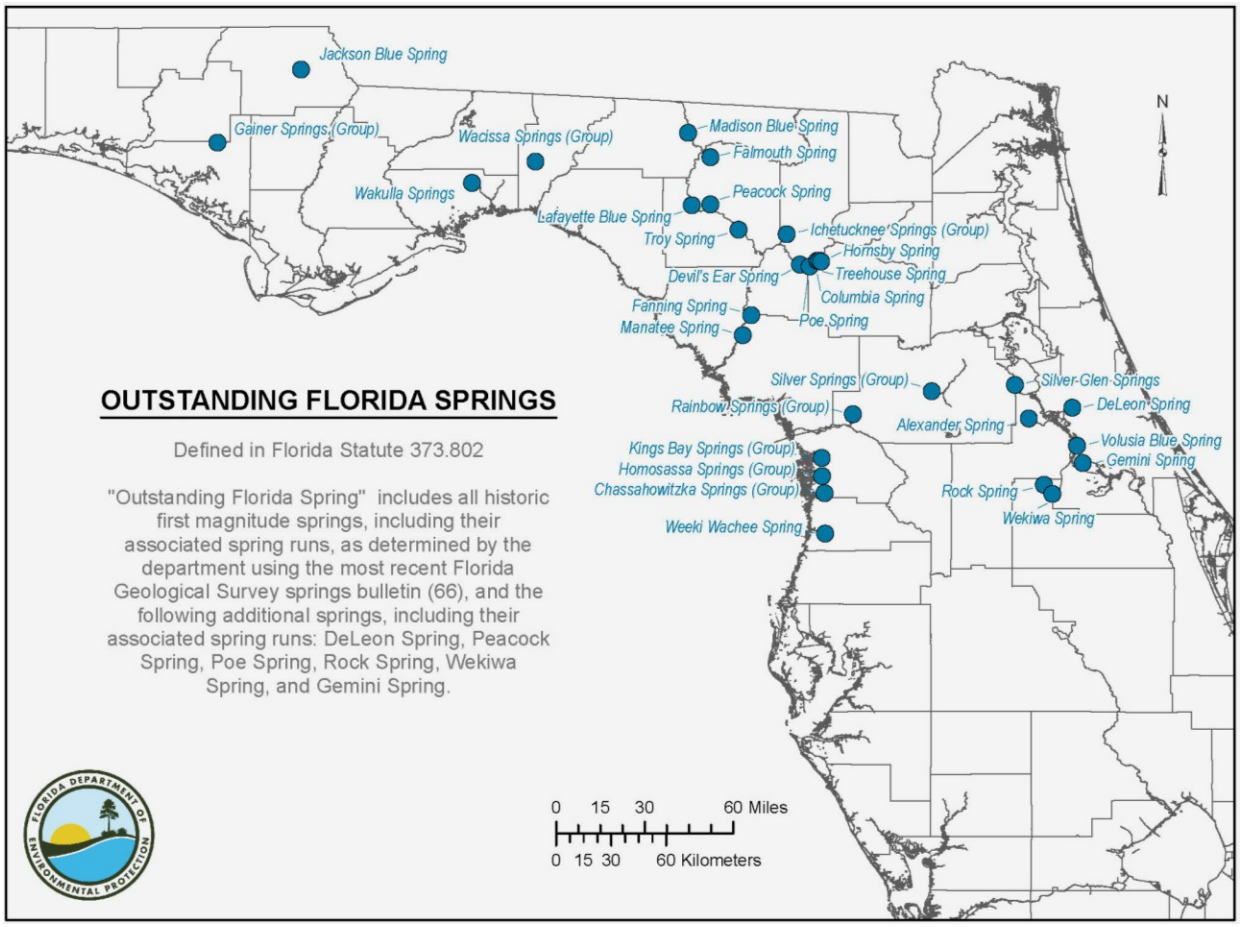


Figure 3.1.10 Map of Outstanding Florida Springs by Florida Geological Survey. Accessed on July 26, 2026, at https://floridadep.gov/fgs/fgs/content/springs

Following are some of the examples illustrating how Florida decidedly won a self-imposed race which state has the most first-magnitude springs in the country, and indeed the world. This accomplishment of having 33 first magnitude springs in 2004 was achieved by a combination of innovative approaches to statistics, treatment of spring groups, river rises, karst windows, and other methods unfamiliar to hydrogeologists and hydrologists practicing their respective sciences outside Florida. The four guiding principles for winning this race were:

1. One flow measurement >100 cfs is sufficient to classify spring as being of first magnitude forever.

According to FGS Bulletin No. 66 (Scott et al., 2004), which is the basis for all regulatory dealings with Florida springs:

Springs are most often classified based upon the average discharge of water. Individual springs exhibit variable discharge depending upon rainfall, recharge and groundwater withdrawals within their recharge areas. One discharge measurement is enough to place a spring into one of the eight magnitude categories (emphasis added). *However, springs have dynamic flows. A spring categorized as being a first-magnitude spring at one moment in time may not continue to remain in the same category. This can result in a spring being classified as a first magnitude spring at one point in time and a second magnitude at another. A spring assigned a magnitude when it was first described continued with that magnitude designation even though the discharge may have changed considerably through time* (emphasis added).

SPRINGS OF FLORIDA—DISCHARGE 37

NUMBER OF SPRINGS OF FIRST MAGNITUDE IN THE UNITED STATES

(Average flow of 100 second-feet or more)

REGION	NUMBER OF SPRINGS
Florida	17
Snake River Basin in Idaho	15
Ozark region of Missouri (including Mammoth Spring just south of Missouri-Arkansas State line)	12
Deschutes River Basin, Oregon	8
Sacramento River Basin, California	7
Willamette and Umpqua River Basin, Oregon	5
Balcones fault belt in Texas	4
Montana	3
Klamath River Basin, Oregon	2
Northern Alabama and adjacent areas	1
Interior basins of Oregon	1
Total in the United States	75

Figure 3.1.11 Table on page 37 of the FGS Bulletin No. 31 entitled Springs of Florida (Ferguson et al., 1947). The accompanying text reads: *Based on this tabulation, Florida has the greatest number of first magnitude springs in the United States. It also has approximately 49 springs of second magnitude, or springs having an average flow of 10 to 100 second-feet. The primary vents of both Silver and Rainbow Springs are believed to have larger average flows than any limestone spring in the United States and possibly in the world. Certainly the total average flows down Silver Springs Run and Rainbow River, (808 and 699 second-feet respectively), will rank these springs among the largest in the world.*

2. The average value of one measurement equals the same measurement.

It is possible that the authors of this new principle of statistics did not intend to become famous and simply forgot to remove word "average" from column 3 of their Table 2 in FGS Bulletin No. 31—Revised (Rosenau et al., 1977). However, this is also unlikely because all FGS spring bulletins, including No. 31 (Ferguson et al., 1947) and No. 31—Revised (Rosenau et al., 1977) or any other publication dealing with the classification of springs based on their discharge rates, clearly cite where this method came from: Oscar Meinzer's 1927 publication (see Chapter 1.2 in this book and Fig. 1.59).

Spring and number by county (refer to figs. 11-15, and 17)	Period of record	Average (ft^3/s)	Discharge Range (ft^3/s)	Number of measure-ments	Average Water temperature C	Average Water temperature F	Average Dissolved solids (mg/L)
Alachua County							
9. Hornsby Spring	1972-75	163	76- 250	2	22.5	73	230
Wakulla County							
2. Kini Spring	1972	176	-	1	20.0	68	110
5. River Sink Spring	1942-73	164	102- 215	6	20.0	68	110
6. Wakulla Springs	1907-74	390	25-1,910	276	21.0	70	153
13. Spring Creek Springs (1,4)	1972-74	2,003	(1)	1	19.5	67	2,400

Figure 3.1.12 Combined screenshots of two portions of Table 2 on page 7 of the FGS Bulletin No. 31—Revised (Rosenau et al., 1977) which lists 27 first-magnitude springs and spring groups of Florida. Note that Kini Spring and Spring Creek Springs have one measurement each and the average discharge rate is that same measurement. Interestingly, Kini Spring (as a first magnitude spring) has all but disappeared from all subsequent FGS publications and reports. Hornsby Spring, which had 2 measurements, now often does not flow at all but is still listed as a first magnitude spring by FGS as of July 2026.

3. The individual spring vents within a group may not discharge enough water to be classed as first magnitude. Decide, at will, where and how many individual springs are needed to create one first-magnitude spring.

The first sentence in the above bullet is the exact quote from the FGS Bulleting No.66, page 6: "*The individual spring vents within a group may not discharge enough water to be classed as first magnitude*."

Apparently, FGS changed their minds when it comes to what should and should not be treated as a first magnitude spring. For example, in the 1947 report by Ferguson et al., Table 4 (Fig. 3.1.13 in this book) shows that some springs at the time were not lumped into a first magnitude spring such as Wacissa Springs where three individual springs are listed but are not lumped together or shown as one first magnitude spring on the map that accompanies the report

NAME	LOCATION	APPROXIMATE WATER TEMPERATURE °F	DETERMINATION OF FLOW DATE	C.F.S.	M.G.D.	G P.M.	FACILITIES AVAILABLE, 1947 DEVELOPMENT OR USE, 1947
HILLSBOROUGH COUNTY							
Buckhorn Spring	2.8 mi. N.E. of Riverview	76	a	11.0	7.1		Swimming, private
Eureka Springs	3 mi. E. of Tampa	74	a	3.9	2.5		Aquarium of tropical fish
Lithia Springs	3 mi. W. of Lithia	76	a	50.2	32.4		Undeveloped, swimming
Messer Spring	3 mi. N.E. of Riverview	77	5- 1-46	.32	.21		House supply, hydraulic ram
Palma Ceia Springs	Bayshore Blvd., Barcelona St.		5- 1-46			42	Abandoned swimming pool
Purity Spring	0.5 mi. W. of Sulphur Spgs.		a			350-850	Public supply, bottled
Spring (no name)	0.1 mi. E. of Buckhorn Spg.		5- 1-46	1.27	.82		Water for stock
Spring (no name)	0.5 mi. W. of Buckhorn Spg.	75	5- 1-46	.09	.06		Water for stock
Sulphur Springs	At Sulphur Springs		ab	52.6	34		Resort, swimming
HOLMES COUNTY							
Ponce de Leon Spgs.	1 mi. S. of Ponce de Leon	68	ab	19.4	13		Resort, bath houses
JACKSON COUNTY							
Blue Springs	5 mi. N.E. of Marianna	70	ab	163	105		Resort, swimming, fishing
JEFFERSON COUNTY							
Wacissa Spgs. group	1 mi. S. of Wacissa		a				Fishing, boating, hunting
Big Spring			7-16-42	69.4	45		
Blue Spring			7-16-42	9.4	6.1		
Garner Spring			7-16-42	17.0	11		

Figure 3.1.13 Screenshot of Table 4 from Ferguson et al. (1947) showing that the Wacissa Springs group was not classified as one first magnitude spring.

4. Although river rises and karst windows are not real springs, they are classified as first-magnitude springs by FGS to increase the number of such springs in the state of Florida.

Karst windows form when the roof of a cave collapses, exposing an underground stream for a short distance. Four karst windows are included in the FGS Bulletin No. 66 (Scott et al., 2004, page 9) and two of them are designated as first magnitude springs. This inclusion of the karst windows into the prestigious group of first magnitude springs is despite the following definition, just a year earlier, in the FGS' own Special Publication No. 52 (Copeland, 2003; page 9) where it is stated:

Note that the FSNC believes that flow through an exposed conduit in an aquifer is different from flow onto the earth's surface. For this reason, the FSNC does not consider a karst window to be a spring. It is an exception to the definition of a spring.

As explained by Follman and Buchanan (2023), formerly called "spring-sink combinations", karst windows are characterized by water that rises from underground, flows a short distance (typically between 100 and 300 yards), and then drains back underground again into a sinkhole. Karst windows have also been described as "long sinkholes"—sites where the surface collapsed above a several-hundred-foot section of the Floridan Aquifer instead of over a pinpointed spot. Rhodes Springs (Leon County), Double Spring (Jackson County), and Owens Spring (Lafayette County) have similar characteristics and should more properly be called karst windows.

River rise (see also Chapter 1.2.1) is the resurgence of river water that descended underground through a sink some distance away. Wilson and Skiles (1989) state that the resurging water may contain a significant portion of aquifer water but is primarily river water and therefore should not be classified as a spring. However, as argued by FGS "*Due to the inclusion of a significant addition of groundwater, river rises have continued to be considered as springs*." (Scott et al., 2004)

Follman and Buchanan (2023) accept that river rises may meet the technical definition of a spring, but state that this acceptance is a little begrudging: "*Lacking the filtration and clear water of other springs, river rises simply do not have the aesthetic, personal, or visual appeal of "traditional" springs*."

The Florida Legislature clearly sided with the opinion of Wilson and Skiles (1989) and other karst researchers, and the river rises were not included in the list of Outstanding Florida Springs.

Submarine Springs. Two groups of coastal submarine springs were classified as first magnitude freshwater springs in the FGS Bulletin No. 31—Revised, authored by Rosenau et al. (1977): Spring Creek Springs in Wakulla County and Crystal River Springs in Citrus County. In the case of Spring Creek Springs, this classification was based on a single flow measurement as shown here in Fig. 3.1.12 (Table 2 of the FGS Bulletin—Revised), and an unknown number of dissolved solids analyses expressed in mg/L. In the same Bulletin No. 31—Revised, the authors emphasize, on page 5, that "*Of the 78 first magnitude springs in the United States, Florida has 27, the most for a single slate. Florida seems to have the largest number of springs and also the largest spring in terms of average flow: a submarine spring* (emphasis added) *at Spring Creek in Wakulla County yields about 2,000 cubic feet per second*."

Table 2. Summary of discharge and water-quality data collected at Florida's 27 first-magnitude springs

[Map number refers to figure 1. All values are averages. ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

Map Number	Name	County	Average discharge ft^3/s	Specific conductance (µS/cm)	Chloride (mg/L)	Sulfate (mg/L)
1	Spring Creek Springs	Wakulla	2,000	4,300	1,200	280
2	Crystal River Springs	Citrus	878	4,300	1,400	200
3	Silver Springs	Marion	799	410	9.5	42

Figure 3.1.14 Top part of Table 2 of the USGS' Fact Sheet entitled *Springs of Florida* (USGS, 1995).

Despite of the glaring inconsistencies in the FGS Bulletin No. 31—Revised when using word *spring* (singular; in the text—"a submarine spring") and *springs* (plural; in Table 2—"Spring Creek Springs"; see Figure 3.1.12), this statement stood the test of time and was reinforced by the U.S. Geological Survey in their Fact Sheet FS-151-95 (Spechler and Schiffer, 1995). This is illustrated by the screenshot of the top part of the USGS Fact Sheet's Table 2 shown here as Figure 3.1.14.

In 2007, a year after it was first reported that the springs in Spring Creek ceased flowing, USGS established a gaging station there and started systematic measurements of streamflow, salinity, specific conductance, water temperature, and several other parameters (Figures 3.1.14 through 3.1.16).



Figure 3.1.14 *Left*: Springs of the Spring Creek Group identified by Florida Department of Environmental Protection. Available at Florida Department of Environmental Protection Geospatial Open Data (state.fl.us). *Right*: Location of the USGS gaging station USGS 02327031. Available at USGS Current Conditions for USGS 02327031 Spring Creek near Spring Creek, FL.

Based on the USGS data, the Spring Creek Springs Group, consisting of 9 springs identified by the Florida Department of Environmental Protection (Fig. 3.1.14), did not flow 42% of time during the period of record. During such times, the flow was reversed – the springs collectively acted as a sink for sea water and this saltwater intrusion propagated 12 miles inland (north) to Wakulla Spring (see description of Wakulla Spring later in this Chapter).

The average flow rate of the intermittent Spring Creek Spring Group, when it is discharging a mixture of sea water and brackish groundwater, is 258 cfs after filtering for tidal influence. This is roughly eight times less than the reported value of 2,003 cfs in Rosenau et al. (1977).

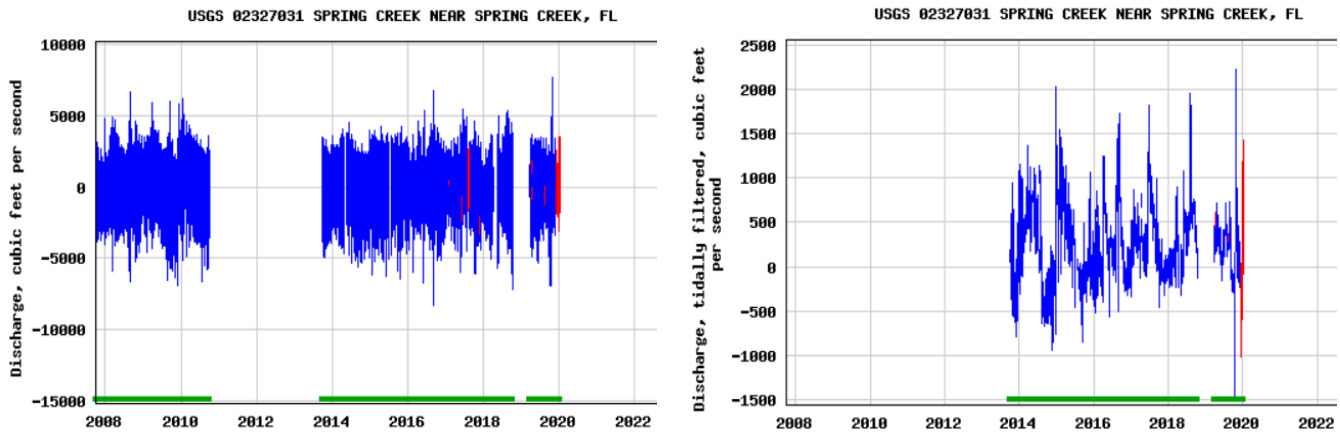


Figure 3.1.15 *Left*: Hydrograph of field-measured Spring Creek streamflow not filtered for tidal influence. Discharge data is not reported after January 15, 2020. *Right*: Hydrograph of continuous discharge measurements tidally filtered. USGS data.

While it has not been reported exactly where, how, and what was measured when the Spring Creek Spring Group was classified as a first-magnitude spring in 1977 based on one single measurement, this group cannot be classified as such: there is no flow 42% of the time, and the water exceeds specific conductance of 10,000 microsiemens per centimeter (µSi/cm) 91% of the time, and it exceeds 3,000 µSi/cm 99.8% of the time (Fig. 3.1.16). The specific conductance of fresh groundwater typically ranges between 200 and 3,000 µSi/cm, although water that is higher than 1,500 µSi/cm is not considered potable water. Sea water is typically about 53,000 µSi/cm but it can vary somewhat from sea to sea (location).

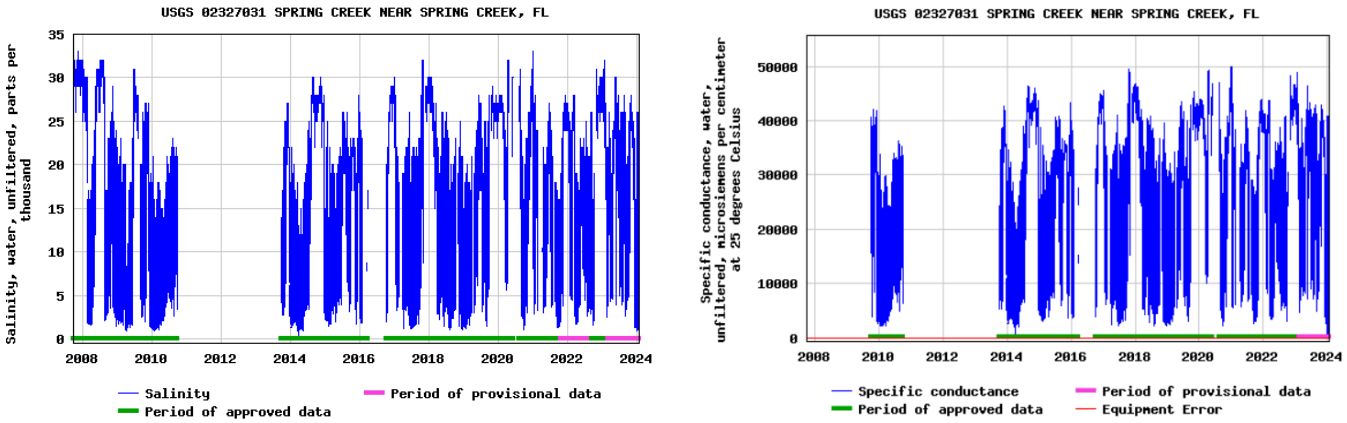


Figure 3.1.16 Graphs of salinity (left) and specific conductance (right) of Spring Creek water measured continuously by USGS. Fresh potable water has a salinity of less than 1 parts per thousand (ppt); by convention, sea water has salinity of 35 ppt which equals 53,000 microsiemens per centimeter (µSi/cm). The wide cyclic range of salinity and specific conductance unmistakably demonstrates that the Spring Creek springs do not discharge real groundwater like virtually all other first-magnitude and outstanding Florida Springs do. Instead, they discharge a mixture of brackish groundwater and sea water reflecting changes caused by the varying interactions between the two waters of different density.

The dramatic decrease in discharge rates of Florida springs and the overall impact of the ever-increasing groundwater withdrawals from the Floridan Aquifer is further illustrated by the fact that six springs classified by FGS as being of first magnitude are not that any more based on the publicly available records (Kresic, 2024). The seven Outstanding Florida Springs that are now truly *historic*, as was perhaps foreseen (or already known) by FGS and the Florida Legislature in 2016, are shown in Table 3.1.1. Several hydrographs are also provided below for illustration purposes.

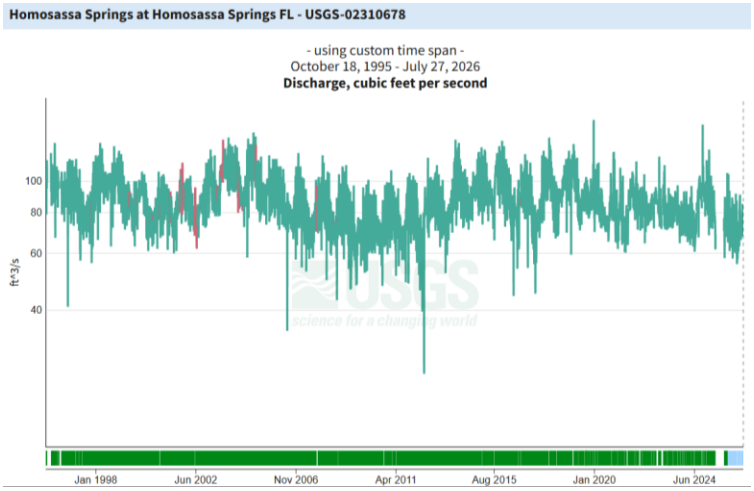


Figure 3.1.17 Daily discharge rate of Homosassa Springs for the complete period of record (31 years through July 27, 2026), as reported by USGS on their official website https://waterdata.usgs.gov/nwis/. The average is 86.7 cfs. Florida Geological Survey still, as of July 2026, lists Homosassa Springs as a first-magnitude spring group having the average discharge rate greater than 100 cfs.

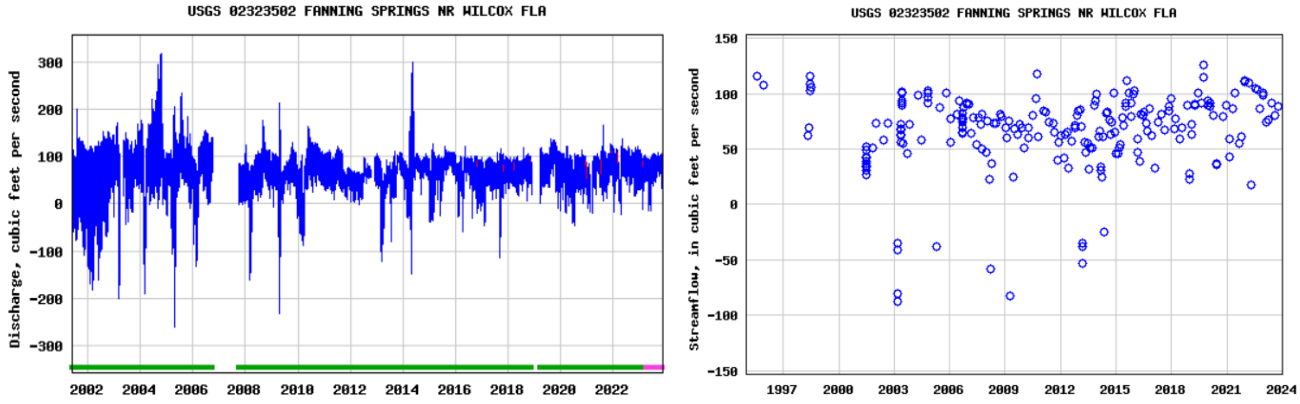


Figure 3.1.18 Fanning Spring discharge rate. *Left*: continuous measurements based on rating curve; the average is 70.6 cfs including flow reversal. *Right*: field measurements, the average is 66.4 cfs including flow reversal.

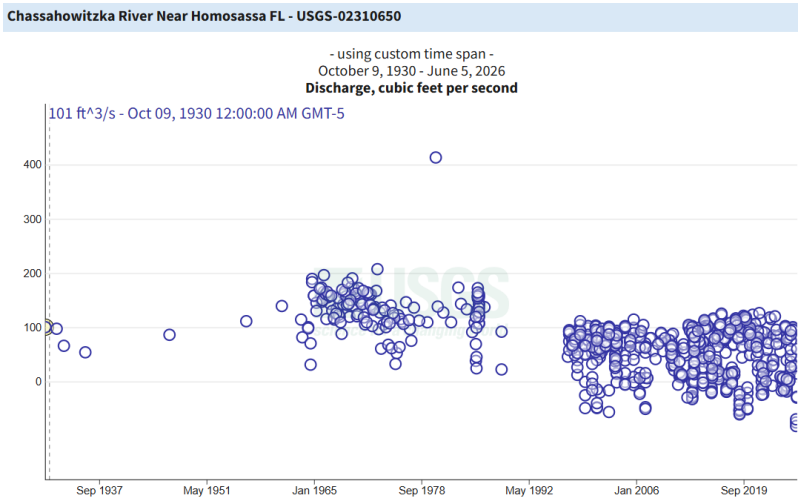


Figure 3.1.19 Chassahowitzka River ("Spring Group") field discharge rate measurements for the entire period of record; the average is 71.6 cfs including flow reversal. For the last 30 years, the average is 57.4 cfs.

Table 3.1.1 Outstanding Florida Springs that are classified by FGS as being of first magnitude but have average discharge rates lower than 100 cfs based on available public records.

Spring	County	Average Discharge Rate (cfs)	Period of Record	USGS Station	Note
Lafayette Blue Spring	Lafayette	52.2	1973-2026	02319950	
Hornsby Spring	Alachua	76.1	1972-2010	02321970	Frequently not flowing
Falmouth Spring	Suwannee	33.5	2006-2025	02319520	
Fanning Spring	Gilchrist	70.6	1995-2026	02323502	
Chassahowitzka River	Citrus	71.6	1930-2026	02310650	"Spring Group"
Silver Glenn Springs	Marion	89.3	1931-2026	02236160	
Homosassa Springs	Citrus	86.7	1995-2026	02310678	

Based on the publicly available records, there are 11 first magnitude, real karst springs in Florida. This includes nine individual springs, and two headsprings of rivers. Although the actual monitoring records are not made available by the USGS or SWFWMD, it is likely that the headspring of Silver River, Silver Springs in Ocala, which is made of 3 closely spaced vents, is still a first magnitude spring.

In December 2023, USGS started collecting field measurements of discharge rates of the headsprings (Rainbow Springs), of the Rainbow River, which consists of several closely spaced vents (Fig. 3.1.20; more on Rainbow Springs is provided further in this chapter). Based on this limited record (through June 2026), the average discharge rate of the Rainbow River headsprings is 305.9 cfs. This is roughly 51 % of the average flow rate of the Rainbow River at Dunnellon (593.6 cfs) for the same period. The Dunnellon USGS station is about 6 miles downstream from the headspring.

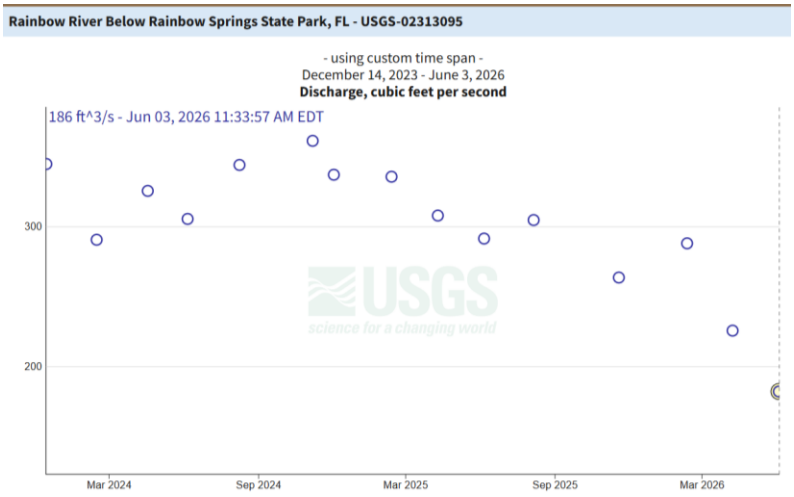


Figure 3.1.20 Hydrograph of field measurements of discharge rate of the headsprings of the Rainbow River by USGS for the period of record. The average is 305.9 cfs.

The nine individual first magnitude real karst springs in Florida are: Wakulla Spring, Jackson Blue Spring, Madison Blue Spring, Troy Spring, Devil's Ear Spring, Manatee Spring, Alexander Spring, Volusia Blue Spring, and Weeki Wachee Spring. They all have average discharge rates higher than 100 cfs based on publicly available record, including over the last twenty years.

In addition to Rainbow Springs and Silver Springs groups, FGS lists the following as first magnitude springs: Wacissa River, Gainer Springs group (section of Econfina Creek), Ichetucknee River, Chassahowitzka River, and Crystal River. However, unlike the headsprings of Silver River and Rainbow River, none of these streams has a headspring that is of first magnitude. Instead, the "required" average flow rate greater than 100 cfs is compounded over their stretches that are sometimes miles long, from both a number of small springs and from the direct diffuse discharge of groundwater from the Floridan Aquifer. Moreover, in case of the Chassahowitzka River, even this compounded flow is on average only about one half of the required 100 cfs over the last 30 years, as seen on Fig. 3.1.19. It is very likely that, decades ago, some of the headsprings of these rivers ("spring groups") were indeed strong and did flow at an average discharge rate greater than 100 cfs. The case in point is the headspring of the Ichetucknee River:

Old Timers who swam in Ichetucknee Spring in the 1920s called it "the Boil". They remember that the spring flowed at a much higher rate than today. Many of the Old Timers remember that you could see the boil was at least 3 inches higher than the water surface. The boil was so strong you could not swim across it. According to several Old Timers you could hear the water boiling out of the spring before you could see it. One said that you could hear it about 300 feet away. No one hears the Ichetucknee Head Spring today. It is silent now as are so many springs in Florida.

From Silenced Springs by Robert L. Knight

The sad destiny of Florida springs is rapidly approaching to what have already happened to its waterways, as illustrated by the following press release of July 28, 2026 (https://peer.org/new-report-finds-majority-florida-waterways-fail-water-quality-standards/)

Tallahassee, FL—A new report released today by Public Employees for Environmental Responsibility (PEER) and Waterkeepers Florida finds that the majority of Florida's waterways are failing to meet state water quality standards while enforcement of the state's environmental laws remains far below historical levels.

The report, Majority of Florida Waterways Fail Water Quality Standards as State Enforcement Remains Near Historic Laws, examines 37 years of Florida Department of Environmental Protection (DEP) enforcement data alongside current water quality data. It finds that fecal bacteria and nutrient pollution are the most widespread contaminants fouling Florida's rivers, lakes, and estuaries — pollution driven by agricultural runoff, wastewater discharges, and excess fertilizer use.

The report finds that while DEP enforcement actions ticked up slightly to 755 in 2025, that number is still less than half the state's historical average. Between 1996 and 2010, DEP initiated an average of 1,303 enforcement cases per year; between 2019 and 2025, that average fell to just 654 — even as Florida's population grew by nearly five million residents over the same period.

"Florida's enforcement program has been hollowed out over the past fifteen years, even as its population and pollution problems have grown," said PEER Executive Director Tim Whitehouse. "You cannot protect clean water with an enforcement program that is running at half strength."

"The data are unambiguous: most of our waterways are not meeting the standards designed to protect public health and the environment. Our current water regulatory system is not working," said Jen Lomberk, Esq., Vice-Chair of Waterkeepers Florida. "Floridians are swimming, fishing, and boating in waters that the state's own data show are impaired. That should alarm every resident and every elected official in this state."

The most alarming, however, is the fact that the permitted groundwater withdrawals in Florida are higher than the flow of all Florida Springs combined. This fact is worth repeating: The permitted groundwater withdrawals in Florida are higher than the flow of all Florida Springs combined.

Excerpts from: ***Opinion. Florida's booming population. 7 charts tell the hidden story***
People love the Sunshine State. But the influx of millions of people poses challenges.

This article represents the opinion of the Tampa Bay Times Editorial Board. Published May 11, 2023|Updated May 12, 2023. https://www.tampabay.com/opinion/2023/05/11/floridas-population-is-booming-some-surprising-ways-editorial/

"Our waterways and springs are already too polluted, walking in many of our cities is too dangerous, too many people live on the streets, and we have too many people in prison. Some of our neighborhoods are flooding more often, even on sunny days. Our electricity rates keep rising, many of our sewer systems are aging, and our interstates are often either a logjam or something out of a "Mad Max" movie.

How many more housing developments do we want to carve out of Florida's limited wilderness or ranch land? At its most basic, that's the choice: With so many more people coming to Florida, we either build smarter by promoting more density in already developed areas or we tear up what's left of Florida's pristine lands to build more single-family homes on oversized lots. The decision should be clear, but we don't act like it is."

There are quite a few organizations, most of which are run entirely by volunteers, that advocate and fight for the protection of Florida springs. Their names and links to their web pages can be found at https://www.floridaspringscouncil.org/springs-organizations

The Florida Springs Council is a 501c3 organization based in Gainesville and focused on the protection and restoration of Florida's springs and spring-fed rivers through education, advocacy, and litigation. The only state-wide advocacy group focused solely on springs, the Florida Springs Council serves as a state-wide umbrella organization, bringing together experts from across the state in science, policy, law, and advocacy to address both local concerns and state-wide issues more effectively (https://www.floridaspringscouncil.org/).

The Florida Springs Institute (FSI) is a 501c3 scientific and educational organization located in High Springs. FSI focuses on gathering data, conducting research, and publishing their findings about the health of Florida's springs (https://floridaspringsinstitute.org/).

More people, more pumping of groundwater for water supply, more sewage, more irrigation with pumped groundwater, more pesticides and fertilizers, more food based on domestic animals, more manure, more land application with human and animal excreta, more contamination of groundwater, and more of political weakness and groupthink = death of Florida springs.

Visiting Florida Springs

Florida springs were the state's first and biggest tourist destination before Disney and the beaches became major draws. They continue to attract about 30 million visitors every year. For example, Silver Springs alone, the flagship of Florida springs, had more than 489,000 visitors during the 2021/2022 fiscal year with a direct economic impact of $61.5 million a year (Toeppen-Sprigg, 2023). Since the 1870s, visitors have viewed their splendor through glass-bottom boats, accentuated in 1932 with the use of electric motors to provide a peaceful experience.

There are currently 27 Florida State Parks developed around springs (https://www.floridastateparks.org/ and https://www.floridastateparks.org/learn/springs-florida-state-parks), and more parks are managed by counties, cities, and private businesses that offer places to swim, dive, snorkel, picnic, camp, kayak or otherwise enjoy the magic of some of the most beautiful springs anywhere in the world. Their nearly constant water temperatures year-round (on average about 72 degrees Fahrenheit or 22.2 degrees Celsius) provide for a welcome escape from the summer heat and the chilly winter air.

Detailed descriptions of many springs including all thirty Outstanding Florida Springs are provided by the Florida Water Management Districts. The most comprehensive source is FGS' Bulletin No.66 *Springs of Florida* which is full of color photographs and available for free download at http://publicfiles.dep.state.fl.us/FGS/

Particularly informative and visually pleasing are presentations on the web page of The Howard T. Odum Florida Springs Institute (https://floridaspringsinstitute.org/) including amazing photographs by a renowned nature photographer John Moran.

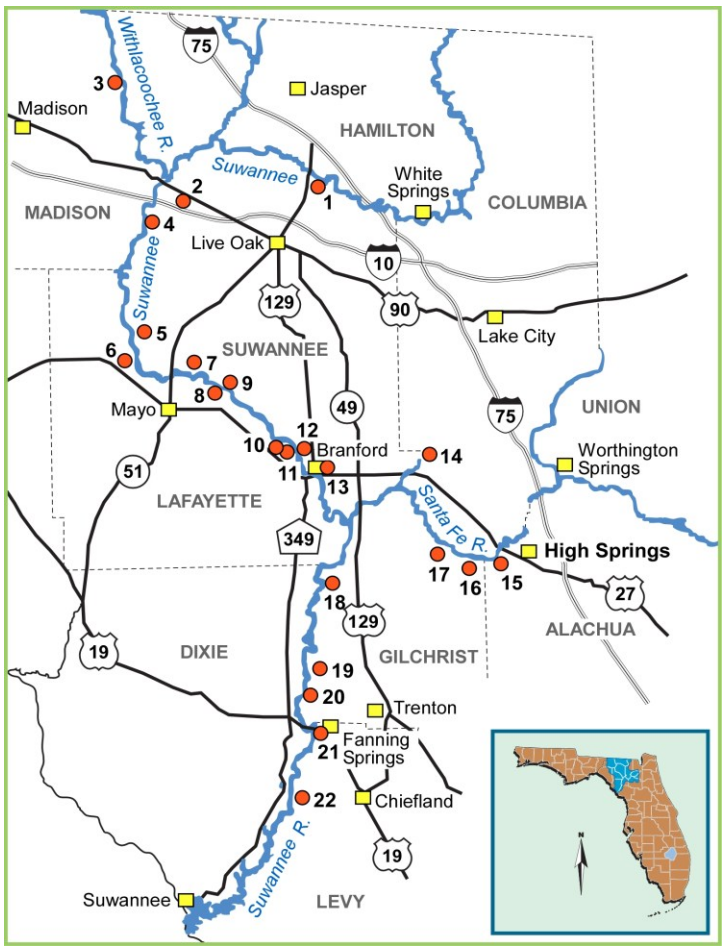
A Field & Recreation Guide to 500 Florida Springs by Joe Follman and Richard Buchanan including photographs is another excellent source available online at http://thespringsfever.com/index.html.

Melissa Watson's book, *Touring the Springs of Florida. A Guide to the States' Best Springs*, is full of useful details and features excellent maps with the locations of the springs. It includes GPS coordinates, descriptions of recreational options, and photographs. It is highly recommended to those who like holding books in their hands.

Table 3.1.2 Outstanding Florida Springs. SWFWMD: Southwest Florida Water Management District. USFWS: United States Fish and Wildlife Service. SRWMD: Suwannee River Water Management District. NWFWMD: Northwest Florida Water Management District. Springs with asterisks are not impaired by excessive nitrate/nitrogen concentrations. Recent data from Florida Springs Institute suggest Poe Spring is now impaired.

Spring Name	County	Management
Alexander Spring *	Lake	US Forest Service
Chassahowitzka Springs Group	Citrus	Citrus County
Columbia Spring *	Columbia	Private
Crystal River / Kings Bay Springs	Citrus	SWFWMD; USFWS; City of Crystal River
DeLeon Spring	Volusia	Florida State Park
Devil's Ear Spring	Gilchrist	Private
Falmouth Spring	Suwannee	SRWMD
Fanning Spring	Levy	Florida State Park
Gainer Springs Group *	Bay	NWFWMD; Private
Gemini Spring	Volusia	Private
Homossassa Springs Group	Citrus	Florida State Park
Hornsby Spring	Alachua	Private
Ichetucknee Springs Group	Columbia	Florida State Park
Jackson Blue Spring	Jackson	Jackson County
Lafayette Blue Spring	Lafayette	Florida State Park
Madison Blue Spring	Madison	Florida State Park
Manatee Spring	Levy	Florida State Park
Peacock Springs	Suwannee	Florida State Park
Poe Springs	Alachua	Alachua County
Rainbow Springs Group	Marion	Florida State Park
Rock Springs	Orange	Florida State Park
Silver Glen Spring *	Marion	US Forest Service*
Silver Springs Group	Marion	Florida State Park
Treehouse Spring *	Alachua	Private
Troy Spring	Lafayette	Florida State Park
Volusia Blue Spring	Volusia	Florida State Park
Wacissa Springs Group	Jefferson	Jefferson County
Wakulla Spring	Wakulla	Florida State Park
Weeki Wachee Spring	Hernando	Florida State Park
Wekiwa Spring	Orange	Florida State Park

An important part of visiting springs along and close to the Suwannee and Santa Fe Rivers is to consider the possibility that some of them may be impacted by a high river stage and not open for swimming due to "brownout". Such conditions are less likely to occur during the dry season and in the summer (except after hurricanes), but there are no guarantees. The lovely little town of High Springs is a natural base for exploring these springs, all less than an hour's drive away (Fig. 3.1.21), while Ocala is a natural hub for visiting 13 Outstanding Florida Springs shown on the map on Fig. 3.1.22, including Silver Springs, the most famous of them all, and only 6.4–mile drive from downtown.



No.	Spring Name
1	Suwannee
2	Falmouth
3	Madison Blue
4	Anderson
5	Charles
6	Lafayette Blue
7	Peacock
8	Convict
9	Royal
10	Troy
11	Ruth
12	Little River
13	Branford
14	Ichetucknee
15	Poe
16	Gilchrist Blue
17	Ginnie
18	Rock Bluff
19	Hart
20	Otter
21	Fanning
22	Manatee
	Florida State Park
	Owned by SRWMD
	County or City Park
	Privately Owned

Figure 3.1.21 Notable springs in the Suwannee River Water Management District (SRWMD). Map based on information provided by SRWMD, and by the Suwannee County at https://visitsuwannee.com/explore-freshwater-springs

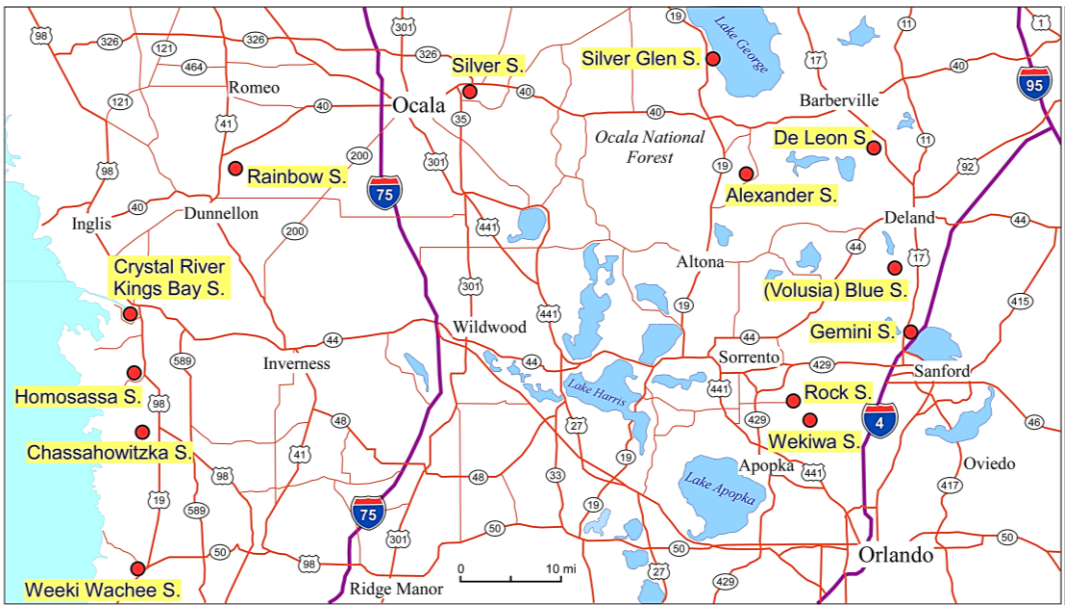


Figure 3.1.22 Outstanding Florida Springs an easy drive from Ocala

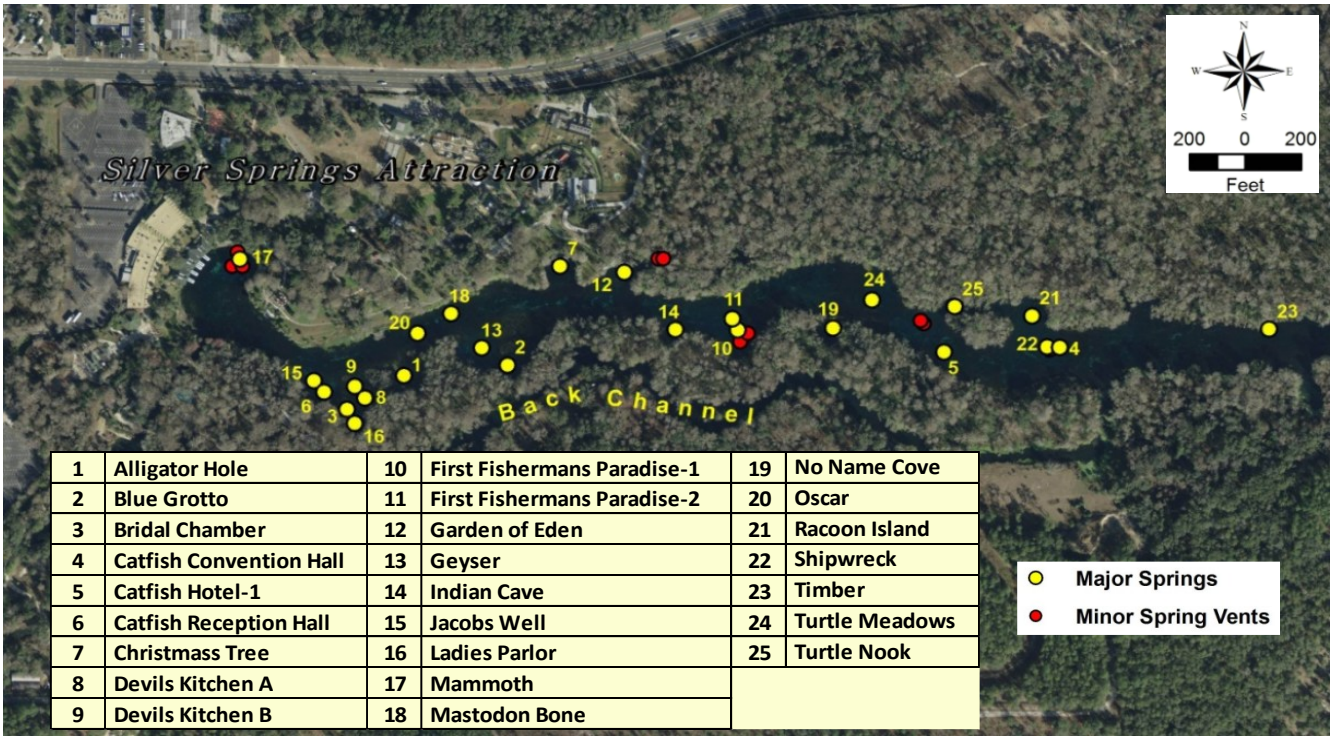
Silver Springs Group, Marion County

The Silver Springs Group, flowing from numerous vents, form the headwaters of the Silver River, a major tributary of the Oklawaha River. There are around 30 springs in the group, with 25 springs named. The largest is Mammoth Spring which is developed in a steep-walled depression in limestone, the headspring pool. It has three vents, the largest of which is located approximately 100 feet east of the glass-bottom boat loading area. The vent is a horizontal, oval-shaped opening about 5 feet high and 135 feet wide beneath a limestone ledge on the northeast side of the spring pool. The depth of water measured over the vent opening is about 30 feet. The second large vent is in the northwestern part of the main pool near the boat loading area.

The spring pool measures about 300 feet north to south and 200 feet east to west. The water is still relatively clear and blue, with aquatic vegetation and algae across the sandy spring bottom and limestone substrate. The spring run is also usually clear and the bottom at all locations is visible.

The Silver River flows from its headspring pool eastward for approximately 5 miles through a dense mixed hardwood and cypress swamp to the Oklawaha River. The Oklawaha River flows northward and is a tributary to the St. Johns River. Higher sandy terrain with pine and the Silver Springs community lie to the west of the springs.

There are three entrances to Silver Springs State Park. The main entrance is located on SR 40 at 5656 East Silver Springs Boulevard, Silver Springs, FL 34488. The camping and Silver River Museum entrance is located on SR 35 at 1425 N.E. 58th Ave., Ocala, FL 34470. The equestrian entrance is located approximately 1.3 miles east of the Main Entrance on SR 40.



1	Alligator Hole	10	First Fishermans Paradise-1	19	No Name Cove
2	Blue Grotto	11	First Fishermans Paradise-2	20	Oscar
3	Bridal Chamber	12	Garden of Eden	21	Racoon Island
4	Catfish Convention Hall	13	Geyser	22	Shipwreck
5	Catfish Hotel-1	14	Indian Cave	23	Timber
6	Catfish Reception Hall	15	Jacobs Well	24	Turtle Meadows
7	Christmass Tree	16	Ladies Parlor	25	Turtle Nook
8	Devils Kitchen A	17	Mammoth		
9	Devils Kitchen B	18	Mastodon Bone		

Figure 3.1.23 Springs of the Silver Springs Group. Modified from Sutherland et al., 2017. The headspring is named Mammoth Spring, but almost no one uses the name; most visitors and others know it simply by the name Silver Springs.



Figure 3.1.24 Two views of the headspring pool of the Silver River. Although it is named Mammoth Spring, it is known simply as Silver Springs. Left photo courtesy of St. Johns River Water Management District. Right photo courtesy of Silver Springs State Park (https://silversprings.com/gallery/).



Figure 3.1.25 The main vent opening of Mammoth Spring with exposed Ocala Limestone. The Ocala limestone is a white, chalky, highly fossiliferous limestone that was deposited in a warm, shallow marine environment more than 35 million years ago. Photo courtesy of St. Johns River Water Management District.



Figure 3.1.26 The Glass Bottom Boat was invented at Silver Springs in the 1870s and ever since these boats have wowed visitors with breathtaking views of underwater life and the many springs that feed the Silver River. Left photo courtesy of Silver Springs State Park.



Figure 3.1.27 Hand-colored postcard from 1941. Accompanying note reads "Florida's International Attraction. Largest flowing springs in the world, over 750 million gallons daily. Electric driven glass bottom boats. Greatest depth 80 feet. Temperature of water 72 [degrees] winter and summer. Shown from sunrise to sunset, in all weather, every day in the year." Courtesy of State Archives of Florida, Florida Memory.



Figure 3.1.28 *Left*: Deane Martin dancing for a fish while man plays ukulele underwater, circa 1960. *Middle*: Ginger Stanley using shears while man mows grass underwater, circa 1955. *Right*: Underwater witch riding a broom, circa 1950. All photographs by Bruce Mozert, made as part of the marketing campaign for Silver Springs Park. Courtesy of State Archives of Florida, Florida Memory.

The exceptional historic clarity and health of Silver Springs were immortalized by famous photographer Bruce Mozert (Figs. 3.1.28 and 3.1.29). His underwater photography series was initially created as a commercial project for Silver Springs Park as part of the park's marketing campaign. It has stood out as his signature project and many of the photographs are now in public domain and electronically available on the web page of State Archives of Florida (https://www.floridamemory.com/). Bruce Mozert is also recognized for his work as a set photographer on iconic film projects such as "Tarzan" and "Creature from the Black Lagoon" filmed at Wakulla Springs.



Figure 3.1.29 Bruce Mozert photographing Ginger Stanley underwater at Silver Springs. Courtesy of State Archives of Florida, Florida Memory

Wakulla Spring, Wakulla County

Wakulla Spring is in Edward Ball Wakulla Springs State Park (www.floridastateparks.org/WakullaSprings), about 15 miles south of Tallahassee via State Route 61 (Wakulla Springs Road), SR 267, and Wakulla Park Drive. After the demise of Mammoth Spring (headspring) of the Silver Springs Group due to excessive groundwater withdrawal from the Floridan Aquifer, Wakulla Spring is now the largest spring in Florida, with the long-term average flow of 409 cubic feet per second (cfs) based on publicly available USGS data as of December 2023 (USGS stopped reporting the spring's discharge rate in 2010 and did not resume it through present day). This is second only to Big Spring, Missouri, the largest spring in the United States (489.8 cfs; see Fig. 3.1.4). However, based on incomplete new data collected after 2007 by private consulting companies, using different methodology as well as modeling, it appears that Wakulla Spring's average discharge has dramatically increased since the USGS measurements. If there are additional, ongoing, and independently verified continuous measurements of the actual (non-modeled) discharge rate of Wakulla Spring since 2010, which would confirm an average higher than 489.9 cfs, Wakulla Spring may become the largest karst spring in the country.

Wakulla is the most dramatic Florida spring featuring a monumental, deep spring pool and submerged vent opening which leads to a vast network of channels explored by cave divers since 1950s. As of January 2023, the newly interconnected cave system of Wakulla Spring-Leon Sinks-Chip's Hole is the longest submerged cave system in the country, extending more than 45 miles below the Woodville Karst Plain (Flanigan, 2023).

The Wakulla Spring pool is roughly circular with a diameter of 315 ft north to south. The maximum pool depth is 185 ft. The vent opening is a horizontal ellipse along the south side of the pool bottom and is estimated to measure 50 ft by 82 ft. Along with a few smaller springs nearby, including a second magnitude Sally Ward Spring, Wakulla Spring gives rise to the Wakulla River.

The conduit system that sustains the flow of water to Wakulla Spring is developed in the lower Oligocene Suwannee Limestone. The sediment was deposited in a shallow sea that inundated Florida between 28 and 34 million years ago. The Suwannee Limestone is typically a white to pale orange limestone composed of sand-sized particles and frequently containing larger fossil shells and corals.



Figure 3.1.29 *Left*: Aerial view overlooking Wakulla Spring pool and spring run, 1967 photo by Richard Parks. Diving tower is in center-right. The spring vent is located below and left (NE) of the diving tower. Courtesy of State Archives of Florida, Florida Memory (available at https://www.floridamemory.com/). *Right*: Tour boat at the spring pool in December 2023.

The Edward Ball Wakulla Springs State Park was designated a National Natural Landmark in 1967 and listed on the National Register of Historic Places in 1993. On December 20, 2018, it was officially designated the newest State Geological Site or an area that DEP's Florida Geological Survey has determined to be significant to the preservation, scientific study and public understanding of geological history and resources in Florida.

In 2023, Wakulla Spring was nominated by this author for inclusion in the elite list of globally significant geological locations maintained by the International Union of Geological Sciences (IUGS). The nomination and the final submission (Stevanovic and Kresic, 2024) were successful, and Wakulla springs is now one of only three springs in the world included on the list (the other two are Vrelo Bune (Buna Spring) in Bosnia and Herzegovina, and Fontaine de Vaucluse in France; see Chapter 1.2 and Figs. 1.7 and 1.47). Wakulla Spring is placed alongside iconic U.S. geologic and natural landmarks such as The Grand Canyon, Mammoth Cave, and The Yellowstone.

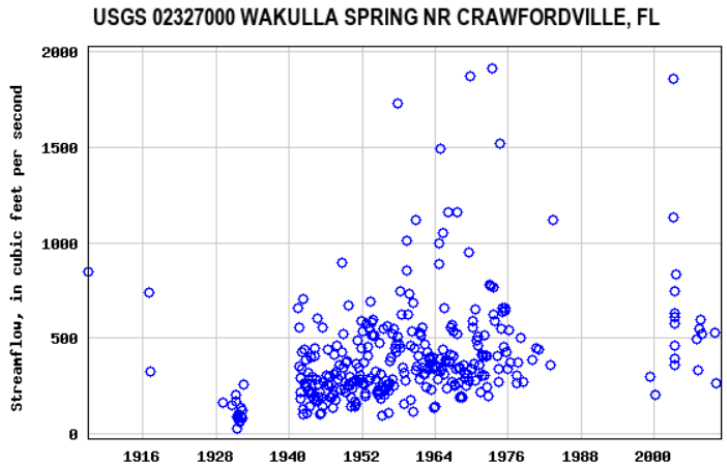


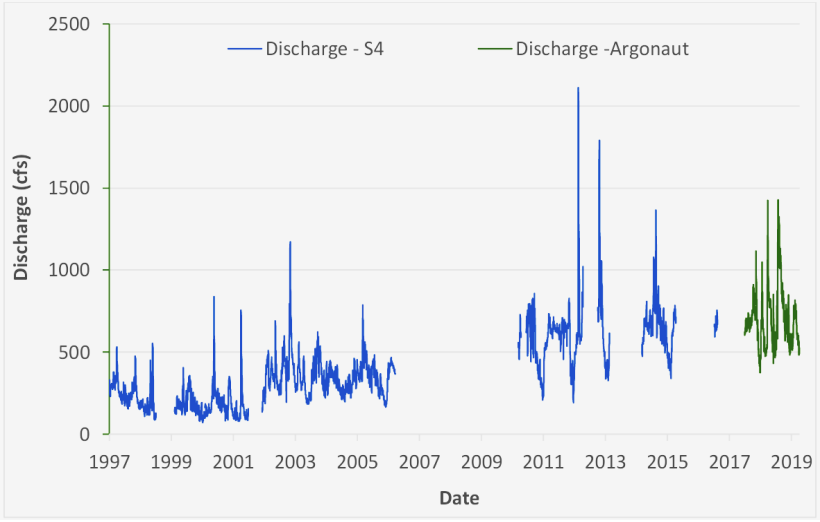
Figure 3.1.30 Wakulla Spring has the greatest known range in discharge among Florida's springs. The minimum of 25.2 cfs was measured on June 18, 1931, and the maximum of 1,910 cfs on April 11, 1973. The average is 409 cfs for the period of record, between February 1, 1907, and March 17, 2010, when USGS stopped reporting the spring's discharge rate.

As explained by Northwest Florida Water Management District (NWFWMD, 2021), discrete discharge measurements have been collected at irregular intervals near the Wakulla Spring vent between February 2, 1907, and December 31, 2019, including measurements not reported by USGS. Discrete discharge measurements are defined here as direct field measurements of discharge, in contrast to discharge estimates from index velocity, stage-discharge, or other types of ratings. The intervals between manual discharge measurements range from less than 1 day to nearly 16 years.

Continuous discharge measurements were performed by NWFWMD between 1997 and 2019 (Fig. 3.1.31). Discharge rate estimates were made using an index velocity relationship between continuously recorded water velocity measured in the Wakulla Spring vent and the volume of water measured just downstream of the main vent. Several long gaps in the continuous discharge time series exist due to equipment malfunction and failure.

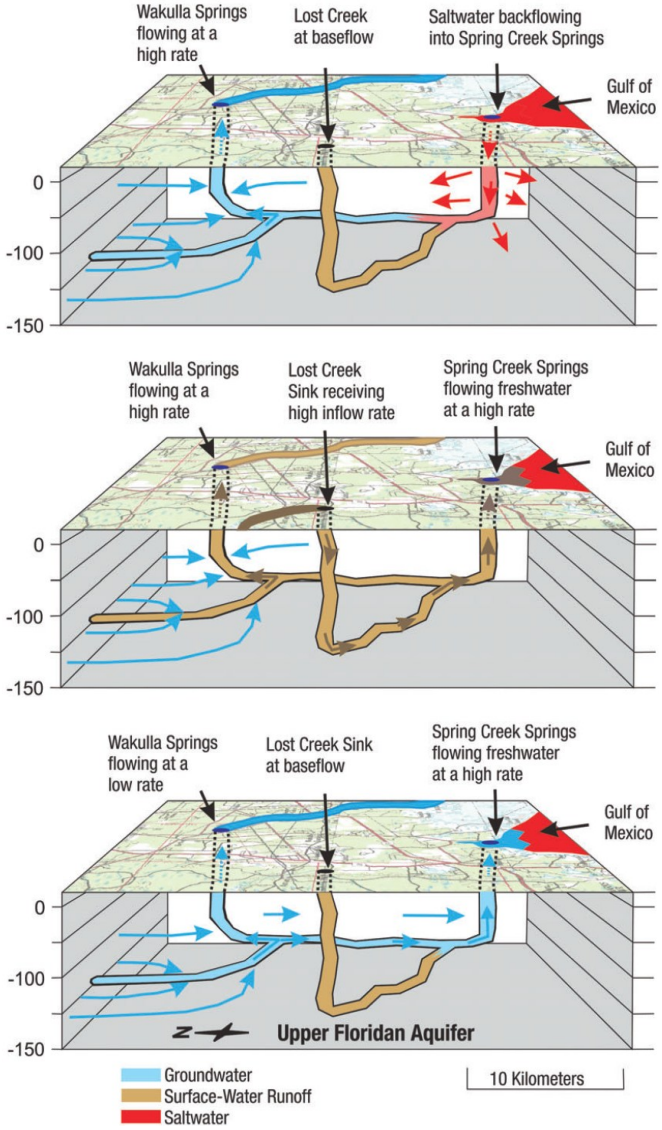
The rate of increase of Wakulla Spring discharge was larger than the proportional change of rainfall, suggesting other factors have led to the increase in spring flow, including (1) Lower river and spring pool stages resulting from changes in the Wakulla River channel which have resulted in additional spring discharge by increasing the gradient between the upper river and spring pool and the Floridan aquifer; and (2) Increases in coastal sea levels which are likely increasing the equivalent freshwater head at the Spring Creek Spring group resulting in intermittent diversions of water from the Spring Creek Spring group to Wakulla Spring (NWFWMD, 2021).

Davis and Katz (2007) suggested two possible reasons for the long-term increase in Wakulla Spring flow: (1) a small rise in sea level along the Gulf coast of Florida from 1932 to 2007 may have contributed additional sea water head on the Spring Creek Springs causing a reduction in flow and a corresponding increase in Wakulla



Springs flow; or (2) the evolution of the submerged cave passages at Wakulla Springs may have allowed for greater groundwater capture in the same way that one river can capture flow from another river through erosional processes. (This process is often called "piracy", and it is common in karst.

Figure 3.1.31 Hydrograph of continuously measured discharge rate of Wakulla Spring by NWFWMD, 2021.



Davis and Verdi (2014) proposed a mechanism for describing varying flows and the presumed connections between Wakulla Spring, the Spring Creek Spring Group, and nearby swallets such as Lost Creek Sink. Three phases were described based upon a changing balance between precipitation events, baseflow, and equivalent freshwater head pressure at the Spring Creek Spring Group submarine vents (Fig. 3.1.32).

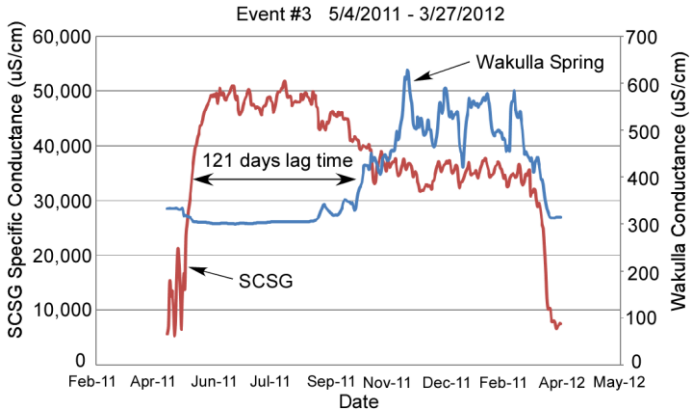
Phase 1 occurs when there is an extended period of low precipitation and estuarine/saltwater flows into the Spring Creek Spring Group vents and recharges the Floridan aquifer where freshwater discharge is blocked due to the higher density salt water. During this phase, groundwater which would be discharged at Spring Creek can be diverted towards Wakulla Spring where discharge increases.

Figure 3.1.32 Conceptual model of groundwater flow between Wakulla Spring and Spring Creek Springs proposed by Davis and Katz (2007). *Top:* Phase 1: Sea water backflow. *Middle:* Phase 2: Surface water inflow. *Bottom*: Phase 3: Groundwater outflow. Vertical scale is in meters.

Phase 2 is characterized by a heavy precipitation event where large volumes of surface water flow into the subsurface creating enough head pressure to overcome the saltwater plug, resulting in freshwater discharge at Spring Creek in addition to increased flow at Wakulla Spring (due to increased surface water inputs).

Phase 3 begins once streams return to baseflow conditions and flow at Wakulla Spring declines with the Spring Creek Spring Group continuing to discharge fresh water.

James Sutton, hydrogeologist with NWFWMD, analyzed the data on specific conductance for Wakulla Spring and Spring Creek Springs waters during periods ("events") of flow reversal when the equivalent hydraulic head of freshwater at Spring Creek Springs was higher than the Wakulla Spring pool elevation. An example of such an event is shown in Figure 3.1.33-*Left*, together with a table providing information on seven major continuous flow reversal events between 2007 and 2019 (Sutton, 2020).



Event	Date of beginning of reversal event at SCSG	Date of end of reversal at Wakulla Spring	SCSG under reversal conditions (Approximate # of Days)	Wakulla Spring with elevated s. conductance (Approximate # of Days)
1	5/7/2007	2/27/2008	296	203
2	4/15/2008	8/31/2008	138	42
3	5/4/2011	3/27/2012	328	207
4	10/27/2012	3/3/2013	127	87
5	4/22/2014	12/30/2014	252	116
6	9/25/2016	1/17/2017	114	42
7	9/10/2017	3/26/2018	197	105
		Average	207 days	115 days

Figure 3.1.33 Analysis of flow reversal events between Spring Creek Springs and Wakulla Spring performed by James Sutton, NWFWMD hydrogeologist. Available at http://wakullaspringsalliance.org/wp-content/uploads/2016/11/Wakulla-Discharge-Analysis_WSA.Sutton.09-25-20.pdf

The analysis shows that the average time of the flow reversal was 207 days, and as long as 328 days, during which the specific conductance measured at Spring Creek Springs indicated that the water was highly brackish, approaching sea water for extended periods of time. With a certain delay, the flow reversals caused significant increases in the specific conductance of Wakulla Spring water, sometimes more than doubling it from the baseline levels, and confirming an alarming sea water intrusion into the Floridan Aquifer.

As the sea level continues to rise, and the Spring Creek Spring's network of submerged cave passages becomes more and more affected by the intrusion of dense (heavier) sea water, the flow reversal will at some point become permanent. In other words, Spring Creek Springs will cease to flow completely, and the Wakula Spring water will have an increasingly higher specific conductance as heavy sea water invades more karst channels supplying water to Wakulla Spring. This process will only accelerate if there is additional lowering of the regional hydraulic head in the Floridan Aquifer due to groundwater extraction: less fresh groundwater water will flow towards the coast and the dense sea water "plugs" in the karst channels will move inland faster.

The only plausible solution to the ongoing saltwater intrusion described above is comprehensive regional management of both surface water and groundwater that would result in a very significant increase in the groundwater levels (hydraulic head) of the Floridan Aquifer. If this increase is sufficiently large, it would result in Spring Creek Springs again discharging enough fresh water to flush out the saltwater residing and moving inland through the karst network.

The Catastrophe

Unfortunately, Wakulla Spring, the only real rival of Silver Springs for decades, is now just a dark shadow of its former self. Photographs like the one in Figure 3.1.34-*Right* are things of a distant past.



Figure 3.1.34 *Left*: Parts of a pamphlet that used to be available to visitors to Edward Ball Wakulla Springs State Park. *Right*: Glass-bottom boats were once big part of the Wakulla Spring appeal. Photo courtesy of Edward Ball Wakulla Springs State Park. The glass-bottom boats have not effectively operated for more than 20 years now because of the dark water of the spring caused by a variety of reasons, all related to negative anthropogenic impacts.

A good starting point to learn why beautiful Wakulla Spring is experiencing the catastrophe is the report by Seán McGlynn (2020; Wakulla Springs Dark Water: Causes and Sources, Phase III Final Report). It reads like a horror story. Below are only a few takeaways.

Tracing saltwater from Spring Creek to Wakulla Spring is positive. The prediction is made by a hydrogeologist that saltwater flow at the spring will increase in the coming years with sea level rising and over pumping.

Dye tracing studies have shown that the four largest karst lakes in Leon County are connected to Wakulla Spring. All these lakes are hypereutrophic and three of them (Lafayette, Munson and Jackson), have impaired water quality and are in various stages of enforcement within the Florida TMDL program. Urban storm water and sewage spills (in which the City of Tallahassee is also fined under a consent order and South Georgia has a history of similar problems) cause these lakes to experience frequent and prolonged algae blooms, including potentially harmful bluegreen algae blooms.

All the karst features, sinking lakes, sinking streams and sinkholes as well as karst depressions that contribute to the egregious contamination of Wakulla Spring are dropped from the official state cleanup plan for Wakulla Springs by the Florida Department of Environmental Protection (FDEP). McGlynn points out that there is a major flaw in FDEP's reasoning and the claim that features are naturally polluted and thus cannot be cleaned up. Most of

the waterbodies, particularly Lake Munson and Lake Lafayette have received sewage either inadvertently spilled or purposefully released in the past and this has made for a high sediment load of nutrients.

The potentially toxic diatom, Nitzschia and unicellular flagellate algae Pelagomonas were both found at highest concentrations at the spring and associated L well. Both are marine species, indicating a connection with the sea (emphasis added).

Samples from the submerged passages of the Wakulla Spring cave system, while they contain some chlorophyll, *are dominated by algae species and by microscopic fecal pellets, occasional amphipods as well as mucosa-like slimy globules* (emphasis added).

It is the hope that Wakulla Spring, the true National and World Treasure, will see better days in a not-so-distant future and that the continuing efforts of the organizations and individuals who fight tirelessly on behalf of the Spring, which cannot speak up for itself, will bear fruit despite the inactions of the Florida Government agencies.

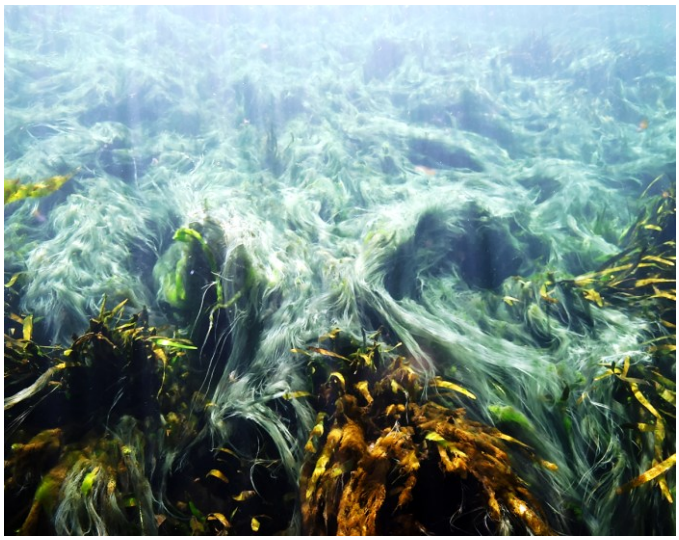


Figure 3.1.35 An underwater photograph from Wakulla Spring showing algal growth on and damage to native submerged aquatic vegetation (SAV). Courtesy of Wakulla Springs Alliance http://wakullaspringsalliance.org/

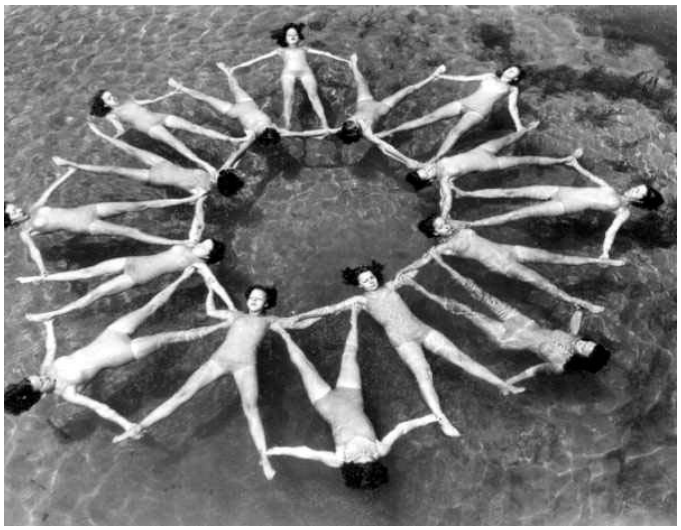




Figure 3.1.36 Glory days of the past. *Left*: Swimmers of the F.S.C.W. Tarpon Club of the Florida State University. *Right*: Visitors crowd the beach, July 4th, 1946. Courtesy of State Archives of Florida, Florida Memory.

Rainbow Springs, Marion County

Rainbow Springs group discharges to the Rainbow River, which, from the headsprings area, flows south for approximately 6 miles and merges with the tannic Withlacoochee River at Dunnellon. The surrounding land has high rolling sand hills with a pine forest, agricultural fields and rapidly expanding areas of suburban development.

The springs are in Rainbow Springs State Park which has 3 entrances: (1) the headsprings and day use area entrance is at 81st Place Road, Dunnellon via U.S. 41; (2) the campground entrance is at 18185 SW 94th St., 3.1 miles south of State Rd. 40 or 2.3 miles north of County Rd. 484; (3) and the tubing entrance is at 180th Ave. Road, Dunnellon (tubing is open seasonally and it is currently run by concessionaire.)

The Rainbow Springs State Park has many visitors on weekends and holidays. They come from around Florida, the country, and the world to visit the Park, to swim and snorkel in the crystal-clear water, to canoe, kayak, and tube down the peaceful Rainbow River, and to enjoy picnicking with friends and families. When the Park reaches capacity at the headsprings entrance, it closes to all visitors. When the Park is closed, vehicles may not wait in line in the park or on adjacent roads.

The springs, in addition to those at and near the head of the Rainbow River, discharge from numerous limestone crevices and sand boils in the bed of the river and along the banks through the upper 2 miles. These locations are easily recognized because of the absence of aquatic vegetation. Rainbow Spring No. 1 is at the head of the Rainbow River. The spring pool measures 330 ft north to south and 360 ft east to west. The large headspring pool has multiple vents. The depth over the main vent is about 10 feet. The bottom is sand with occasional limestone boulders. The water is crystal-clear. A boil is visible over the main vent. Aquatic vegetation is patchy, including some exotic plants. Motorized boats are prohibited, but the area is accessible by canoe or kayak. There is a designated swimming area on the west side of pool.

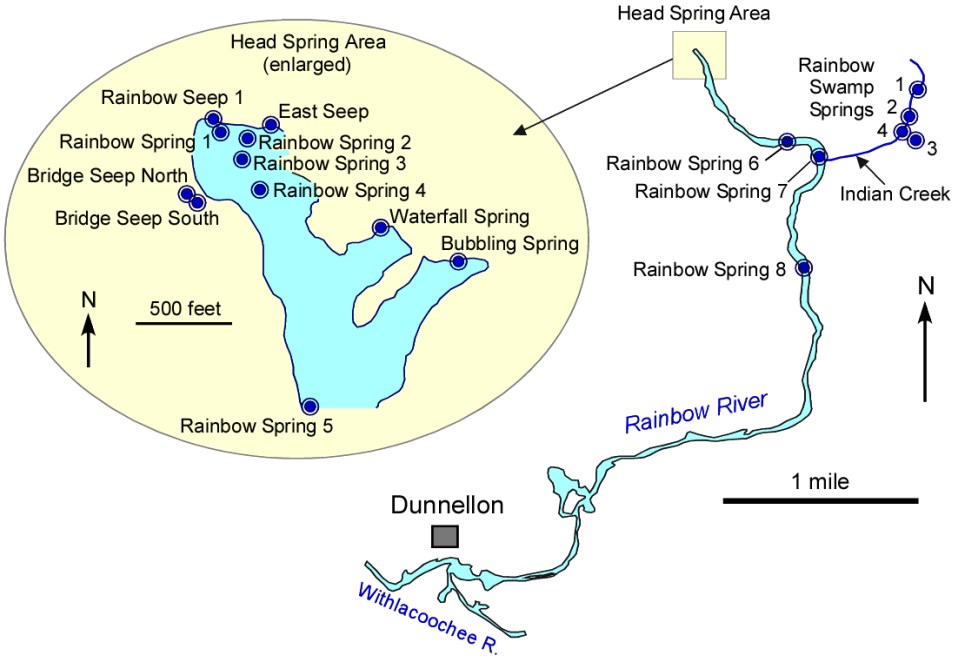


Figure 3.1.37 Locations of spring vents in the Rainbow Springs spring complex. From Jones et al., 1996. Discharge rate of the Headspring area is about 50% of the Rainbow River flow recorded at the USGS Dunnellon station.

In December 2023, the USGS started collecting field measurements of discharge rates of the headsprings (see Fig. 3.1.20). Based on this limited record (through June 2026), the average discharge rate of the Rainbow River headsprings is 305.9 cfs. This is roughly 50 % of the average flow rate of the Rainbow River at Dunnellon (593.6

cfs) for the same period. The Dunnellon USGS station is about 6 miles downstream from the headspring and was routinely used by the FGS to state how Rainbow Springs is the second largest in Florida (before it became obvious that the Silver Springs headspring was not the largest anymore), and one of the largest in the country.



Figure 3.1.38 Pool of the headspring of Rainbow Springs, December 2023. Red buoys mark the swimming area with crystal-clear water and a sandy bottom.



Figure 3.1.39 Rainbow River, 2017. Photographs by John Moran; all rights reserved. Printed with permission.

Although Rainbow Springs has some of the healthiest submerged aquatic vegetation and fish population, it has one of the highest nitrate levels among the west-central Florida spring systems which fuels algae growth. Large amounts of algae growth can cause reduced water clarity and extreme fluctuations in dissolved oxygen, which is stressful to aquatic life. In addition, unhealthy Hydrilla and Lyngbya dominate in the lower portion of the river.

Ichetucknee Springs, Columbia County

The Ichetucknee Springs are in the Ichetucknee Springs State Park which has two entrances (North Entrance is for swimming areas, and South Entrance is for tubing). The North Entance is 17 miles from the town of High Springs via US-27, SW Junction Rd, SW Elm Church Rd, and 260th St.

The spring group is comprised of eight named and many unnamed springs along the upper 2.5-mile stretch of the Ichetucknee River. The most northerly spring forms the head of the river and is named Ichetucknee Headspring. From here, the river flows about 1.5 miles south, then 4 miles southwest to discharge into the normally darker tannic water of the Santa Fe River.

Other named springs are Blue Hole, Mission Spring, Cedar Headsprings, Devil's Eye Spring (not to be confused with the spring in the Ginnie Springs Group by the Santa Fe River), Grassy Hole Spring, Mill Pond Spring, and Coffee Spring.

The Ichetucknee Springs Group is considered by many to be the crown jewel of the Suwannee region. It is popular year-round for its clear, cool waters, and is a tourist destination for its many amenities, including tubing. The two most visited springs are the Headspring and Bue Hole where swimming is allowed at all times, without any concern for brownouts which are common at other springs along the Suwannee and Santa Fe Rivers.

The Headspring pool measures 102 ft east to west and 87 ft north to south. The depth measures 17 ft over the vent. The water is clear and light blue and issues from a fracture in the limestone forming a visible boil. The spring has a sand and limestone bottom with little or no aquatic vegetation and is a popular swimming hole.

The Blue Hole Spring is the largest of the Ichetucknee Springs and often overlooked by visitors. It is reached by a 1/3-mile-long boardwalk and nature trail from Headspring. The spring pool measures 87 ft east to west and 117 ft north to south. The depth measured over the vent is 37 ft. The water is always clear and blue, and a boil is visible on the pool surface. Water issues from a cavern in limestone (Figure 3.1.41-*Right*).



Figure 3.1.40 Ichetucknee Headspring, December 2023.



Figure 3.1.41 *Left*: Blue Hole Spring pool. *Right*: Entrance to cave passage at the bottom of Blue Hole, called "The Jug" by the locals and cave divers. The name comes from the cone-shaped entrance to the submerged cave system, which has nearly 600 feet of explored passages. Photo by John Moran; all rights reserved. Printed with permission.

Tubing on the Ichetucknee River, one of the most popular activities in the park, is a relatively recent innovation. For many decades the springs of the Ichetucknee have been prized by locals as favorite gathering spots. In the days before automobiles, people used to endure hours on dusty, bumpy back roads by horseback or wagon to enjoy the cool waters. The Headspring in particular was popular for family reunions, baptisms, picnics and camping. Old-timers tell stories of chilling watermelons in the small feeder springs around the Headspring. Women used to tie up their skirts to go fishing, trapping their catch bare-handed against logs and throwing them up on shore.



Figure 3.1.42 Floating down the Ichetucknee River, 1990. Photo by John Moran; all rights reserved. Printed with permission.

Ginnie Springs, Gilchrist County

Ginnie Springs Group is in a privately-owned park about 8.6 miles west of High Springs off County Road 340. The group of seven springs that are known as Ginnie Springs, as well as the surrounding 600 acres, have been privately owned by the Wray family since 1971. Ginnie Springs Outdoors LLC has been in operation since 1976. The park, nestled along the banks of the scenic Santa Fe River, is very popular especially during spring break and summer months and the entrance fee is worth every penny. Strict Park rules are enforced for the safety of all visitors and can be viewed and downloaded prior to visit at (https://ginniespringsoutdoors.com/).

Ginnie Springs achieved an unrivaled fame among scuba divers of all skill levels when Jacques Cousteau dove here in 1974 and praised the crystal-clear water (72°F year-round) as "visibility forever." It is the international hotspot for scuba diving.

The main Ginnie Spring basin is a large, bowl-shaped depression measuring over 100 feet across and 15 feet deep (Fig. 3.1.43). A 150-foot-long run connects the basin to the nearby Santa Fe River. The chief attraction here is the Ginnie Cavern, whose wide, open entrance can be found at the bottom of the basin. Ginnie Cavern is among the handful of sites that experts consider sufficiently safe to allow exploration by divers who lack formal cavern or cave diver training.

Certified divers of all experience levels may take lights into the water with them at Ginnie Spring and use these lights to explore the underwater cavern. The cavern's upper room is illuminated by light from the entrance. Looking back toward the entrance from this room provides a breathtaking view. Like most of the cavern, the upper room's walls are composed of an extremely light and highly reflective limestone, which adds to its natural beauty.



Figure 3.1.43 Ginnie Spring, December 2023. *Left*: Future scuba diver (in lower right) being introduced to the spring magic for the first time. *Right*: "One for the camera!"



Moving to the back of the upper room, divers pass through a large opening into the amphitheater-sized area called the "Ballroom." Although surface light is clearly visible from most places within the Ballroom, divers will want to carry dive lights to see everything there is to see.

Figure 3.1.44 "Ballroom" at Ginnie Spring Cavern. Courtesy of Ginnie Springs Outdoors; available at https://ginniespringsoutdoors.com/dive-sites/ginnie-ballroom/

The Ballroom provides divers with the opportunity to examine many of the unusual geologic formations that are unique to the Floridan Aquifer. The Ballroom's ceiling contains an excellent example of spongework–a gigantic, limestone Swiss cheese. At the northwest corner of the Ballroom is a beautifully carved phreatic tube–a perfect example of the most common form of underwater cave formation.

The Devil's Spring System is home to three closely spaced but separate springs: Devil's Eye, Devil's Ear, and Devil Spring ("Little Devil"), which together are classified as a bona-fide first-magnitude Outstanding Florida Spring producing on average nearly 110 million gallons of water daily and keeping at bay the dark tannic water of the Santa Fe River.



Only certified cave divers may enter the water at the Devil Spring system while carrying dive lights. This helps prevent untrained divers from entering any area where their lack of training, experience, and specialized equipment could endanger them.

Figure 3.1.45 Devil's Spring System at Ginie Springs. Courtesy of Ginnie Springs Outdoors.

Devil Spring (also known as "Little Devil", see Figure 3.1.46-*Left*) is a four-foot-wide fracture at the head of the Devil's Spring System run. It is 50 feet long and almost as deep. Divers who descend to the bottom of this crack will be rewarded with a breath-taking view as they look skyward. Even from the very bottom, it is not unusual to look up through the clear water and be able to count the leaves on the trees overhead.



Figure 3.1.46 *Left*: Divers preparing to explore Little Devil Spring at the head of the Devil's Spring System short spring run. *Right*: View down the spring run towards the Santa Fe River visible in the distance. December 2023.

Devil's Eye is a round opening, 20 feet across and equally deep. At the bottom is the entrance to a small, intricately decorated cavern. Certified divers may enter the cavern and explore up to the limit of what they can see, using available sunlight.

Devil's Ear is a canyon-like opening located where the Devil Spring run joins the Santa Fe River. At the bottom of this opening, water gushes from a cave opening with nearly fire-hydrant-like force. Although the water in the Devil's Ear basin is generally crystal clear, it is common for it to be covered with a thin layer of tannin-stained river water. This phenomenon enables divers to sit in the basin's clear water and look up at the sun and trees through a unique, stained-glass effect created by the river water. Based on 17 available field measurements by USGS, the average discharge rate of Devil's Ear Springs is 170 cfs (no data is available after 2010).

More on the cave system of Ginnie Springs is provided in Chapter 1 (Figs. 1.67 through 1.69).

Gilchrist Blue Springs, Gilchrist County

Ruth B. Kirby Gilchrist Blue Springs State Park is in Gilchrist County about five miles to the west of High Springs off Northwest 182nd Avenue (County Road 340) in the north-central part of the state along the Santa Fe River.

The park is the newest addition to Florida State Parks (https://www.floridastateparks.org/parks-and-trails/ruth-b-kirby-gilchrist-blue-springs-state-park) and contains a collection of springs, including a large second-magnitude spring known as Gilchrist Blue (Fig. 3.1.47). This spring is the headspring of a shallow, about 1/4-mile-long run discharging to the Santa Fe River. Its remarkable aesthetic appeal stems from the extraordinary clarity of its waters owing to the extensive subterranean filtration of aquifers that render it visually transparent. With an average daily discharge of approximately 42 cubic feet per second, the main spring sustains a stable temperature of approximately 72°F (22°C) year-round (Florida Springs Institute, 2020b).



Figure 3.1.47 Gilchrist Blue Spring in Ruth B. Kirby Gilchrist Blue Springs State Park. December 2023.

The Park currently offers swimming at the main spring only. The other springs are under restoration (2023-2024) but are available for viewing: Little Blue Spring, Naked Spring (also a second-magnitude spring), Kiefer Spring and Johnson Spring.

With mounting anthropogenic impact from increasing visitation and potential introduction of invasive species, the spring and its surrounding environs have encountered environmental challenges, necessitating conservation measures to safeguard the fragile balance between human enjoyment and ecological protection. The headspring sits downhill from a picnic area which has gradually been stripped of vegetation over time. To prevent erosion, plastic barriers were installed. This erosion control infrastructure may not be sufficient as there are regular erosion issues at Gilchrist Blue (Florida Springs Institute, 2023).

According to Florida Department of Environmental Protection (FLDEP, 2019), the discharge of Gilchrist Blue Spring (combined with Naked Spring and Little Blue Spring at the mouth) was first measured in April 1975 with a flow of 42 cubic feet per second (cfs). The average recorded flow for Gilchrist Blue Spring is 45.16 cfs based on 106 measurements.

Madison Blue Spring, Madison County

Madison Blue Spring is in Madison Blue Springs State Park about 10 miles east of Madison via US 90 and Florida State Road 6E. The park experiences frequent closures between the hours of 10 a.m. and 3 p.m. on weekends and holidays due to high visitation. It provides a wide variety of recreational activities including swimming, picnicking, hiking, paddling and scuba diving.

The Spring flows from an 80-foot diameter spring pool, down a 100-foot spring run and into the Withlacoochee River. A large opening about 30 feet below the surface of the spring leads to an extensive underwater cave system. Over 26,000 feet of passages have been mapped by certified cave divers, making it one of the longest underwater caves systems in the state. The cave system extends well outside of the park boundary and passes under the Withlacoochee River just south of the State Road 6 bridge.

Madison Blue Spring's average discharge rate of 103 cfs is uniform over the last 20 years, with occasional flow reversal during very high stages of the Withlacoochee River (Kresic, 2024).



Figure 3.1.48 In 2015, Madison Blue was voted the Best Swimming Hole in the United States by USA Today. It is a favorite destination for family and a great place to spend the day. Panoramic photo courtesy of Suwannee River Water Management District (SRWMD).

Peacock Springs, Suwannee County

Peacock Springs is in Wes Skiles Peacock Springs State Park, about 19 miles southwest of downtown Live Oak via FL-51 and 180th St., or about 7 miles north of Mayo via FL-51. It is 47 miles northwest from High Springs via U.S. Hwy 27 and FL-51.

This rural state park is more natural and is much less developed than other state parks in Florida featuring springs. It contains five second-magnitude springs, named Peacock Springs I, II and III, Bonnet Spring and Orange Grove Sink. Two distinguished individuals lend their names to this park, and both are responsible for preserving and caring for the land and resources. Dr. John Calvin Peacock moved from Troy, North Carolina, with his family to the area near Peacock Springs, settling in 1855 near the Suwannee River. In 2011, the park's name was amended to honor the late Wes Skiles, a cave diver, explorer, photographer, documentary filmmaker and springs advocate who worked tirelessly throughout his life to protect this park and all of Florida's water resources.





Peacock Springs has one of the longest underwater cave systems in the continental United States with over 30,000 feet of surveyed cave passages. It attracts certified cave divers from all over the world. They must show proof of their scuba certification before being permitted to explore the underwater caverns.

It wasn't until 1956, however, that the first recorded cave dive into the Peacock system was made. In the subsequent 60-plus years, divers have explored and mapped much of the underwater world here and continue to do so today.

In 1985 the Nature Conservancy purchased 250 acres of land around the springs, hoping to protect the unique stand of hardwood forest Florida maples and cave systems. Peacock Springs State Park was later acquired by the state of Florida and was opened to the public in 1993.

Figure 3.1.49 *Top*: Peacock Spring, mid-December 2023. *Bottom*: Peacock Spring Divers, 2018. Photo by John Moran, all rights reserved. Printed with permission.

Fanning Spring, Levy County

Fanning Spring is in Fanning Springs State Park and the town of Fanning Springs. The park entrance is located on the east side of the Suwannee River on US 19/27/98. It is approximately 0.2 miles east of the bridge over the Suwannee River.

The spring is in a conical depression with steep sand and limestone banks. The spring pool measures about 200 ft north to south and 140 ft east to west. The depth of the spring pool measured over the vent is 18 ft. The vent area is nearly funnel shaped, with sand and limestone bottom and limestone sides, and it issues from the southeast side of the depression. The main vent flows horizontally from a small orifice in the limestone; however, multiple small boils can be seen during high aquifer levels (Scott et al., 2004).



Figure 3.1.50 Panoramic view of Fanning Spring with the designated swimming area. 450-ft long spring run to the tannic Suwannee River is beyond red buoys and floating walkway. December 2023.

Visitors can enter the park by boat from the Suwannee River. An overlook at the park provides a view of the spring in its entirety.

Fanning Spring is classified as a first-magnitude spring by FGS based on 8 field measurements reported in Rosenau et al., 1977, and one measurement by Suwannee River Water Management District in 2001. Only four of these measurements were >100 cfs. Graphs of all publicly available discharge rates measured by USGS in the field, as well as continuously, show that Fanning Spring is a second-magnitude spring with an average discharge rate of 70.6 cfs based on continuous flow measurements in the period 2002-2024 (see Fig. 3.1.18).

Manatee Spring, Levy County

Manatee Spring is in Manatee Spring State Park approximately 7 miles west of Chiefland via County Road 320. The spring and its run are on the east side of the Suwannee River within a densely wooded, lowland floodplain.

Manatee Spring discharges into a conical spring pool which measures 60 ft north to south and 75 ft east to west. The depth of the spring pool reaches a maximum of 30 ft. The bottom is mainly sandy with numerous submerged

logs. There is a limestone ledge 3 ft below the water surface. Walkways and a rock wall are built along the south shore of the spring pool where steps lead down into the water for swimming access. The north shore is relatively pristine and wooded.

An extensive underwater cave system, once known as the longest in the world, has been mapped at Manatee Spring. There are four unique entrances to the system, however only two are readily accessible to divers, with a third restricted to divers possessing full cave diver certification. Due to the amount of flow produced by the entrance to the cave, most divers choose to avoid entering the cave system from the headspring. However, enjoyable snorkeling and open water scuba diving activities can be had at the headspring (https://extreme-exposure.com/manatee-springs/).

Manatee Spring is one of the nine individual first-magnitude karst springs in Florida. With an average discharge rate of 153 cfs, it is tied with Blue Spring in Volusia County for the title of the third largest, after Wakulla Spring and Weeki Wachee Spring.

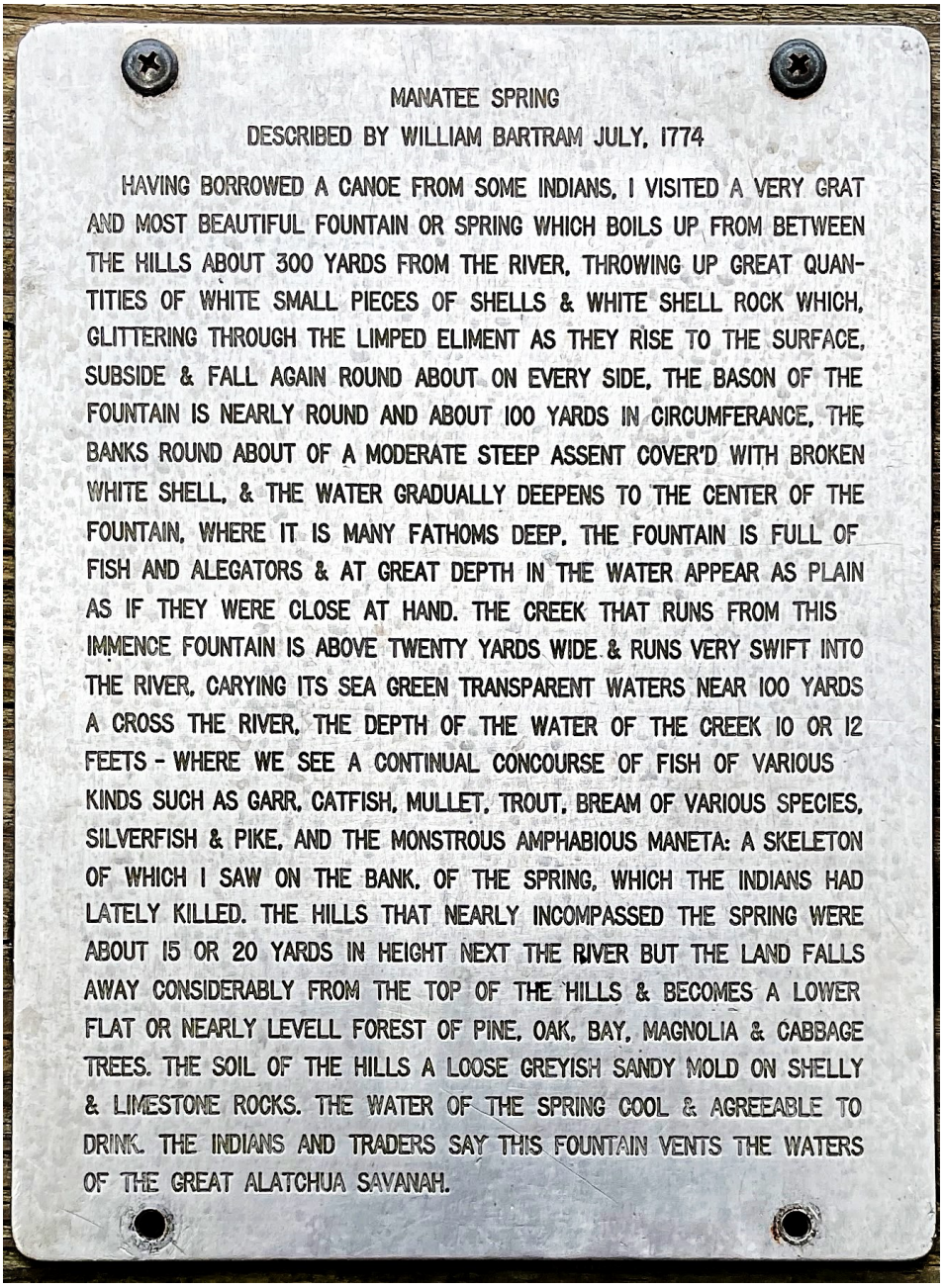


Figure 3.1.51 Manatee Spring, December 2023

In 1954 Manatee Spring became the first spring to become a Florida State Park. Various excavations at the Manatee Spring Park have revealed that the Indian village was densely populated throughout history. Many articles have been found at the village site, such as arrowheads, bone awls, saltwater shells, and pottery. All these things have led historians to speculate that the natives of Manatee Spring State Park used the Suwannee River to travel to the Gulf of Mexico.

William Bartram visited the Manatee Spring in 1774 and gave it its current name after witnessing a manatee carcass on the shores of the spring.

Major General Andrew Jackson carried out an attack near the Manatee Spring during the Seminole Wars. It killed many Seminole Indians and forced the rest of the population out of Florida. The area was thus open to the settlers and the farmers who moved to Manatee Spring to harvest timber and grow cotton.



The park website describes Manatee Springs as "one of Florida's breathtaking first-magnitude springs." It could also be described as one of the most heartbreaking. Severe algal growth has resulted in thick green mats along the surface and algae clinging to anything that will provide a foothold in the pool. Manatee is considered one of the most polluted springs in Florida with typical nitrate levels much higher than the 0.35 milligrams per liter set by the state as a standard for first-magnitude springs that are designated as Outstanding Springs.

Cindy Swirko, The Gainesville Sun, October 30, 2021

Crystal River (Kings Bay) Springs Group, Citrus County

Crystal River (Kings Bay) Springs Group is in the city of Crystal River, on US 19/98 coming from north. Crystal River is approximately 40 miles southwest of Ocala via FL-40E, FL-45 and County Roads 488/495, and 80 miles north of Tampa via FL-589. There are over 70 springs including spring clusters with multiple vents that either issue from exposed limestone at the bottom of the 600-acre Kings Bay embayment or flow into the bay from side creeks. Their combined flow forms the headwaters of Crystal River, which flows approximately 7 miles northwest to the Gulf of Mexico. The average depth in Kings Bay is about 8 feet, but the shallow tidal flats in the southwestern part of the bay are sometimes exposed at low tide.

In the early 1960s, a network of 75-foot-wide canals was dredged along the eastern edge of the bay as part of waterfront residential development. The coastal lowlands with brackish marsh and hardwood-palm hammock lie to the west and the City of Crystal River to the east. The whole system is tidally influenced, and Kings Bay is brackish. Rosenau et al. (1977) referred to the springs discharging to Kings Bay as the Crystal River Springs Group.

As described by the Florida Springs Institute (2016), prior to the 1970s, Kings Bay was a fisherman's and scuba diver's paradise. Eelgrass covered the bottom of the bay like a lawn of unmowed waving grasses. Water clarity was so good that divers and fishermen could see fish, manatees, and other aquatic wildlife hundreds of feet away. The river was originally called *Weewahiiaca* by local Creek Native Americans, which means "clear water".



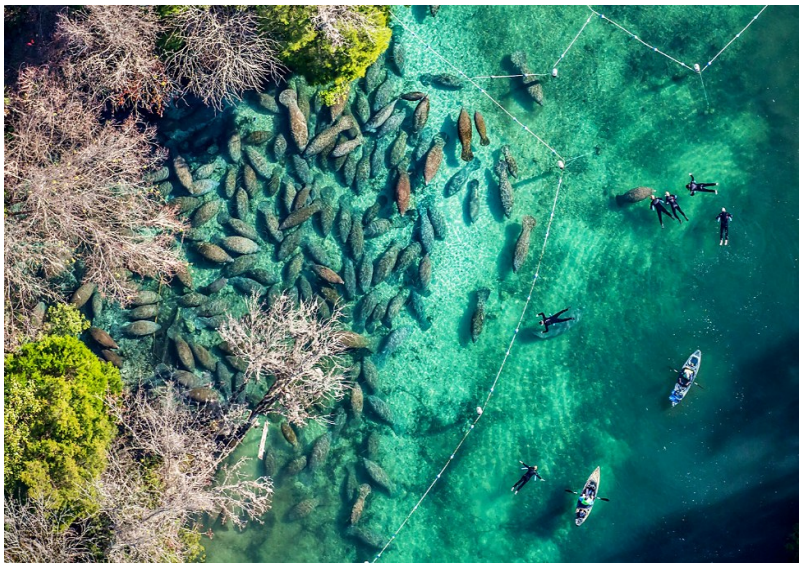
Figure 3.1.52 Map of individual springs in Kings Bay included in the FDEP Geospatial Open Data. Modified and annotated for clarity. An example of a spring description from the database is shown for Sid's Springs. Springs described in this book are highlighted. Basemap with springs available at https://geodata.dep.state.fl.us/

By the 1980s and 1990s, poorly considered plant management measures had freed the bay from hyacinths and hydrilla dominance but had also largely led to the unintentional eradication of the desirable eelgrass. Spring flows continued to decline as the region's population grew, bringing increased reliance on groundwater use for watering manicured landscapes and for farm irrigation. As a result of declining spring flows, combined with elevated nutrients and the loss of much of the native aquatic vegetation in Kings Bay, undesirable planktonic and benthic algae proliferated and there was a marked increase in salinity in the springs and bay. With these physical changes, water clarity in much of Kings Bay declined to less than 20 feet.



Figure 3.1.53 Mother manatee and calf pose for the camera in the clear warm water of Three Sisters Springs. Photo by Gregory Sweeney. Courtesy of U.S. Fish & Wildlife Service.

As explained on an informative web page of River Ventures, in 1893, Florida passed its first law designed to protect the manatee. In 1907 the law was revised to add a $500 and/or six months of jail penalty for molesting or killing a manatee. In 1966, Congress enacted the Endangered Species Preservation Act, the manatee was one of the first species to be added to this act. On March 11, 1967, the United States Fish and Wildlife Service classified the manatee as endangered and in threat of extinction. Details about more legislation that followed to further protect manatees can be found at https://riverventures.com/kings-bay-and-three-sisters.



The peak season for observing manatees in Kings Bay is between December and February when the local manatee population swells to its largest size. Manatee tours occur year-round. Tour companies on Kings Bay in Crystal River operate under Special Use Permits issued by the U.S. Fish and Wildlife Service's Crystal River National Wildlife Refuge.

Figure 3.1.54 Manatee sanctuary at the mouth of Three Sisters Springs run, 2016. Photo by John Moran; all rights reserved. Printed with permission.

At Kings Bay swimming with manatees is only allowed in a restricted area at Tarpon Hole Spring. This is also the only place in Florida where people are allowed to swim with the gentle mammals. Otherwise, manatees can be seen from water by kayaking, stand up paddle-boarding, and boat tours in non-critical areas where it is allowed. All these tours can be arranged through quite a few local tour companies. More details about arranging a manatee tour can be found at https://www.discovercrystalriverfl.com/. Public kayak launches are Hunter Springs Park and Kings Bay Park.

Except for Three Sisters Springs and Hunter Spring, all other springs in Kings Bay can be accessed only by water as the land along shores is privately owned.

Three Sisters Springs, a unit of the Crystal River National Wildlife Refuge (CRNWR), is the gem of Florida's Nature Coast and one of the most beautiful springs in Florida. Its water is always mesmerizingly clear. A restored 50+ acres surrounding the springs attempt to show visitors how Florida's nature may have looked like before the newcomers from the Old World messed it all up.

The Three Sisters Springs Center (https://www.threesistersspringsvisitor.org/sisters) manages land access to Three Sisters Springs by shuttle service, walk-in, or bicycle-in which all require a fee. There is no parking at the refuge except for handicapped vehicles.

To preserve the shoreline vegetation, control erosion, and maintain water clarity, CRNWR and the City of Crystal River do not allow water access to visitors from the refuge, nor do they allow land access from the water. Visitors must arrive by paddle craft or motorized vessel to get to the spring run at Three Sisters Springs; however, motorized vessels are not permitted inside the Springs. Paddle-craft are permitted from April 1 to November 14.

The boardwalk has viewing platforms to observe the springs and native wildlife. There are also nature trails that offer views of Magnolia Springs, Lake Crystal, and the wetlands. Three Sisters Springs is a world-renowned winter sanctuary for the West Indian Manatee. Cold winter days bring 100's of them seeking warm water refuge into the springs. For the safety and protection of the manatees, in-water access to Three Sisters Springs can be closed by US Fish & Wildlife Service when water temperatures in the Gulf of Mexico drop below 62.2 degrees Fahrenheit. Updates on temporary closures can be checked on Crystal River NWR Facebook page.



https://firstmagflorida.com/2019/10/05/crystal-river-kings-bay

Figure 3.1.55 Three Sisters Springs. Photo by Frank Moore. In the upper right is Little Sister, in the middle is Deep Sister, and in the lower left (the widest separate pool) is Pretty Sister. The spring run flows to the southwest ("up" in the photo) where it empties into a dredged canal with the stagnant Kings Bay water. At the spring run mouth, another favorite sanctuary for manatees, are three springs with equally clear water (named, for an unknown reason, Idiots Delight #1, #2, and #3,) which add to the unforgettable experience.



Figure 3.1.56 Three Sisters Springs. Photo courtesy of River Ventures, Crystal River, Florida.

https://riverventures.com/kings-bay-and-three-sisters

Tarpon Hole Spring, also known as King's Spring, is the largest spring in the group of springs with the same name. It issues from a deep, conical depression in limestone on the south side of Banana Island. The spring pool measures approximately 450 ft north to south and 550 ft east to west. The depth measured over the vent, which is a large circular hole in limestone, was reported to be 58 ft (Scott et al., 2004). However, more recent information from divers is that the depth is not more than 25-30 feet, and the hole is apparently "gone". In calm weather and during off-manatee season there is visible boil of water above the spring, and water is relatively clear and bluish except for high tide conditions.

Tarpon Hole Spring is a very popular dive site and can get very crowded, which at times significantly reduces visibility. During winter, when hundreds of manatees come to this sanctuary, tour boats bring dozens upon dozens of snorkeling tourists to a designated area to "swim with manatees". During such times, the visibility decreases to just a few feet, especially on weekends and holidays. Since this is the only place in the whole country where people are allowed to swim with manatees in the wild, most visitors do not mind. All are, however, rewarded with many close and sudden encounters with these beautiful, strange and gentle creatures, appearing sometimes from nowhere. A lucky snorkeler or two in a group may even get a kiss from a manatee and instantly fall in love for life.



Figure 3.1.57 In peak season, on weekends and holidays sometimes a dozen or so tour boats bring many snorkelers to "swim with manatees" in a small, restricted area at Tarpon Hole Spring. December 2023.

Hunter Spring issues vertically from the bottom of a conical depression in the middle of a side creek channel feeding the eastside of Kings Bay (see map in Fig. 3.1.52). The spring pool is circular and measures 210 ft in diameter. The depth measured over the vent, which is some 100 ft offshore, is 13 ft.



Hunter Spring is in Hunter Spring Park managed by the city of Crystal River. The park offers a small beach area leading to a roped-off swimming area, kayak/canoe launch, a boardwalk along the waterway, where one is likely to spot waterbirds, a playground area, and other amenities.

Figure 3.1.58 Hunter Spring State Park in the city of Crystal River. The beach and swimming area are in the middle, marked by light green-blue color. Photo courtesy of the city of Cristal River.

The combined flow rate of all springs discharging into brackish Kings Bay and any other groundwater inflow from the Floridan Aquifer along a 3-mile section of the river downstream of the bay is measured at a USGS gaging station on Crystal River.



Figure 3.1.59 USGS streamflow gaging station on Crystal River is shown with red arrow. From https://waterdata.usgs.gov/nwis/

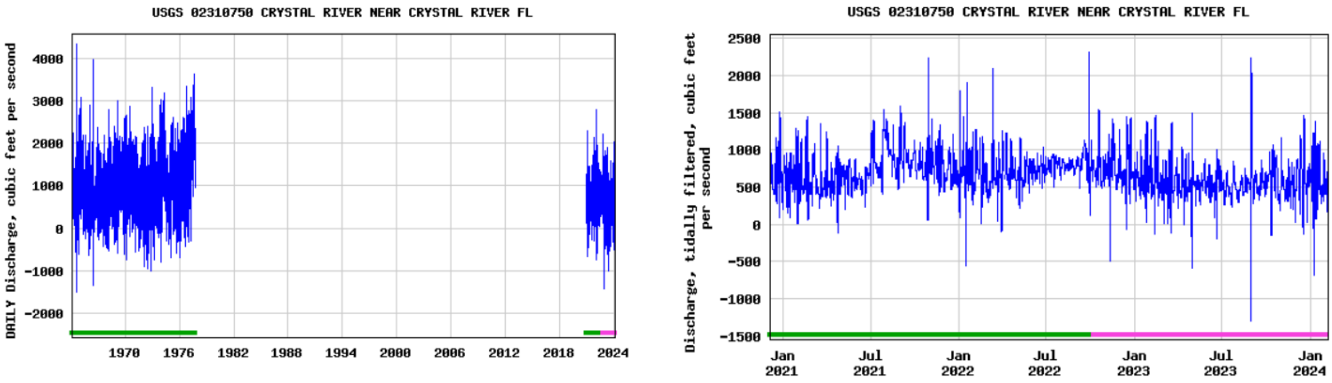


Figure 3.1.60 Hydrographs of flow rate of the Crystal River measured by USGS. *Left*: Entire period of record. Average for 1964-1977 is 971 cfs. *Right*: Tidally filtered average flow for period January 2020-January 2024 is 672 cfs.

Weeki Wachee Spring, Hernando County

Weeki Wachee Spring is in Weeki Wachee Springs State Park located at the intersection of State Road 50 and US-19, 22.6 miles south of Homosassa Springs via US-19, and 50 miles north of Tampa via FL-589N. Weeki Wachee Springs was designated a National Historic Landmark in 2020.

When it comes to Florida springs, Weeki Wachee is in a league of its own. Its water is still crystal-clear, and the flow of the spring is strong, gifting hundreds of thousands of visitors an amazing array of blue and green colors each year. Weeki Wachee is one of Florida's most legendary and unique family destinations, with exceptionally diverse offerings to entertain audiences of all ages since 1947. The Park is open 365 days a year and during the busy summer months, it often reaches capacity. It is highly recommended to plan a visit early in the day because once the park is full, it does not allow further entry for the remainder of the day. Various Park facts and rules can be found at https://weekiwachee.com/park-rules-faqs/.

"Weeki Wachee" was named by the Seminole Indians. It means "little spring" or "winding river." The main spring is headspring of the Weeki Wachee River which flows 7.4 miles to where it meets the Gulf of Mexico at Bayport in Hernando County, Florida.



Figure 3.1.61 *Left*: Paddling down Weeki Wachee River. Photo courtesy of Weeki Wachee State Park *Right*: 2021 Sirens of the Deep Camp; Friends of Weeki Wachee, https://friendsofweekiwachee.com/gallery/



Figure 3.1.62 Water slides at Weeki Wachee's Buccaneer Bay. Photo courtesy of Weeki Wachee State Park.



The Little Mermaid

We invite you to come see our world-famous Mermaids as they perform their version of Hans Christian Andersen's The Little Mermaid live in our submerged 400-seat auditorium.

You will enjoy this classic told unlike any other as The Little Mermaid celebrates her birthday and comes face to face with her prince!

Yearning to have legs like him, she makes a deal with the sea witch to give her what she wants in exchange for her beautiful voice.

As the prince struggles to save the Little Mermaid's beautiful voice, a fierce battle ensues between him and the evil sea witch. The prince prevails, proving that "love conquers all."

Figure 3.1.63 The Little Mermaid show advertised at Weeki Wachee Spring for 2023 and 2024 seasons. https://www.floridastateparks.org/parks-and-trails/weeki-wachee-springs-state-park/mermaid-shows

In the 1950s, Weeki Wachee was one of the nation's most popular tourist stops. The attraction received worldwide acclaim. Movies were filmed at the spring, like Mr. Peabody and the Mermaid. Sights at the park included the mermaid shows, orchid gardens, jungle cruises, Indian encampment and a new beach. The mermaids took etiquette and ballet lessons.



Weeki Wachee's heyday began in 1959, when the spring was purchased by the American Broadcasting Co. (ABC) and was heavily promoted. ABC built the current theater (Figure 3.109), which seats 400 and is embedded in the side of the spring 16 feet below the surface. ABC also developed themes for the underwater shows, such as "Underwater Circus", "The Mermaids and the Pirates" and "Underwater Follies."

Figure 3.1.64 Underwater theater at Weeki Wachee Spring. Courtesy of Weeki Wachee State Park. https://weekiwachee.com/history/

As posted on the Park's website "*The spring is so deep that the bottom has never been found. Each day, more than 117 million gallons of clear, fresh 74-degree water bubbles up out of subterranean caverns. Deep in the spring, the surge of the current is so strong that it can knock a scuba diver's mask off. The basin of the spring is 100 feet wide with limestone sides and there, where the mermaids swim, 16 to 20 feet below the surface, the current runs a strong five miles an hour. It's quite a feat for a mermaid to stay in one place in such a current.*"

With a little update, the average flow of the headspring was 172.5 cfs (111.5 million gallons per day) until 2010 when USGS stopped measuring it. The depth of the vast submerged cave system of Weeki Wachee Spring is 429 feet as of February 2024 (https://karstunderwater.org/weeki-wachee/) making it the deepest underwater cave in Florida and the third deepest in the country, after Roaring River Spring in Missouri (>520 ft); and Phantom Spring Cave in Texas (493 ft).



Figure 3.1.65 Submerged passages of Weeki Wachee are being explored by divers of Karst Underwater Research. Photo by Andy Pitkin, courtesy of Karst Underwater Research, https://karstunderwater.org/weeki-wachee/

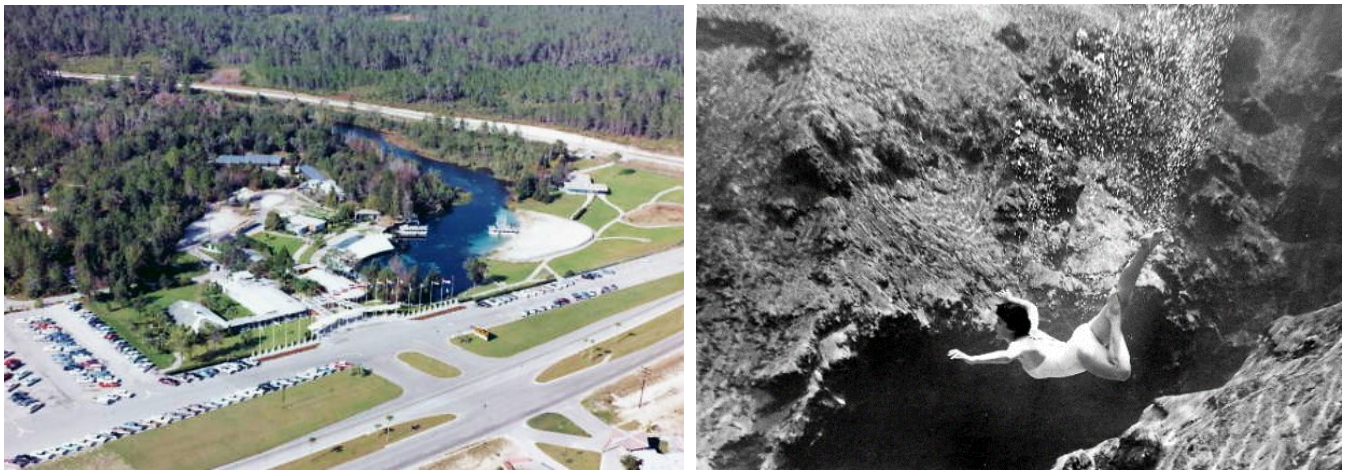


Figure 3.1.66 *Left*: Aerial view overlooking the Weeki Wachee Springs amusement park - Hernando County, Florida, 1965. *Right*: Swimming at Weeki Wachee Spring. Photo by Walton Hall Smith. Historic photographs courtesy of State Archives of Florida, Florida Memory.

Alexander Spring, Lake County

Alexander Spring is in Alexander Springs Recreation Area within Ocala National Forest, in the northeast corner of Lake County between Astor and Altoona, Florida. The Area is 44 miles east of Ocala via FL-40E and County Road 445.

Alexander Spring is a first-magnitude spring that flows from the large, cavernous opening in the bottom of the central part of the pool. The large pool measures more than 300 feet from north to south and 250 feet from east to west. The pool bottom near the beach is mostly sandy, and the water is constantly 72 degrees and extraordinarily clear. Aquatic vegetation surrounds the area of the main spring vent, where the pool bottom falls away to reveal a large open area of exposed limestone rock and boulders to a depth of about 25 to 28 feet.

Flow from the discharging water creates a large and powerful boil over the spring opening that is readily visible from the shore. The average discharge rate is 105.2 cfs for the period of record. A broad sand beach forms the southwest edge of the pool, with mixed hardwood and palm forests around the spring. The pool discharges to Alexander Springs Creek that flows approximately 10 river miles until it reaches the St. Johns River.



Figure 3.1.67 *Left*: Aerial view of Alexander Spring. Photo by Harley Means; from FGS Bulletin No. 66. *Right*: Alexander Spring. Photo by John Moran; all right reserved. Printed with permission.

The spring area has been developed by the USDA Forest Service into a multiple-use recreational facility open to the public. Visitors can swim, snorkel and dive year-round in the crystalline waters of the spring. The spring is the only place in the Ocala National Forest where scuba diving is permitted, and a broad and naturally gently sloped spring pool feels like a natural water park.

Silver Glen Spring, Marion County

Silver Glen Spring is part of the USDA Forest Service's Silver Glen Springs Recreation Area within Ocala National Forest. It is located 47 miles east of Ocala via FL-40E and FL-19N 445.

This second magnitude spring (average discharge rate is 89.3 cfs for the entire period of record, 1930-2026, and 83.1 cfs for the last 20 years) has an outstanding water quality and clarity. It discharges to a large, semicircular pool that measures 200 feet from north to south and 175 feet from east to west. Most of the strong flow emerges from two cavern openings in the rock at the bottom of the pool, with large boils at the water's surface over the

vents. The vertical cave opening called the Natural Well in the southwestern edge of the pool is about 12 to 15 feet in diameter and 40 feet deep. The vent in the east part of the pool is a conical depression about 18 feet deep. Most of the spring pool has sand and limestone on the pool bottom, with areas of aquatic grasses. Large fresh and saltwater fish are common in the pool and around the vents. Additional flow is from sand boils in the bottom of the spring run downstream from the head of the springs. Water from the springs flows eastward down a run about 200 feet wide for 0.75 miles to Lake George. The water temperature is constat 73 degrees Fahrenheit year-round.

The recreation area is used for swimming, snorkeling, picnicking, fishing, and boating. Boating is not allowed in the spring pool, but the spring run is a popular spot for recreational boaters. Canoe rentals are available onsite. Diving and scuba diving are not allowed, but snorkeling is permitted. The park features two trails, the Spring Boils Trail, and the Lake George Trail, and is an important archeological site.



Figure 3.1.68 Silver Glen Spring. Photo by John Moran; all rights reserved. Printed with permission.



Figure 3.1.69 Silver Glenn Spring. Photo courtesy of SJRWMD.

According to the USDA website the spring is designated as critical habitat for the manatee, and the spring and run have the potential to serve as a major manatee refuge. However, manatee use has been limited due to a high degree of human activity and damage to aquatic vegetation.

Volusia Blue Spring, Volusia County

Volusia Blue Spring is 6 miles southwest of Deland in Blue Springs State Park, via US-17/92 (FL-15S) and County Road 4142 (W. French Avenue).

The spring is at the head of Blue Spring Run about 0.25 miles north of the parking area and is accessed by an elevated wooden boardwalk along the east bank of the spring run. It discharges into a circular spring pool in a conical depression with a notable boil in the center. The spring pool measures 135 ft north to south and 105 ft east to west. The depth of the spring measured over the vent is 20 ft. The bottom of the spring is limestone and sand. The spring vent is an elongated opening in the limestone about 15 feet from the north edge of the pool. From the limestone ledge, the vent slopes precipitously to about 40 feet in depth.

The spring run has steep sandy banks and flows south and west approximately 1,050 ft to the St. Johns River through dense hardwood and palm forest. The run varies from 70 feet to 100 feet in width and is bounded by steep wooded slopes except for the lower southeast bank, where the terrain flattens considerably. The flow of the spring is retarded by backwater during high stages of the St. Johns River. The average discharge rate for the entire period of record, 1932-2026, is 154.3 cfs, and for the last 20 years it is 146.9 cfs.



Figure 3.1.70 Aerial view of Volusia Blue Spring. Photo by Frank Moore; available at https://firstmagflorida.com/2022/05/08/blue-spring/

Blue Spring State Park is owned and operated by the state of Florida and provides a wide range of recreational activities, including swimming, diving, canoeing, fishing, hiking, and camping. Full facilities are available (see https://www.floridastateparks.org/parks-and-trails/blue-spring-state-park).

Blue Spring is a designated manatee refuge and the winter home to a growing population of West Indian Manatees. During manatee season, which runs approximately from mid-November through March, hundreds of manatees can be viewed atop the spring's overlooks on cold days. The spring and spring run are closed to all water activity from mid-November to at least mid-March. Swimming or diving with manatees is not permitted; this rule is strictly enforced.



Figure 3.1.71 Manatees in Blue Spring, 2019. Photo by John Moran; all rights reserved. Printed with permission. See also https://floridasprings.org/outstanding-florida-springs-volusia-blue-spring/

Wekiwa Spring, Orange County

Wekiwa Spring is part of Wekiwa Springs State Park, approximately 9.7 miles northeast of the town of Apopka via East Welch Road and Wekiwa Road.

Wekiwa Spring is a second-magnitude spring in a semitropical forest setting at the base of a northeast-sloping, grassy, open-wooded hillside. The average discharge rate for the entire period of record, 1932-2010, is 67.7 cfs.

Two areas of discharge can be observed as surface boils near the edge in the southeast half of the spring. The strongest boil is over a large, irregularly shaped vent, about 35 feet long by 5 feet wide, located in the limestone bottom about 15 feet below the surface. The other boil is above a rock ledge in the extreme southeast edge of the pool.. The spring pool is kidney-shaped, about 200 feet long and 100 feet wide, elongated southeast. A 2- to 3-foot-high retaining wall encloses the pool and extends a short distance down the run. The clear, bluish-green water forms the headwater of the Wekiva River, which flows northeast through state land approximately 17 miles into the St. Johns River.



Figure 3.1.72 Wekiwa Spring. Photographs courtesy of Wekiwa Springs State Park.

Rock Springs, Orange County

Rock Springs is in Dr. Howard A. Kelly County Park next to Rock Springs Run State Preserve, approximately 6 miles northeast of Apopka, via FL-435 and E. Kelly Park Road. In contrast to most large springs in peninsular Florida, Rock Springs has no well-defined large pool at the spring head—it emerges from a horizontal cave at the base of a 20 ft high vertical limestone and sand bluff. The cavern opening is about 5 feet in diameter at its mouth and tapers horizontally inward to a throat about 3 feet in diameter. Clear, blue water discharges with considerable turbulence that cuts into the limestone, eroding sand and fossil shells into the bottom of the 15- to 20-foot-wide spring run. Rock ledges jut out from the banks of the run for about 100 feet below the cavern opening. About 10 feet downstream from the cavern opening, additional water is discharged through a submerged opening in the channel bottom.

Average discharge rate for the entire period of record, 1931-2010, is 58.3 cfs. USGS stopped monitoring the spring in 2010.

For a few hundred feet, the stream bottom has sand and marine fossil shells that eroded out of the limestone. There is no vegetation and only minor algal growth. Lush ferns and moss blanket the bluff and upper stream banks. The upper part of the run averages 15 – 20 ft wide and 5 ft deep. The cave and immediate vicinity are closed to use, but the rest of the run serves as swimming, snorkeling, and tubing hotspot.



A boardwalk crosses over the run about 120 feet downstream. Several hundred feet below the spring, some of the flow is diverted left from the spring run to a large swimming area mostly bounded by concrete retaining walls.

Figure 3.1.73 Rock Springs. Photo courtesy of SJRWMD.



Rock Springs Run is an 8.6-mile river which forms the boundary between Wekiwa Springs State Park and Rock Springs Run State Reserve. After 8 miles, Rock Springs Run eventually flows into the Wekiva River, which then runs 15 miles and empties into the St. Johns River.

Figure 3.1.74 Swimming area at Rock Springs. Photo courtesy of SJRWMD.

Jackson Blue Spring, Jackson County

Jackson Blue Spring is in Florida Panhandle, approximately five miles east of Marianna via US-90, FL-71, and Blue Springs Road. The headspring and six smaller springs supply water to a 202-acre artificial reservoir known as Merritt's Millpond, a nationally known fishing site. More than forty years ago, the Federal Government owned the Blue Springs site and operated an officer's club for members of Graham Air Force Base.



Figure 3.1.75 Jackson Blue Spring, 2015. Photo by John Moran; all rights reserved. Printed with permission.

Jackson Blue Spring is the main spring at the head of the pond. Its vent is situated about 10 ft west of the diving platform. The spring pool diameter is approximately 240 ft southwest to northeast and 233 ft northwest to southeast. Maximum depth over the vent is 16.5 ft. The vent is elliptical and approximately 5 ft high and 25 feet wide. Limestone is exposed near the vent, and it bears backhoe scars. Clear bluish water issues from the vent. A boil is slightly visible at the surface. An extensive underwater cave system has been mapped at the Spring.



The average discharge rate for the entire period of record, 2003-2011, is 130.1 cfs. USGS stopped monitoring the spring in 2011.

The spring pool is a designated swimming area separated from the rest of Merritts Mill Pond by a chain link fence across the channel approximately 300 ft downstream. Surrounding the spring, are concrete retaining wall near shore, slides, a diving board, and picnic tables.

Figure 3.1.76 Jackson Blue Spring; spring vent below diving platform. Photo by Harley Means, FGS, 2001.

Gainer Spring Group, Bay County

Gainer Spring Group is the largest spring group contributing water to Econfina Creek in Washington and Bay Counties where much of the inflow is derived from groundwater discharge due to the karst nature of the geology in the region. In this area, the creek is incised into the Floridan aquifer, resulting in the formation of numerous springs along the creek. Barrios and Chelette (2004) identified 11 springs or spring groups with more than 36 individual vents within the middle portion of Econfina Creek. The Gainer Spring Group is located just south of SR 20 as well as the Bay-Washington County line (Figs. 3.1.77 and 3.1.78). It comprises two primary spring runs as well as Emerald Spring, which is the largest of 15 vents within the spring group. Willford and Sylvan Spring Groups are of second magnitude. (Northwest Florida Water Management District (NWFWMD), 2025).

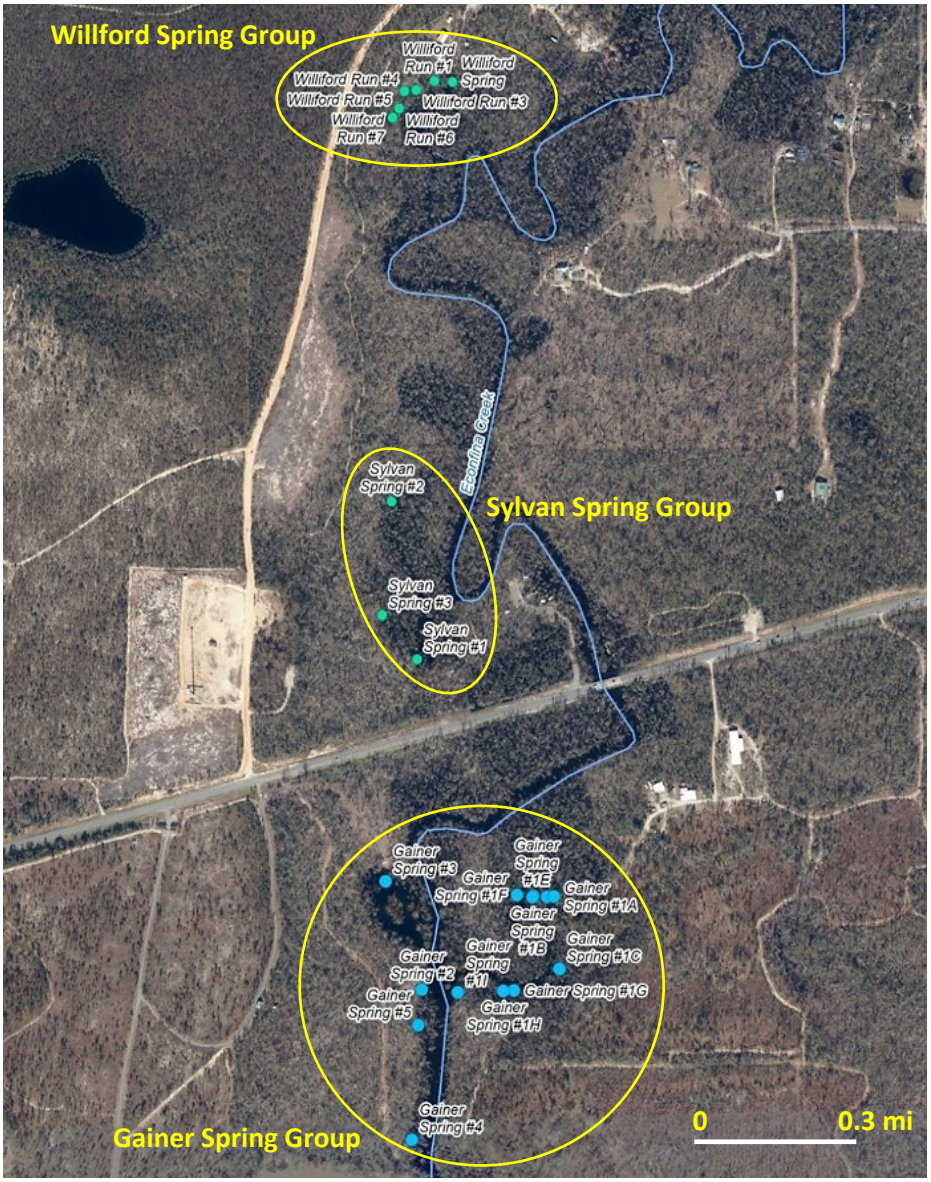


Figure 3.1.77 Locations of Gainer Spring, Williford Spring, and Sylvan Spring Groups along Econfina Creek. These three spring groups collectively comprise approximately 42% of total flow to Econfina Creek as measured at USGS Station 2359500 Econfina Creek Near Bennett, FL. From NWFWMD, 2025 (some annotation added).

The Gainer Springs #1 run is located on the east side of Econfina Creek, entering the creek across from Gainer Spring #2 (Emerald Spring). The Gainer Springs #1 run consists of eight individual spring vents located within 0.29 miles from the confluence of Econfina Creek. Spring vents located along the Gainer Springs #1 run vary from small vents with no noticeable boil to larger vents up to 25 feet across with noticeable surface boils. The largest

vent along the Gainer Springs #1 run is Gainer Spring #1C, known locally as McCormick Spring, located approximately 0.17 miles up the shallow spring run. This sizable, sandy vent is imbedded in the bottom of a pool approximately 25 feet wide and there is a continual plume of sediment moving in the pool. Maximum depth measured in the vent is 11.5 feet.

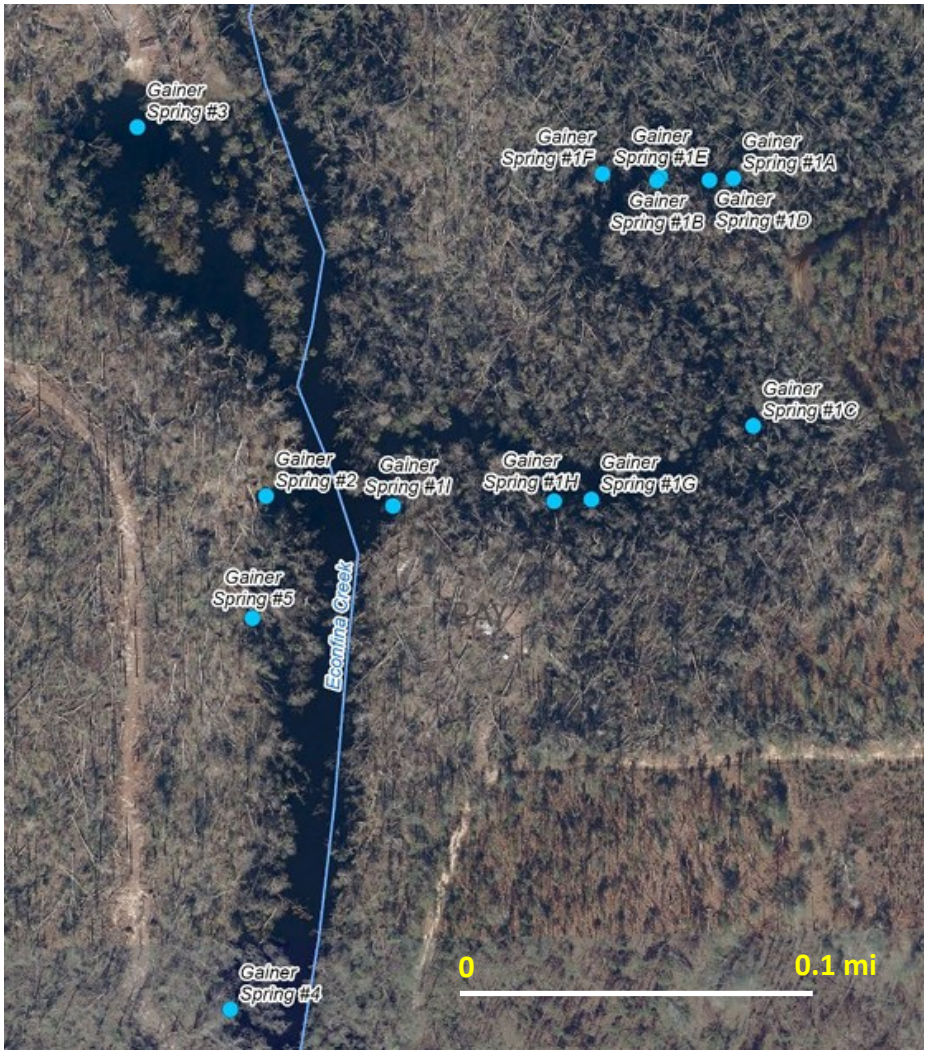


Figure 3.1.78 Individual springs (vents) of the Gainer Spring Group. Emerald Spring, the largest vent in the group, is known officially as Gainer Spring #2. From NWFWMD, 2025 (some annotation added).

The largest vent within the Gainer Spring Group, known as Emerald Spring locally and as Gainer Spring #2 officially, is a crevice at the base of a 25-foot limestone bluff on the west side of the creek (Fig. 3.1.79). The cove is approximately 30 feet in diameter with a maximum depth of approximately 12 feet. There is a strong continuous boil at this vent and a crevice in the limestone bluff to the north of the main vent which also discharges groundwater.

Gainer Spring #3 is located along a relatively wide spring run on the west side of the creek just above Gainer Spring #2 and the Gainer Spring #1 run (Fig. 3.1.79). The run turns north and parallels the creek for 400 feet. The spring pool is located at the head of the spring run, approximately 250 feet in diameter with a small, man-made beach to the north and a small island in the center. There are several vents opening in the bottom, near the edges of the pool. The maximum depth measured in one of the vents is 11 feet. The vent is on private land, and the spring is used for recreation.

The springs in the middle reach of Econfina Creek contribute approximately 300 million gallons of water a day to the Deer Point Lake Reservoir that is Bay County's primary water supply. The reservoir provides water for more than 90 percent of the population of Bay County, including the residents of Panama City, Panama City Beach and neighboring communities. Overflow from the reservoir provides critical fresh water to St. Andrews Bay. In part to ensure protection of the water quality and quantity flowing into the reservoir, the District has purchased more than

42,000 acres of the primary recharge area of the Econfina Creek springs. This land, including the surrounding springs in the middle reach of Econfina Creek, is publicly accessible and has high recreational value.

As discussed by NWFWMD (2025), the observed increase in the Gainer Spring Group discharge is likely due to increased precipitation, with several drought periods occurring toward the beginning of discharge record analyzed in the 2000s, and several years of above-average rainfall occurring from 2013-2022. Increases in Gainer Spring Group discharge are consistent with trends for Econfina Creek stream flow and baseflow, as well as groundwater levels in the vicinity. A significant data gap exists prior to 2002 when flow measurements were collected inconsistently by entities other than the NWFWMD.



Figure 3.1.79 *Left*: Emerald Spring, the largest spring in the Gainer Spring Group. *Right*: Gainer Spring #3. From NWFWMD, 2025.

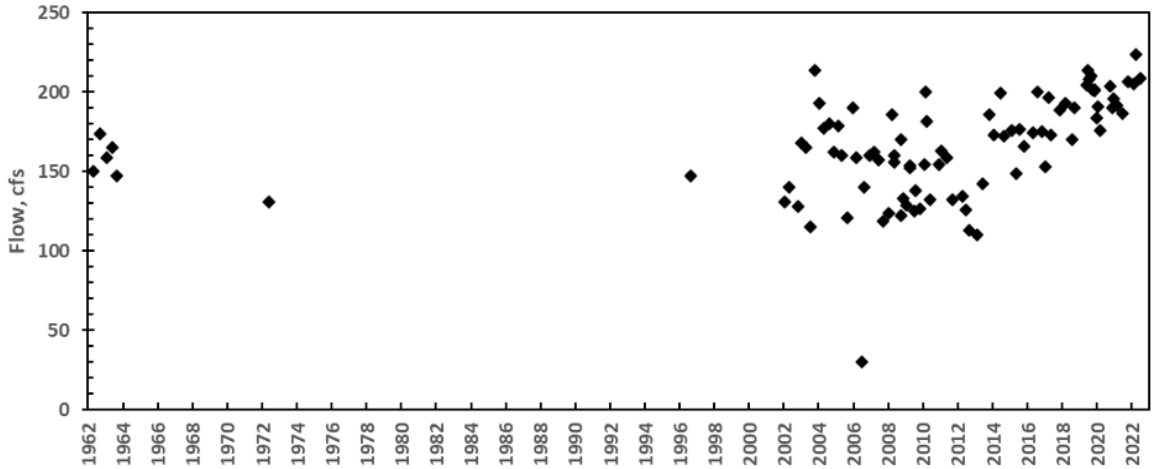


Figure 3.1.79 Gainer Spring Group composite discharge rates. The average is 165 cubic feet per second (cfs). From NWFWMD, 2025.

Gainer Springs is one of only five Outstanding Florida Springs (OFS) which is considered not to be impaired (see Table 3.1.2), where impairment is defined as an excessive concentration of nutrients, primarily nitrates/nitrogen which triggers thick algal blooms and chokes out native eelgrass.

The impairment status of more than 1,000 remaining Florida springs is unknown.

Importantly, for all OFS, regardless of the nitrogen and nitrate concentrations, Water Management Districts must establish Minimum Flows and Minimum Water Levels (MFLs) to guarantee that groundwater withdrawals do not physically deplete the springs.

The excerpts below are from the web page of Florida Springs Council, illustrating an ongoing fight to try and save Florida springs, despite the inactions and the resistance from Florida Government Agencies and current Legislators (https://www.floridaspringscouncil.org/springsharmrule).

On Jan. 16, 2025, the Florida Springs Council (FSC) filed an administrative petition to invalidate the Florida Department of Environmental Protection's (FDEP) proposed "Springs Harm Rule," continuing the organization's commitment to ensure FDEP follows the law.

This is the next step in a multi-year effort to hold FDEP accountable to safeguard Florida's springs from harmful water withdrawals.

FDEP's proposed Springs Harm Rule is circular, vague, and essentially the same as the consumptive use permitting rules already in place. After eight years of delay and inaction, to propose essentially the same permitting rules in 2025 that have been in effect since 2014 is an insult to the people of Florida and the Legislators who worked for years to put this provision in law.

Outcome at the Division of Administrative Hearings

The Administrative Law Judge sided with FDEP, finding that the proposed rules:

- *did not need to be more protective than existing water use permitting rules*
- *did not need to comply with the requirements of the Florida Springs and Aquifer Protection Act*
- *did not need to prevent harm to Outstanding Florida Springs.*

On Aug. 13, 2025, FSC filed an appeal with the 1st District Court of Appeals to overturn the decision made by the Administrative Law Judge in our legal challenge against FDEP's water use permitting rules proposed for Outstanding Florida Springs.

FDEP's Rules are an unlawful end-run around the Legislature's mandate in section 373.219(3), Florida Statutes, that FDEP adopt rules that prevent groundwater withdrawals from harming Outstanding Florida Springs. The new Outstanding Florida Springs permitting standard in 373.219(3), Florida Statutes, required FDEP to adopt new CUP rules that prevent harm specific to Outstanding Florida Springs. FDEP instead re-adopted existing rule language already applicable to all water bodies generally. As a matter of law, this Court should reverse the ALJ's ruling upholding the Rules because: (1) the ALJ misinterpreted Supreme Court precedent that a judge need not make a threshold determination of statutory ambiguity before turning to available tools of statutory construction; and (2) the ALJ misinterpreted the statute's plain language.

For over a decade, water management districts have continued to issue permits that cause harm to our water resources, and spring flow has continued to decline. Florida's springs have suffered immensely.

The springs we cherish cannot survive another decade with meaningless rules in place that will not put an end to overpumping. From ineffective plans to clean up polluted springs to frivolous water use permitting rules, FDEP is failing our springs, rivers and aquifer. FDEP has a mandate to put politics aside, focus on the health of our springs, and adopt valid rules that will actually prevent harm to Outstanding Florida Springs.

3.2 Georgia

3.2.1 Floridan Aquifer Springs

In Georgia and Florida, the Coastal Plain deposits (deposits south of the Fall Line) are grouped into two principal facies by the USGS (Williams and Kuniansky, 2016): (1) predominantly warm, shallow marine, platform carbonate rocks that have been deposited in a thick continuous sequence beneath southeastern Georgia and the Florida peninsula; and (2) predominantly nearshore clastic rocks that have been deposited along the Coastal Plain extending from the Fall Line southward and eastward toward the Gulf of Mexico and the Atlantic Ocean.

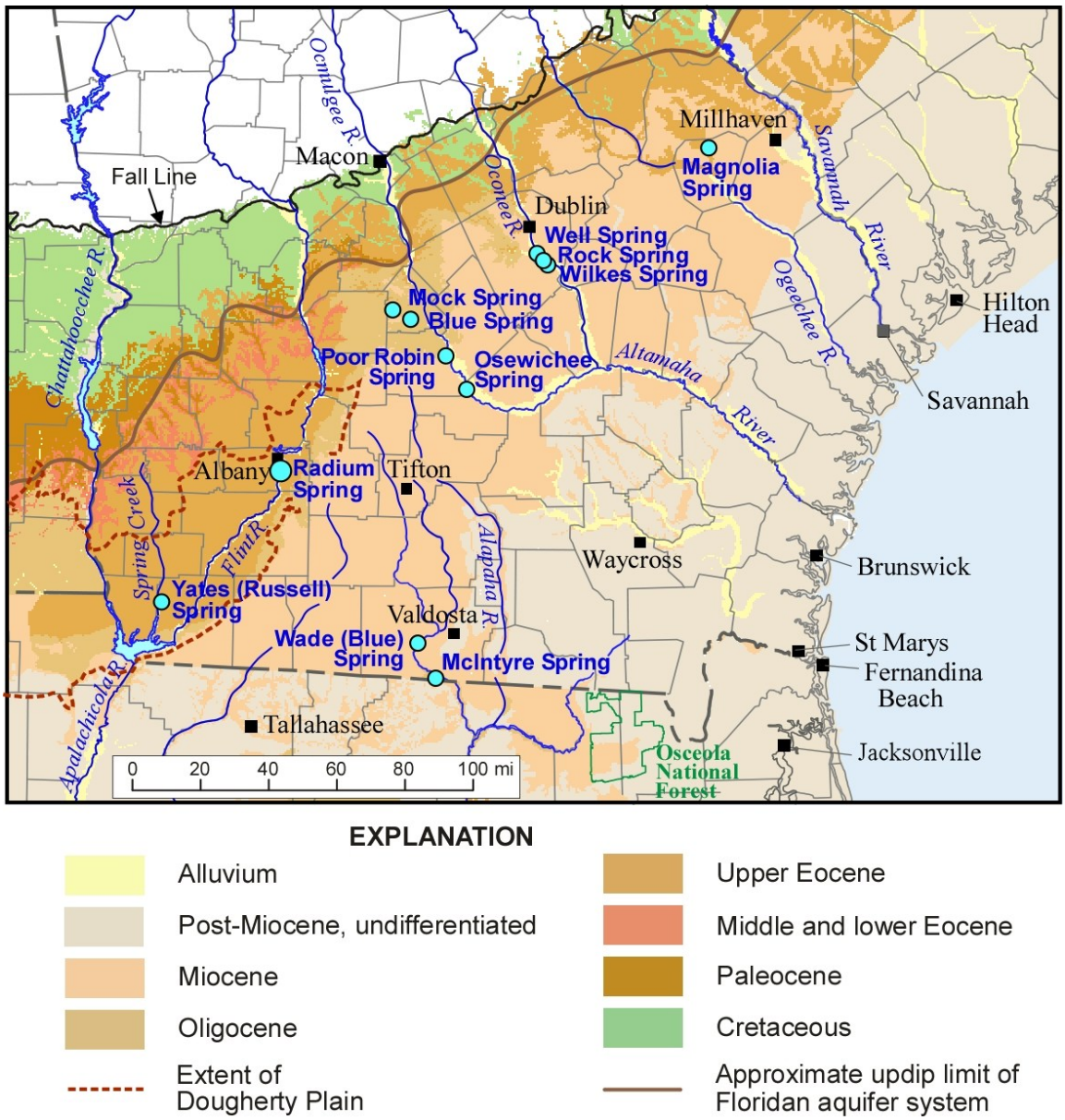


Figure 3.2.1 Springs of the Upper Floridan Aquifer in Georgia. Main geologic units of the Upper Floridan Aquifer are Ocala and Suwanee Limestones of the Upper Eocene. Geology from Williams and Kuniansky, 2016.

These two major facies are respectively divided into the mostly carbonate Floridan aquifer system and the underlying, mostly clastic Southeastern Coastal Plain aquifer system. In Georgia and parts of northern Florida, the carbonate and clastic facies form a gradational sequence, generally characterized by limestone of successively younger units that extend progressively farther updip. Miocene and younger sediments of mostly clastic origin overlie the older carbonate rocks in most areas, except where the clastic sediments have been removed by erosion or were never deposited. In the part of the system farthest updip (in central Georgia, generally south of Macon) it is difficult to distinguish the aquifers as separate units and they may behave as a single hydrogeologic unit (Williams and Kuniansky, 2016).

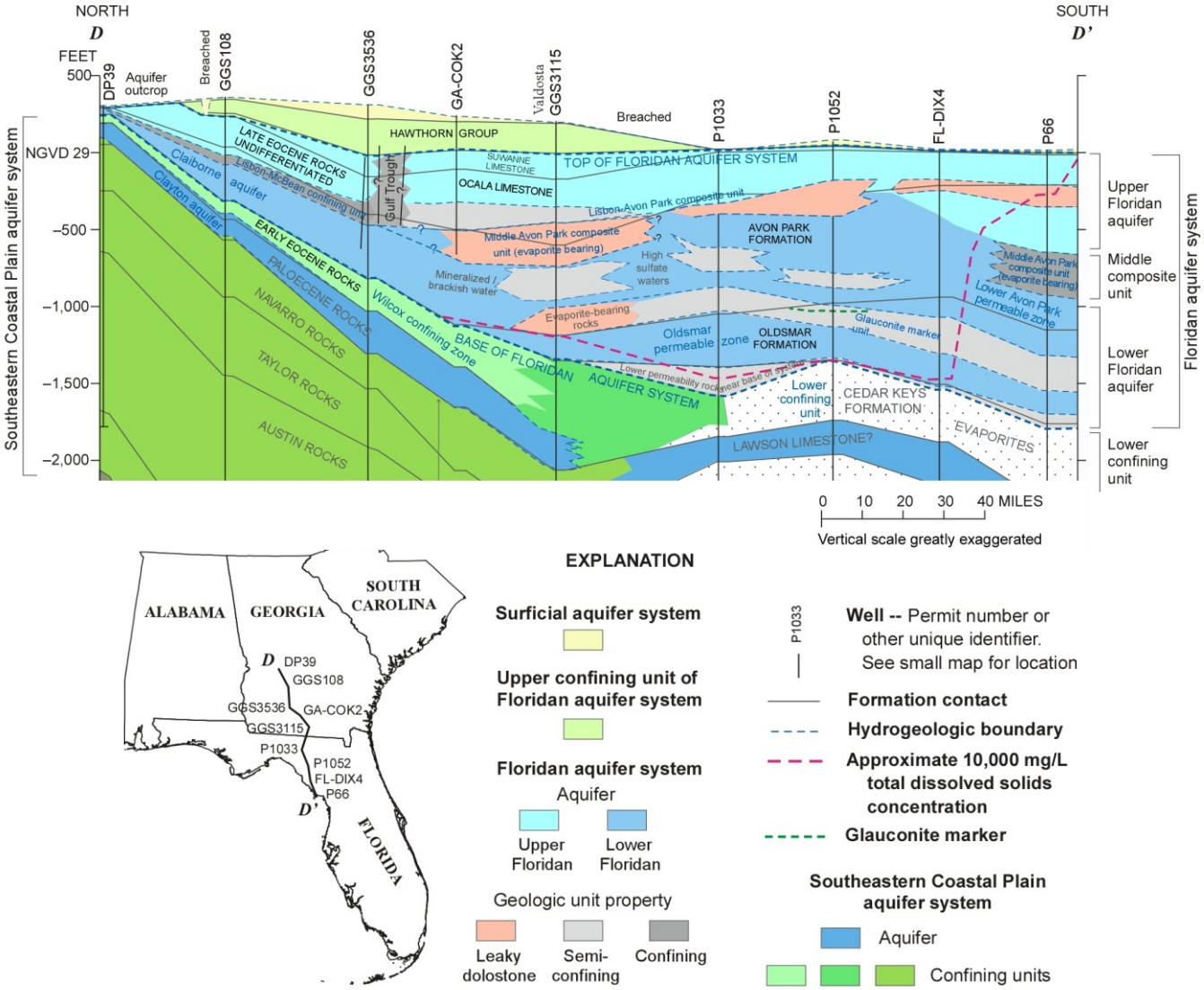


Figure 3.2.2 Hydrogeologic cross section of the Floridan Aquifer System from its outcrop area in west-central Georgia to the Gulf Coast near Tampa, Florida. Modified from Williams and Kuniansky, 2016.

In the northernmost, updip extent of the Floridan Aquifer System, in central Georgia, the Upper Floridan aquifer outcrops. Here, the aquifer is recharged by (1) infiltration through a residuum unit, (2) leakage along losing stream segments, or (3) complete capture of streams into the aquifer system. In and near Albany, the Upper Floridan aquifer consists of highly permeable Miocene to late Eocene carbonate rocks. In this area, and farther north toward

the outcrop area, clastic rocks of the Claiborne aquifer are hydraulically connected to the Upper Floridan aquifer. In this updip location, downward hydraulic head gradients from the Upper Floridan aquifer allow for leakage to the underlying Claiborne aquifer though the Lisbon-McBean confining unit (also known as the Lisbon confining zone). Farther south, gradients become negligible or reverse as the Claiborne aquifer merges with the Floridan aquifer system along a line coincident with, or just north of, the Gulf Trough.

In southcentral Georgia, near Tifton, low permeability rocks in the Gulf Trough greatly impede the movement of groundwater through the Upper Floridan aquifer. Farther south near Valdosta, intergranular gypsum and thin and intermittent layers of evaporite minerals in middle Eocene rocks decrease the permeability in the lower part of the Floridan aquifer system. Here, the evaporite bearing units act as lower permeability barriers to flow, and freshwater moving from the Claiborne aquifer in southwestern Georgia may move upward and over the evaporite units, or slowly through them, towards discharge areas. Farther south, rocks of the Upper Floridan aquifer merge with thicker highly permeable solution zones in the unconfined areas of northcentral Florida (Williams and Kuniansky, 2016).





Figure 3.2.3 Cores of Ocala Limestone (top) and Hawthorn clay (left) obtained by rotosonic drilling at a site in southcentral Georgia. Ocala Limestone is soft and loosely cemented and may sometimes appear as “sand” to inexperienced geologists when samples are retrieved by rotosonic drilling, as opposed to classic coring techniques.

The Upper Eocene Ocala Limestone, the most important and productive part of the Upper Floridan Aquifer, is present throughout all southern Georgia. Together with the overlying, thinner Oligocene Suwannee Limestone, it supplies water to all major karst springs shown on Fig. 3.2.1. The Ocala Limestone consists of soft, white, porous coquina that is composed of bryozoan and echinoid fragments and large foraminifera, cemented loosely by limestone mud (micrite). The lower part of the Ocala is soft, finegrained, micritic, fossiliferous limestone that is dolomitized in places and contains glauconite in southern Georgia. The Suwannee typically consists of cream to tan, crystalline limestone that contains abundant molluscan casts and molds and is commonly highly vuggy (Williams and Kuniansky, 2016).

Miocene beds, which overly the Upper Floridan Aquifer over most of its extent, are locally absent in northwestern peninsular Florida and southwestern Georgia where they have been eroded away. The thickest and

most extensive Miocene unit is the Hawthorn Group. The lithology of the Hawthorn varies greatly between areas, but mostly consists of phosphatic clay, silt, and sand that range in color from cream or gray to green to brown. The entire formation forms a thick, generally clastic, highly variable sequence of lower permeability rock that, where present, is considered to be the upper confining unit of the Floridan aquifer system.

In a study of the Floridan aquifer system in southwestern Georgia, Torak and Painter (2006) describe karst features in the exposed limestone of the Floridan aquifer system that are hydraulically connected to the principal rivers and lakes in that region, thereby creating a stream-lake-aquifer flow system (Fig. 3.2.4). In such areas, the karst features along incised streams that flow over the limestone strongly connect surface water features with the groundwater flow system. In localized areas, surface water recharges the aquifer where the level of the streambed is higher than the water table surface of the aquifer, and in other areas, groundwater discharges into the stream either at distinct springs or along diffuse reaches of the streams.

The Dougherty Plain of southwestern Georgia (Fig. 3.2.1), where limestone is thinly covered with surficial materials or weathered into a residuum, has one of the highest concentrations of sinkholes in Georgia and Florida. Incidentally, the Dougherty Plain (sometimes referred to as Dougherty Sinkhole Plain) also has one of the highest densities of center-pivot irrigation systems in the country. The associated heavy groundwater withdrawals, especially during droughts, have caused both the ongoing development of new sinkholes due to lowering of the hydraulic head in the Upper Floridan Aquifer, and aquifer contamination due to the use of pesticides and fertilizers.

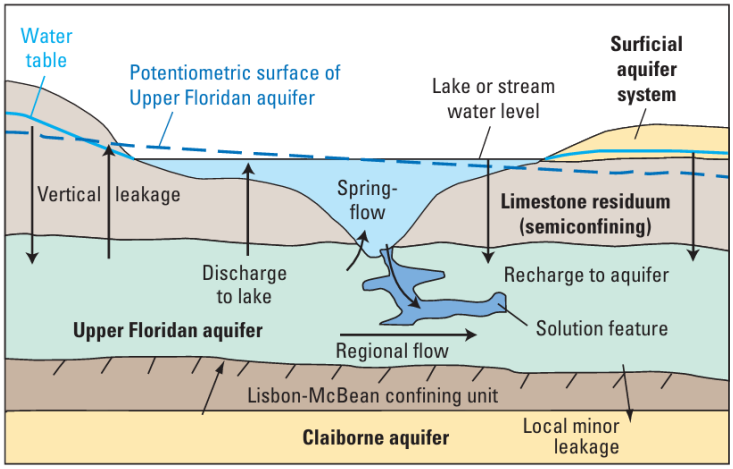


Figure 3.2.4 Conceptual diagram of groundwater and surface water flow in the interconnected stream-lake-aquifer flow system in southwestern Georgia (from Williams and Kuniansky, 2016; modified from Torak and Painter, 2006).

Because of heavy groundwater withdrawals for irrigation, many smaller springs, which would normally be discharging into surface streams, often dry up entirely during the irrigation season (early spring through summer), and some of the larger springs have greatly reduced discharge rates or dry up. Torak and Painter (2006) note how during the growing seasons of 2001 and 2002, hydrographs of four USGS monitoring wells located near irrigation pumpage, recorded typical cyclic-drawdown patterns with local drawdown of as much as 30 ft in one of the wells.

This irrigation cycle has a profound effect on the surface streams connected to the Upper Floridan Aquifer as described in detail by Milewski et al. (2019), and Rugel et al. (2012). For example, the Spring Creek Basin is the most heavily allocated in Georgia in terms of groundwater resources, with documented decreases in summer base flow and transition from a perennial to an ephemeral stream since the beginning of widespread groundwater pumping for irrigation in the mid-1970s. The hydrograph from a USGS stream gage confirmed that a stretch of Spring Creek studied by the authors periodically ran dry throughout the study period. The general area contributing



flow to this section of Spring Creek completely overlaps with the highest groundwater withdrawal permit density in the Dougherty Plain (Milewski et al., 2019).

Figure 3.2.5 A GPR (ground-penetrating radar) unit, which uses radar waves to detect underground anomalies, sits in one of the many sinkholes near Ichawaynochaway Creek. Many of these sinkholes formed in the 1990s during two major flood events that helped scour out underground passages. Photo by Joe Honings. Courtesy of The Jones Center at Ichauway. https://www.jonesctr.org/hydrogeology-guide/

Unlike most other states in the East that have significant karst areas and, by extension, large karst springs, Georgia agencies did not produce a publication focusing specifically on springs. Instead, less than a handful of historic reports on groundwater resources of Georgia and southeastern states provide rudimentary information on the Georgia springs. In case of the Floridan Aquifer springs in Georgia, this includes works by McCallie (1908; *A Preliminary Report on the Underground Waters of Georgia*), Stephenson and Veatch (1915; *Underground waters of the Coastal Plain of Georgia*), Callahan (1964; *The yield of sedimentary aquifers of the Coastal Plain, Southeast River Basins*) and Stringfield (1966; *Artesian Water in Tertiary Limestone in the Southeastern States*).

This lack of a more substantial publication describing hydrogeology and other characteristics of the Floridan Aquifer springs in Georgia is likely due to their much smaller number and size compared to the famous karst springs in Florida. The following quotes from McCallie (1908), and Stephenson and Veatch (1915) illustrate this:

*Some of the springs, such as Blue Spring in Dougherty county near Albany (*author's note: now known as Radium Springs*), compare favorably in size and in the transparency of their water with the famous Silver Spring of Florida. These springs are in the lime-sink region, which usually marks the outcropping of some of the more porous and permeable limestones. In these regions, it is no uncommon thing to see the surface stream disappear underground to reappear again, probably only a few hundred yards away. Such regions are noted for their numerous lime-sinks and small lake or ponds, which mark the course of subterranean streams. The flow of the large springs, here referred to, is frequently affected by droughts. In some instances. springs, which ordinarily flow several millions of gallons per day, may, occasionally, during a long drought, entirely cease to flow*. (McCallie, 1908)

A few large springs are of physiographic and geologic interest. These springs are in limestone areas and seem to be connected with subterranean streams. Their water is clear and very transparent, though faintly bluish in color, is but little affected by rains, and probably comes from considerable depths. At Blue Spring, 4 miles south of Albany, the water rises under pressure through a roughly circular opening in limestone and has an enormous flow. Discharge measurements by B. M. and M. R. Hall varied from 26.4 second-feet to 135 second-feet, or approximately 18,000,000 to 87,000,000 gallons in 24 hours. The spring is the largest in the State. Similar springs are Blue or Wade Spring, 7 miles east of Quitman; Mclntyre Spring, on the Withlacoochee near the Florida line;

Blue or Russell Spring, in Decatur County; Well, Wilkes, and Rock springs, in Laurens County; and Magnolia Spring, in Jenkins County (Stephenson and Veatch, 1915).

The locations of eight springs listed by Stephenson and Veatch, together with four additional notable springs, are shown in Fig. 3.2.1, while Table 3.2.1 provides the related information. Notably, except for the Radium Springs near Albany, there is no information on the average, minimum or maximum discharge rates for any of the springs, with four of them lacking a single official single measured or even an estimated value.

Table 3.2.1 Large springs discharging from Upper Floridan Aquifer in Georgia

Spring	County	Measured Discharge Rate (cfs)	Source	Spring Status
Radium	Dougherty	dry to 103	USGS	County park
Yates (Russell)	Decatur	24.1 & 41.2	USGS	Private
McIntyre	Brooks	46.42	Stringfield, 1966	Private
Wade (Blue)	Brooks	18.9 & 23.2	Stringfield, 1966	Private
Mock	Pulaski	6.47, 5.57 & 9.28	Stringfield, 1966	Private; recreation fee
Blue	Pulaski	1.66 & 4.64	Stringfield, 1966	Private
Osewichee	Wilcox	18.57	Stringfield, 1966	Private
Poor Robin	Wilcox	0.62, 2.75 & 4.52	Stringfield, 1966	Private
Well	Laurens	--		Private
Rock	Laurens	--		Private
Wilkes	Laurens	--		Private
Magnolia	Jenkins	--		State park

Excerpts below are from a March 13, 2025 article by Rose Schabel published on WUFT News and Public Media for North Central Florida; 25 years after tri-state water wars, Georgia farmers get green light to tap into the Floridan Aquifer

Farmers in southwest Georgia will be able to apply for new or expanded permits to pump water from the Floridan Aquifer to irrigate their crops starting April 1.

They've been cut off from the vast, water-filled cave network that underlies the southeast corner of the U.S. since 2012, when a two-year drought dried up rivers that flowed through Florida, Georgia and Alabama.

The Apalachicola-Chattahoochee-Flint River Basin was a key site in the decades-long "Water Wars" during which the three states accused each other of mismanagement of their shared water resources.

"Banks were more interested in loaning money for you to put in irrigation to stabilize the income than they were, you know, making an operating loan," said Campbell, who also serves as chairman of the Lower Flint-Ochlockonee Water Planning Council.

Growers pulled water from interconnected surface streams and underground aquifers for their cotton, peanuts, vegetables, soybeans and other crops. The irrigated area grew from fewer than 200,000 acres in 1970 to nearly 1.3 million acres statewide in 2022.

Farmers in the Southeast, no strangers to dry spells, faced repeated, severe droughts from the 1990s to the 2010s. Heat records, fueled by climate change, were set and broken growing season after growing season. Mounting withdrawals to protect crops exacerbated dry conditions.

Georgia's loosening of agricultural withdrawals came as bad news to Robert L. Knight, founder of the Florida Springs Institute.

"I'm disappointed," said Knight. "I think it's going to make it definitely harder to recover the aquifer to the level where it should be to protect the springs and the rivers."

Wakulla Springs is one of many water bodies already feeling the effects. Typically, caves in southern Georgia and north Florida swallow dark streams underground and shuttle their waters to the Gulf.

Pumping in southern Georgia, Leon and Wakulla counties decreases flow, which means tannic water doesn't make it to the Gulf and instead escapes at Wakulla Springs, turning crystal waters murky.

"We're just adding insult to injury with every one of these permits," Knight said. "Georgia's not the only bad actor. It's Florida as well."

On June 28, 2022, Kamilah Williams authored an article and video for 13WMAZ Local News entitled *"I hope that it can come back': Natural spring in Hawkinsville closes due to drought*. (Natural spring in Hawkinsville closes due to drought | 13wmaz.com). Below are several excerpts illustrating the demise of once powerful and famed Mock Springs located roughly 8.5 miles southwest of downtown Hawkinsville in Pulaski County.

HAWKINSVILLE, Ga. — With the intense heat of the summer, you usually want to jump in the pool, go to the lake or perhaps a water park or splash pad. However, in Hawkinsville, the big question at one popular cool-off spot is, "Where did all the water go?"

Howard Vaughn manages the Mock Springs. He says the family who created the swimming hole split it from the nearby creek decades ago.

"It's been real prosperous over the '50s, '60s, and '70s. There's been a lot of people that come down here," Vaughn said.



Figure 3.2.6 Mock Springs, completely dry, in June 2022. Screenshot from a video by Kamilah Williams, courtesy of 13WMAZ (Natural spring in Hawkinsville closes due to drought | 13wmaz.com)

From late night swims, slip-and-slides, and people simply cooling off, the fun has vanished. Vaughn noticed the water levels were getting low last Wednesday. He says the water is usually shared with nearby farm crops.

We keep just adjusting the water level by stopping the overflow because the spring, when it's operating, puts out so much water so we can control up or down, but then it got to the point that it wasn't doing that."

One woman lives down the road from the natural spring. She said she used to go to the natural springs as a kid. When she drove by it, she was sad the water was gone.

"I hope that it can come back eventually and the kids growing up right now can be there and enjoy it like we did when we were kids," she said.

Vaughn said the water is pumped from the same aquifer the swim hole and farm crop use. He says the farms pump more water, which is part of the reason why the water levels are low. Along with little rain in the area, the swimming hole fell into a drought. He's talked with city leaders about water regulations and hopes to open again because it's a popular place for the community of Hawkinsville can go to.

It appears that Mock Springs, unfortunately, is following in the footsteps of two other, once famed Georgia springs, which were the destinations to go in the South in the early 20th century: Wade (historically called Blue) Spring in Pulaski County, and Poor Robin Spring in Wilcox County.

Wade (Blue) Spring, Brooks County

In 1908, McCallie wrote this about Wade Spring*: This spring, which is located near the right bank of the Withlacoochee River, seven miles east of Quitman, has, in recent years, become quite a local pleasure resort. The improvements consist of a small hotel, or boarding-house, and a number of cottages. for the accommodation of guests. The spring is a typical so-called blue spring, of the limestone region of South Georgia. It seems to be the outlet of a large subterranean stream, which ascends, with considerable force, through a large opening. At the time of the writer's visit to the spring, in November, 1903, a rough estimate showed, that it was then flowing about 15 million gallons per day. It was learned, however, that, during an extremely dry season, some years ago, the spring went dry.*

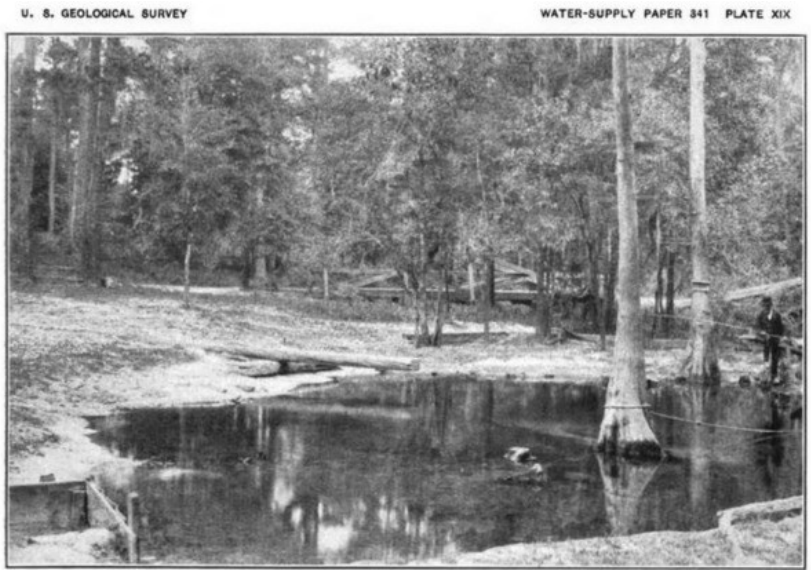


Figure 3.2.7 Historic photograph of Wade Spring; from McCallie, 1908.

WWALS (Withlacoochee, Willacoochee, Alapaha, Little, and Suwannee River) Watershed Coalition writes the following about the spring: Blue or Wade Spring just south of US 84 and the railroad tracks and north of Blue Springs Road, was once a famous resort, with a custom-built railroad. It was actually two springs, one inland at the resort and one in the river, measured in 1937 at 19.9 and 23.21 cfs. The past tense is because, according to a reliable source, attempts to improve the spring by digging it out destroyed it. Pictures of Wade Spring are surprisingly hard to find, other than this postcard of a building, of unknown date (https://wwals.net/2017/03/22/brooks-county-springs-capital-of-georgia/):

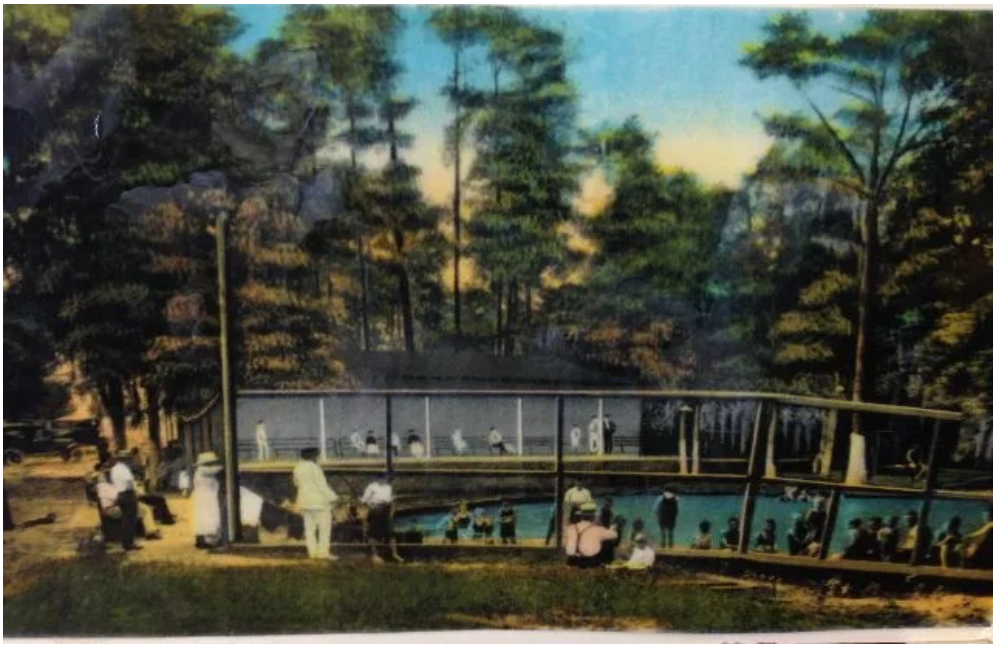


Figure 3.2.8 Historic postcard of Wade Spring. Courtesy of WWALS.



Figure 3.10.9 The ghostly remains of the Wade Spring pool in what was once a famous resort. Right photo was taken when the former pool was completely dry. The current owner informed WWALS that, when her father bought the place in the 1960s, the spring was already destroyed. The Brooks County Manager speculates that somebody tried to enlarge it and destroyed it, perhaps using dynamite. Photographs courtesy of local cave diver Aaron Sirmons, and WWALS Watershed Coalition.

Poor Robin Spring, Wilcox County

Poor Robin Spring is located just north of downtown Abbeville on the Ocmulgee River. It is possibly named after an Indian chief Robin, who was said to have been healed by bathing in the waters of the spring (Krakow, 1975). During its heyday in the first half of the 20th century, the spring was developed into a bustling local tourist attraction featuring a large commercial swimming pool. The pool no longer exists and has been reclaimed by nature. The spring is privately owned and there is no public access.

In 1913, Georgia State Geologist S.W. McCallie wrote "*The spring has long been known and within the last few years a considerable amount of the water has been sold. No information could be obtained from the owners concerning the flow of the spring or the improvements, although a number of letters requesting this information were addressed to the company operating the spring."*

In 1915, Stephenson and Veatch wrote "*Poor Robin Spring, a mile north of Abbeville, yields 5,000 gallons per minute, according to the owner, W. L. Du Vail. The water rises under considerable pressure through openings in the bottom of a small limestone basin 15 or 20 feet deep and is remarkably clear. Fragments of flint found near the spring contain coral and other fossils which probably indicate that the limestone belongs to the Chattahoochee formation. Therapeutic properties have been ascribed to the water and the place is a local resort*."



Figure 3.2.10 Historic postcards of Poor Robin Spring in Abbeville, once a bustling local tourist attraction. The spring is now on private property with no public allowed.



Yates Springs, Decatur County

Yates Spring, historically also known as Russell Spring, is located on Yates Spring Road near the small town of Brinson and just northwest of Bainbridge. Via a short run, the spring discharges into Spring Creek, a major tributary that flows south toward Lake Seminole. Historically, Yates Spring operated for a time as a local gathering place and swimming hole. Longtime locals share fond memories of swimming in its cool waters, and a strict past property owner, Mr. Yates, who famously enforced quirky rules—such as banning alcohol and refusing entry to any man whose hair touched his ears. The spring is still privately owned and current owners do not allow public access.

Figure 3.2.11 Yates Spring in Decatur County. Photograph copyright Alan Cressler. Many more photographs of springs and nature by Alan Cressler are available at https://www.flickr.com/photos/alan_cressler/

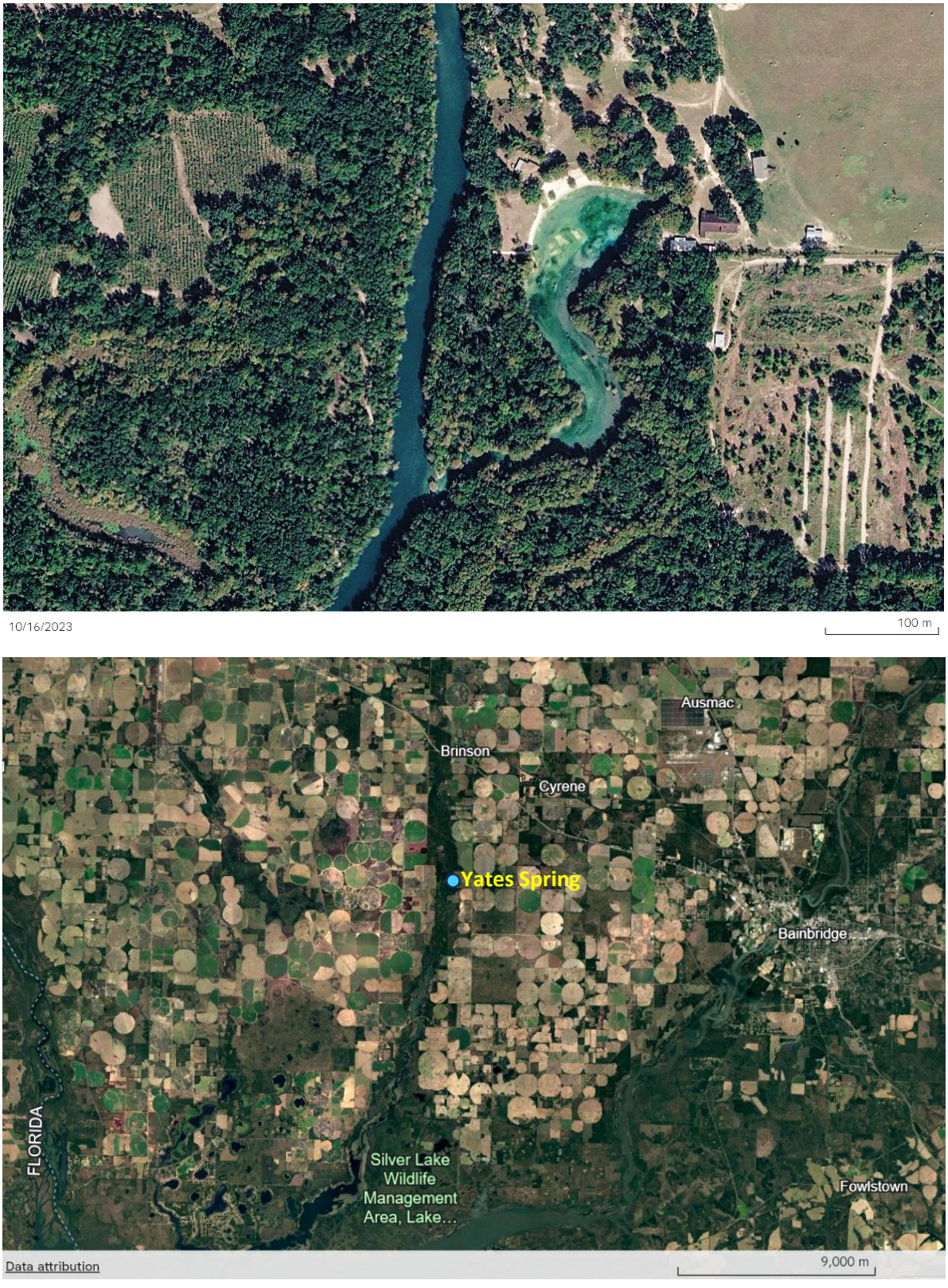


Figure 3.2.12 Google Earth images of Yates Springs. The spring sits in Dougherty Plain, which has one of the highest concentrations of center pivot irrigation systems in the country. The center pivots are fed by wells pumping from Upper Floridan Aquifer.

McIntyre Spring, Brooks County

McIntyre Spring is located about half a mile upstream from where the Withlacoochee River crosses into Florida for the first time. It discharges directly into the river via submerged karst passages totaling 4,610 feet in length, and 190 feet depth below the level of the Withlacoochee River. The quest of diving and surveying this second largest spring in Georgia is explained by Valdosta cave-diver Guy Bryant on his blog and includes many cave diving photographs and historic drawings of the cave.

Land access to McIntyre Spring is privately owned and closed, but the spring itself is readily accessible in the river, as viewed on a photo of the WWALS Watershed Coalition outing of July 9, 2016 (Fig. 3.2.15).

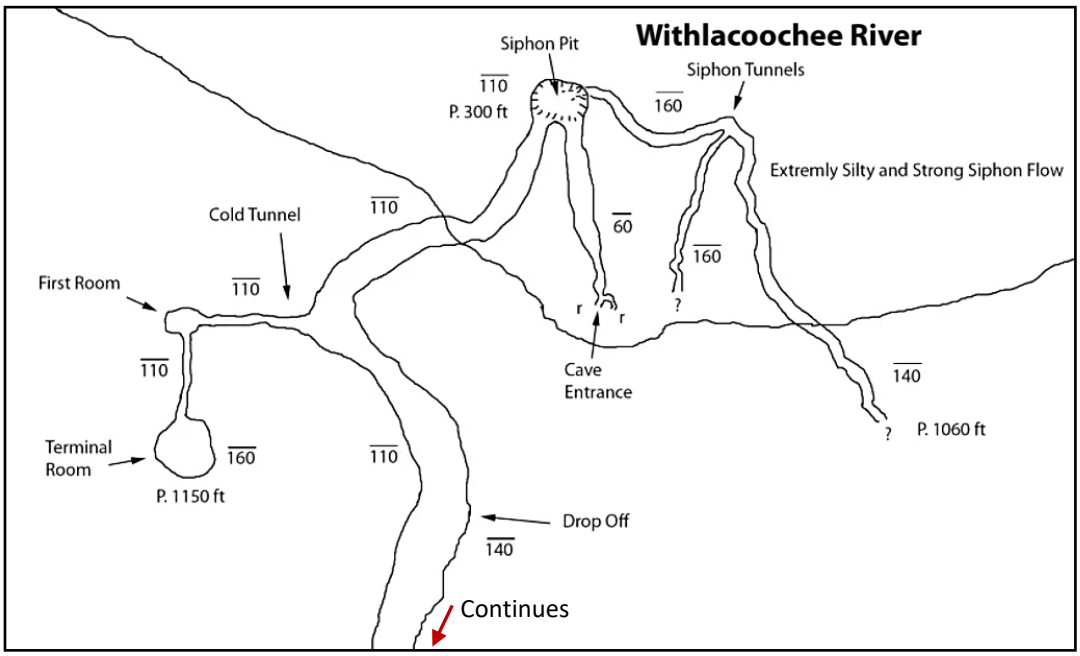


Figure 3.2.13 Portion of a map of the submerged cave passages supplying water to McIntyre Spring, created by Valdosta cave diver Guy Bryant. Available at https://guybryantcavedivingblog.wordpress.com/2016/04/19/mcintyre-spring/.



Figure 3.2.14 An old photo of Guy Bryant taken by Gene Powel at the jump to the Cold Tunnel about 800 feet back in the cave, Aug 2007, McIntyre Springs, Withlacoochee River, Georgia. Courtesy of WWALS.



Figure 3.2.15 McIntyre Spring during outing of the WWALS Watershed Coalition on July 9, 2016. Photo by John S. Quarterman; https://wwals.net/2016/04/02/blue-spring-and-mcintyre-spring-withlacoochee-river-brooks-county-ga-1903-11/

Radium Springs, Dougherty County

Radium Springs are in Radium Springs Gardens located on the outskirts of Albany in Dougherty County, (address is 2501 Radium Springs Rd. Albany, 31705 GA). The park is on the site of a former casino that had its heyday in the 1930s. The casino was demolished in 2003 after sustaining serious damage when the Flint River flooded in 1994 and 1998. The spring is now preserved as an ecological and environmental park which features a restored terrace, new sidewalks, garden, and gazebos of the former casino, as well as nature trails and an observation desk along Skywater Creek (the spring run) outside the gardens. Although swimming is no longer allowed, the spring served that purpose for many years and once was one of Georgia's most popular resort areas.

Radium Springs, which discharge from a large main and several nearby, smaller vents into the spring pool are fed by an extensive submerged cave system, developed in highly porous and karstified young Ocala limestone. The submerged passages have been explored by cave divers entering through the main vent. A 3300-feet long spring run flows into the Flint River through a southern marshland teaming with wildlife.

Radium Springs is the largest spring in Georgia and was reported as a historic first-magnitude spring by USGS. On an information panel by the spring, and on various web sites one can read that the spring is flowing at “70,000 gallons per minute” (equivalent to 187 cfs). However, it is unknown where this number came from since the only available official record of any flow measurements at the spring is by USGS, painting a very different picture. Discharge rate of Radium Springs (aka Blue Springs) was measured 31 times in the field, between 1937 and 2011.

The spring nearly or completely dried up 4 times during this period (in July 2011, November 1986, May 1981, and July 1981). The maximum of 109 cfs was recorded in April 1982, and the average for the entire period of record is 33.7 cfs.



Figure 3.2.16 Radium Springs in Albany is the largest spring in Georgia. The main vent discharges from a submerged cave system in the Ocala Limestone. Entrance to the cave ("blue hole") is in the center right.



Figure 3.2.17 Screenshot of a diving video at Radium Springs, October 31, 2015, taken by Guy Bryant with divers Kelly Jessop and Peter Buzzacott. Note a wide-open fracture in the Upper Eocene Ocala limestone in the ceiling. Video is available on YouTube (CDroHO56F-Y).

The fascinating history of Radium Springs is described in detail on the excellent *Explore Southern History* website (https://exploresouthernhistory.com/naturalwonders.html). The Spring was well known to both prehistoric and later Creek Indians, who lived and hunted in the surrounding area while fishing in the crystal-clear water. By the time English settlers arrived in South Carolina and Georgia, the area around Albany was controlled by the

Lower Creeks and early accounts mention the magnificent spring. English settlers and explorers began to use the springs for swimming and fishing, marveling its depth, constant 68-degree temperature, and clarity of the water.

In 1925, traces of radium were discovered in the water, and Blue Springs was renamed Radium Springs as the first step in its development as a major resort. Bathing in mineral waters was believed to be beneficial for improving the health of people suffering from a variety of illnesses.

Barron G. Collier (Collier County in Florida is named in his honor), a noted developer and national figure of the early 20th century, purchased the springs and began work on a major development. His plans for Radium Springs were magnificent and it was reported at the time that he spent nearly $1,000,000 on the project. The development included a casino and bathhouses overlooking the spring, a hotel named *Skywater* (after the Creek Indian name for the spring), cottages, riding and walking trails and one of the finest golf courses in the South. The resort opened to the public in 1927 and was an instant success. Guests came by train to Albany from across the country to soak in the waters and enjoy the other amenities.

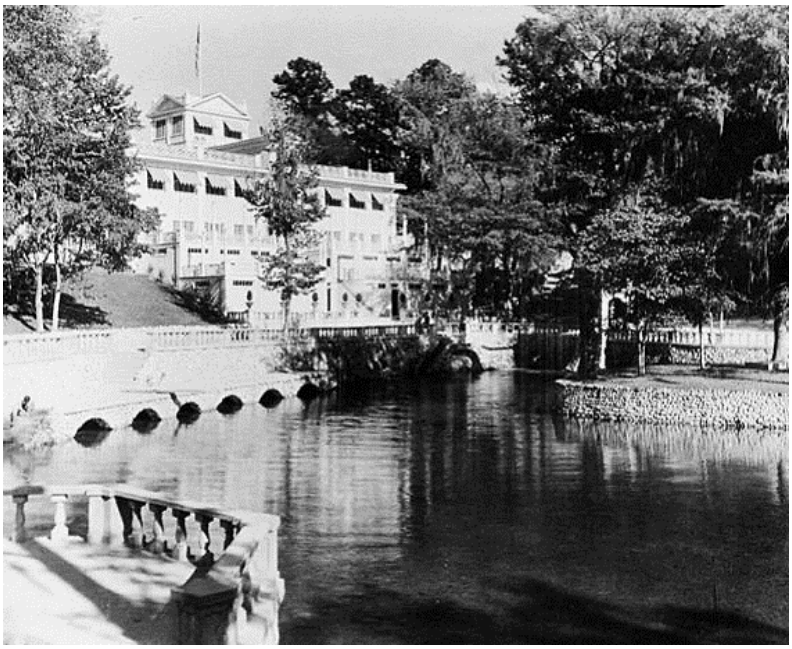


Figure 3.2.18 Radium Springs, one of Georgia's Seven Natural Wonders, was the site of a casino that had its heyday during the 1930s. The Spring was still a popular swimming place for Albany area residents until 1994 when the casino and other historic structures suffered heavy damage in the Tropical Storm Alberto. A second flood inflicted even more damage in 1998, and the casino was demolished in 2003. Courtesy of Georgia Archives, Vanishing Georgia https://dlg.usg.edu/record/dlg_vang



Figure 3.2.19 *Left*: In the summer of 2012, when South Georgia was experiencing drought conditions and excessive groundwater withdrawals for irrigation, the flow in Radium Springs stopped due to falling water table levels in the Floridan aquifer supplying water to the spring. Photo by Alan Cressler, USGS. *Right*: Spring in April 2024.

Magnolia Spring, Jenkins County

Magnolia Spring is in Magnolia Springs State Park, just north of the city of Millen. A boardwalk spans the spring pool, allowing visitors to look for alligators, turtles and other wildlife. A small lake is available for fishing. Overnight guests can choose from cottages and a campground.

On an information panel by the spring one can read "*So important is this feature that the park and even the town of Millen may never have been created without it. Reportedly, the name originated from the tremendous Southern Magnolia (Magnolia grandiflora L.) growing near the springs, giving park its present name. The spring delivers almost 9 million gallons of crystal clear water each day. Long before Europeans landed in North America, the native peoples and the animals they hunted knew of the spring's refreshing waters.*

Just south of the fall line in Georgia, the spring flows from the Ocala aquifer through an area mostly comprised of limestone riddled with sink holes. Most of the water is delivered from a depth of 250 feet, with an average temperature of 72 degrees Fahrenheit throughout the year.

During the War Between the States from 1863 to 1865, this was the site of Camp Lawton, the largest prisoner of war camp in the entire Confederacy. This site was chosen because there was plenty of local timber for building, the soil drained quickly, a railway was nearby, and most of all, the springs supplies fresh clean water which helped to keep thousands of prisoners alive and free of diseases."



Figure 3.2.20 Magnolia Spring. Photo courtesy of Georgia State Parks.

3.2.2 Appalachian Karst Springs

In the Valley and Ridge, and Appalachian Plateaus Provinces of Georgia, karstic units include the following Paleozoic rocks: Bangor Limestone, Chota Formation, Conasauga Group, Copper Ridge Dolomite, Devonian and Mississippian rocks, undifferentiated, Fort Paye Chert, Holston Limestone, Knox Group undifferentiated, Newala Limestone, Pennsylvanian rocks, undifferentiated, Sandersville Limestone, Shady Dolomite, and an unnamed limestone member in Floyd County. The Mississippian aged Bangor Limestone (Fig. 3.2.21) is the most cave-rich lithologic unit in the state (Weary, 2008; Anderson, 1993).





Figure 3.2.21 *Top*: Byers Cave in Fox Mountain Preserve, Dade County, is developed in the Mississippian Bangor Limestone and owned by Southeastern Cave Conservancy. It is one of Georgia's largest cave systems, inhabited by a wide variety of unique invertebrate organisms (Campbell et al., 2012). *Bottom*: Frick's Cave in Frick's Cave Preserve, Walker County is also developed in the Mississippian Bangor Limestone and owned by Southeastern Cave Conservancy, It is the summer home of over 5,000 endangered Gray bats, Georgia's only known population of the rare Tennessee cave salamander, and 33.8 acres of north Georgia karstland. Due to the presence of the endangered bats and salamanders, Frick's Cave is closed to all visitation, except as authorized by the SCCi Board, but one can visit the preserve during warmer months to watch the nightly bat flight from the cave. Photographs copyright Alan Cressler. All rights reserved. Over his decades-long career, which includes extensive fieldwork with the U.S. Geological Survey, Alan has built an archive of thousands of outstanding photographs available at https://www.flickr.com/photos/alan_cressler/

The most comprehensive information on the karst aquifers and springs in the Georgia's Appalachians is included in a report authored by Cressler et al. and published exactly 50 years ago (1976), entitled *Availability of Water Supplies in Northwest Georgia*.

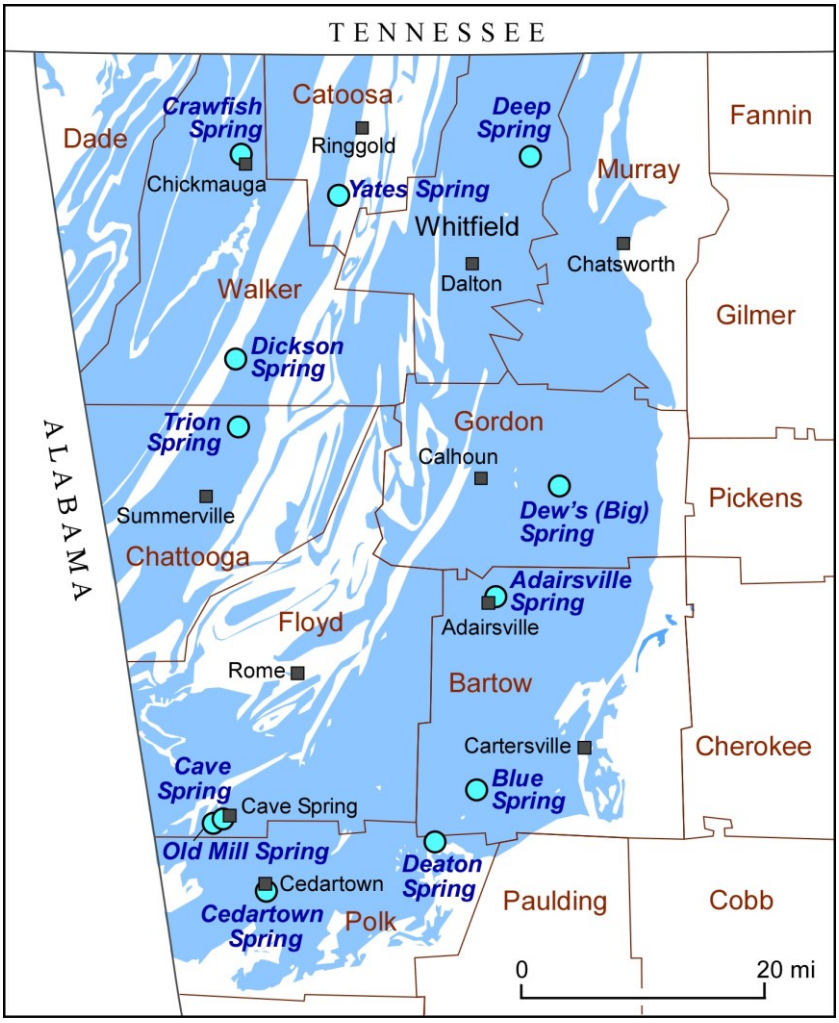


Figure 3.2.22 Large karst springs in Georgia's Valley and Ridge Physiographic Province (far northwestern part of Georgia). Karst areas from Weary, 2008.

Notably, more recent publications do not yet exist and so the findings of this old report are most likely outdated. Nevertheless, it provides an excellent overview of the region's karst water resources and their utilization at the time. The locations of major karst springs shown on Fig. 3.2.22 are based on the information in Cressler et al. (1976), while the descriptions of individual springs further in this section also include the information provided by McCallie (1908).

For several years after 1960, northwest Georgia experienced a rapid influx of industry that created an unprecedented demand for water supplies. Consequently, new supplies had to be developed. The development and management of groundwater supplies were hampered, however, by a lack of knowledge about the area's groundwater resources. To obtain the needed information, the U.S. Geological Survey, in cooperation with the Earth and Water Division of the Georgia Department of Natural Resources (formerly the Department of Mines, Mining and Geology), made studies of the geology and hydrology of the area. The results of these studies were published in seven reports (Cressler et al., 1976).

Most of the report area lies within the Valley and Ridge Province. The terrain consists of northeast-trending parallel valleys separated by ridges. The valleys are between 600 and 900 feet above sea level. The highest ridges rise to an altitude of about 1,600 feet. Dade County and parts of Walker and Chattooga Counties lie in the Cumberland Plateau Province. This is a large tableland of nearly flat-lying rocks, having an altitude of more than 2,000 feet. Occasionally, where a stream has eroded through the rocks, a deep flat valley stretches for miles in a northeast-southwest direction. The valley floors are about 1,200 feet below the top of the plateau. Eastern Murray County extends across the Great Smoky Fault into the Blue Ridge Province. The area is dominated by rugged mountain peaks that rise about 3,000 feet above sea level and stand 2,000 feet above the adjacent Valley and Ridge Province.

The 10-county area shown on Fig. 3.2.22 has abundant supplies of both groundwater and surface water. All the counties have carbonate aquifers that supply 25 to 500 gpm to wells less than 350 feet deep. Most of them have aquifers that can yield 100 to 1,000 gpm. Wells in Polk County yield as much as 1,500 gpm. The well water is moderately mineralized and can be used for many purposes without treatment. Springs in each of the 10 counties discharge hundreds of gallons of water per day. Some of the springs discharge more than 5,000 gpm (11.1 cfs), most of which is unused. The spring water generally is moderately hard to hard and has low iron concentration. Several industries use the water untreated. Most of the area's towns and industrial centers lie along streams or rivers that have large enough flows to supply future needs. The Dalton area is a major exception; Dalton now pumps 40 million gallons of surface water per day during the average work week. This pumpage is approaching the combined low flows of the Conasauga River, Coahulla Creek, and Mill Creek, as they flow by Dalton (Cressler et al., 1976).

Springs provide the largest single source of groundwater in northwest Georgia. Many springs discharge between 200 and 5,000 gpm (0.44 and 11.1 cfs) and are used by a number of large industries and by several municipal and county water systems. Springs supply part or all of the water distributed by the cities of Cedartown, LaFayette, Chickamauga, Adairsville, Cave Springs, Chatsworth, Kensington, and Summerville. Spring water offers the advantages of being readily available, inexpensive to develop, and fairly constant in temperature and chemical quality. Most of the springs being used for water supply have a dependable flow and rarely become turbid enough to require filtration. The large unused springs in the area represent a valuable undeveloped resource (Cressler et al., 1976).



Fig. 3.2.23 Crawfish Spring in Walker County has the 2nd largest measured discharge rate in northwest Georgia. This historic photograph is from McCallie, 1908.

As explained by Cressler et al. (1976), springs in northwest Georgia do not flow at a constant rate but fluctuate throughout the year in response to seasonal variations in precipitation. Most springs reach a period of maximum discharge sometime during the winter or early spring and decline steadily to a period of minimum flow that generally occurs in autumn. Depending on the individual spring, the minimum annual flow may be 20 to 90 percent less than the maximum flow. The authors provide discharge measurements (or estimates) for most springs in the 10-county area, emphasizing that nearly all these measurements were made in late summer or autumn, so the smallest amount listed for a spring is generally an approximation of its minimum annual flow. Table 3.2.2 reflects this and includes other basic information for the major karst springs shown on Fig. 3.2.22.

Table 3.2.2 Large karst springs in northwestern Georgia. Estimated minimum discharge rate from Cressler et al. (1976); aquifer units from Lawton et al., 1976.

Spring	County	Estimated Minimum Discharge Rate, gpm (cfs)	Aquifer	Spring Status
Crawfish Spring	Walker	6,200 (13.8)	Knox Group carbonates	Municipal supply
Dickson Spring	Walker	700 (1.6)	Bangor Limestone	Municipal supply
Yates Spring	Catoosa	4,270 (9.5)	Knox Group carbonates	Municipal supply
Deep Spring	Whitfield	1,040 (2.3)	Knox Group carbonates	Private
Trion Spring	Chattooga	5,350 (11.9)	Knox Group carbonates	Municipal Supply
Dew's (Big) Spring	Gordon	3,100 (6.9)	Knox Group carbonates	Municipal supply
Adairsville Spring	Bartow	4,100 (9.1)	Knox Group carbonates	Municipal supply
Blue Spring	Bartow	3,200 (7.1)	Knox Group carbonates	Private
Cave Spring	Floyd	1,660 (3.7)	Knox Group carbonates	Municipal supply
Old Mill Spring	Floyd	3,240 (7.2)	Knox Group carbonates	Municipal supply
Cedartown Spring	Polk	1,950 (4.3)	Newala Limestone	Municipal supply
Deaton Spring	Polk	10,800 (24.1)	Newala Limestone	Municipal supply

Crawfish Spring, Walker County

Crawfish Spring, which has the second largest recorded instantaneous discharge rate among the large springs in northwestern Georgia (20,600 gpm; Cressler et al., 1976) was described in 1908 by the Georgia State Geologist Samuel Washington McCallie (see Fig. 3.2.22): "The water, as it flows from the base of a small dolomite hill, forms a beautiful stream several rods wide and from two to five feet deep. This stream, which joins Chickamauga Creek about half-a-mile away, contains several other large springs, which, in the aggregate, are said to furnish an amount of water equal in volume to Crawfish Spring. The geological position of Crawfish Spring is near the contact of the Chickamauga limestone and the Knox dolomite. The latter formation forms a very prominent chert ridge, known as Missionary Ridge, a short distance to the west, which appears to be the catchment area that supplies the springs. The only improvement in the immediate vicinity of the spring is a large, well-constructed hotel, which, during the mobilization of the troops at Chickamauga Park, at the beginning of the Spanish-American war, was used as a hospital. There seems to have been an effort made, some years ago, to establish a summer resort at Crawfish Spring; but the undertaking appears to have been unsuccessful."



Figure 3.2.24 Crawfish Spring. Photo copyright Alan Cressler. All rights reserved. https://www.flickr.com/photos/alan_cressler/

Today, Crawfish spring is utilized for municipal water supply by the City of Chickamauga.

Dickson Spring, Walker County

Dickson Spring, owned by the City of LaFayette, is utilized by the municipal government as a critical part of its local public water supply. After retiring the original Dickson Spring treatment facility in the 1990s, the city recently renovated and reopened the Dickson Spring Water Treatment Plant to accommodate local community growth and ensure a redundant water supply.



The average discharge rate of the spring is 3,800 gpm (Cressler et al., 1976; period of record 1954-1961).

Figure 3.2.25 New water treatment plan at Dickson Spring treats about 1 million gallons of water per day, with plans for further expansion. Photo courtesy of the City of LaFayette.

Yates Spring, Catoosa County

The land containing Yates Spring and the historic Presley and Rachel Thedford Yates Home in Catoosa County, Georgia, is owned by the Catoosa Utility District Authority (CUDA). The spring serves as a core public drinking water source for the CUDA which, on average, delivers 5 to 6.5 million gallons of water to customers daily. Because of its importance and vulnerability, the Georgia Environmental Protection Division (EPD) enforces a strict Wellhead Protection Plan around the spring to guard against agricultural runoff, stormwater, and utility corridor pollution.

Dew's (Big) Spring, Gordon County

Dew's Spring, also referred to as Big Spring, is located about eight miles east of Calhoun, the county seat. McCallie (1908) describes it as "…a very large spring, furnishing, according to Mr. B.M. Hall, Consulting Engineer, U. S. Geological Survey, 7,200 gallons of water per minute. The spring flows from a large cavernous opening at the base of a bluff, near the contact of the Knox dolomite and the underlying Connasauga shale. The water from the spring forms a good sized stream, which operates a flour mill, located only a short distance from the spring. The flowage of the spring is said to be but little affected by the seasons. The water is hard, and nearly always transparent. The catchment area of the spring seems to be the dry, cherty Knox dolomite ridges lying to the west."

The spring, its surrounding property, and water rights were in 2010 purchased by the City of Calhoun from previous owners, who operated Big Spring Pure Water, Inc. The City of Calhoun provides water service to most of Gordon County. The eastern half of Gordon County is served by groundwater, via the City's wells and Big Spring.



Part of the water from Big Spring is still used for bottling and marketed as *Nature's Big Spring Water* by a family-owned company in Calhoun.

Figure 3.2.26 Big Spring is at the opposite end of Dew's Pond, known during the Civil War as Dew's Lake. Photo courtesy of David Seibert of Sandy Springs, Georgia.

Trion Spring, Chattooga County

Trion Spring is owned and utilized by Mount Vernon Mills, one of the largest denim manufacturing plants in the world and Chattooga County's largest employer. Water from the spring also supports drinking water provisions for the Town of Trion.

Adairsville (Lewis) Spring, Bartow County

Adairsville Spring, officially documented by the USGS as Lewis Spring (Monitoring Location USGS-342226084570201), is a highly productive karst spring located on a mountainside just west of downtown Adairsville in northwest Bartow County. The spring has been utilized for over a century. The city council originally approved a municipal pumping station at the spring in 1906. For generations, it was a locally famous gathering spot known for its exceptionally pure, crystal-clear water.

The tension between preserving the karst aquifer system feeding Adairsville Spring (Lewis Spring) and accommodating rapid industrialization has become one of the defining conflicts in local government meetings and community forums. Because the City of Adairsville relies entirely on the spring for its municipal supply, local city councilmen and county commissioners are facing massive pressure regarding infrastructure protection, zoning, and environmental oversight. Several excerpts from the media, provided below, illustrate the ongoing fight for saving the aquifer and the spring.

Associated Press, Updated 10:23 AM EDT, July 21, 2020 (Northwest Georgians warn rock quarry could hurt water supply | AP News)

ADAIRSVILLE, Ga. (AP) — Opponents are warning that a planned rock quarry in northwest Georgia could threaten water supplies for some residents.

Yellowstone LLC is asking Bartow County to rezone 466 acres for mining.

But nearby resident Sharon Nelson Viktora tells The Rome News-Tribune that the project could threaten water supplied from Lewis Spring to Adairsville and surrounding portions of Bartow, Floyd and Gordon counties.

Viktora says that the mining could harm the recharge of underground water, also hurting the water supplies of people who rely on wells and aren't served by public water systems.

Also opposing the quarry are the owners of the nearby Barnsley Resort, saying the mining could harm streams, lakes and wetlands and disturb wildlife.

Resort President David Friederich also warns that blasting poses "imminent risk" to pre-Civil War ruins of a mansion that are the centerpiece of the resort.

The Northwest Georgia Regional Commission is reviewing the proposal.

The outcome: residents and nearby institutions—including the historic Barnsley Resort—successfully argued that heavy blasting and mining operations just 700 feet from the spring's unconfined aquifer recharge zone could irreparably disrupt the groundwater table, contaminate the flow, or cause the spring to dry up completely.



June 2026, Facebook post by Jenny Smith and Associates:

Let's talk about the data centers coming to Bartow County, because I don't think many of us are exactly thrilled about it.

There are three things keeping me up at night. The noise, because some folks say they can't sleep through that constant hum. The water, because nobody wants to risk our wells or that beautiful Adairsville spring. And the electric bills, because none of us signed up to help pay for the power these things burn through.

I'm not here to tell you how to feel. I'm here because I live here too, and I think it matters that we talk about it honestly.

https://www.jennysmithandassociates.com/blog/bartow-county-data-centers-what-they-mean-for-homeowners/

Figure 3.2.27 Image courtesy of From Quarks to Quasars. Available at A Georgia data center drained 30... - From Quarks to Quasars | Facebook

Local homeowners and riverkeepers have swarmed public zoning boards and community forums. Even when developers promote "closed-loop technology" to lower standard water consumption, residents point to recent crises—such as a data center in nearby Fayetteville, that secretly drained 30 million gallons of unmetered groundwater during a drought—as proof that the state's groundwater cannot withstand this rapid expansion.

New York Post: *Georgians outraged after data center drains 30M gallons of water amid drought conditions*: report by Taylor Herzlich, published May 11, 2026 (https://nypost.com/2026/05/11/business/georgians-outraged-after-data-center-drains-30m-gallons-of-water-amid-drought-conditions-report/)

Residents of a suburban Georgia town are furious after they discovered a massive new data center had guzzled up 30 million gallons of water without initially paying for it – leaving members of the populace with weak water pressure during a drought.

Georgians living in Annelise Park, a mansion-packed neighborhood in Fayetteville, which has a roughly 20,000 population, noticed last year that their water pressure was unusually weak, according to a Politico report.

A county investigation found a nearby 6.6 million-square-foot data center project by Quality Technology Services, a Blackstone-owned developer, was to blame, according to the publication.

Two industrial-scale water hookups had been connected to the campus – but one was installed without alerting the local county utility, and the other was not linked to QTS's account, so neither were being charged, according to a May 15, 2025 letter from the Fayette County water system to QTS.

Cave Spring, Floyd County

McCallie (1908) provides the following description of Cave Spring which is located in the southern part of Floyd county, in Rolater Park in the central part of the town of Cave Spring. "It emerges from the base of a Knox dolomite hill, near the line of contact of the Connasauga shale and the Knox dolomite. On the hillslope just above the spring, is a cave which extends down to the submerged karst channel which supplies the spring. This spring is much used by the residents of the town for general domestic purposes; and it also supplies the Georgia Deaf and Dumb Asylum, located nearby (it is now named Hearn Academy). The water is hard and clear, never becoming turbid after rains. The flow of this spring, measured by the U.S. Geological Survey in 1904, is 3,444,868 gallons in 24 hours." (McCallie, 1908).

Cave Spring is located on the Trail of Tears in Georgia and was home to a major resistance of the Cherokee against the whites who were forcefully removing them from their own, ancestral land.



Figure 3.2.28 This stone castle at the entrance to the cave at Cave Spring, and the 1½-acre swimming lake in the shape of the state of Georgia, fed by the spring, were built by the Civilian Conservation Corps in the 1930s. Rolater Park was established in 1931, when Dr. J.B. Rolater, a Cave Spring resident and former student at Hearn Academy in the park, gave 29 acres of land with the natural cave and clear spring for a public park. The Rolater Park Governing Board oversees it today, and it is popular with walkers and joggers. Photo courtesy of the City of Cave Spring.

The earliest recorded description of the cave at Cave Spring is from Adiel Sherwood's 1837 edition of A Gazetteer of the State of Georgia. The Gazetteer included an article copied from a Rome newspaper dated January 15th, 1837, and was signed "W.K.B". In the description it says (https://www.rolaterpark.net/history):

"The county presents one and only one natural curiosity that has been discovered, and it is a subterranean cave, in the lower part of Vaun's Valley, about 15 miles from this place (Rome). It is situated on the summit of a lofty eminence, and the visitor before he undertakes the ascent may refresh himself with a rich draft of pure limestone (water), which issues from the base of the hill in a stream, sufficiently large to supply all the water power necessary for the successful operation of a whole manufacturing village in New-England".

Cedartown (Big) Spring, Polk County

McCallie (1908) provides the following description of Cedartown Spring, more commonly known as Big Spring: "This is a very large limestone spring at Cedartown, the county-seat of Polk county. The capacity of the spring is said to be about 2,500,000 gallons a day. It emerges as a large stream from cavities in the limestone rock, at the base of a small hill near the center of the town. This spring, which furnishes the town with water, is surrounded by a substantial wall of masonry. This wall, in addition to its protecting the spring from surface drainage, is also used as a part of the foundation of the power house of the pumping station, which forces the water to the stand-pipe located on a hill in another part of the town. Some anxiety has been expressed, from time to time, as to the possible surface contamination of the Cedartown Spring. It has been thought by some, as the spring becomes muddy after rains; that a certain lime-sink in the neighborhood has connection with the sub terranean stream which supplies the spring. This supposition seems never to have been conclusively demonstrated; but the writer has been informed that the town authorities have taken steps to guard against any contamination from this source."

The spring was the site of a ball field and ceremonial dance ground of the Cherokee Indian natives until the early 1800s. According to legend, rights to the main water source, The Big Spring, were won by the Cherokee, who challenged the Creek in a peaceful ballgame. Asa Prior purchased the land around Big Spring in 1834. In 1852, Prior deeded the spring and adjacent land to the newly charted city of Cedartown.



The spring still serves as the primary supply of potable water for approximately 10,000 people in the Cedartown area. A modern water treatment facility was installed on the site at 301 Wissahickon Avenue, which pumps water through pipelines to the surrounding areas. In 2000, the American Water Works Association named the Cedartown Water Plant an American Water Landmark. In 2011, the Big Spring was named a certified site on the Trail of Tears, as it was the site of Camp Cedar Town, a Cherokee removal camp in 1838.

Figure 3.2.29 Big Spring Run in Big Spring Park, Cedartown. Photo copyright Alan Cressler, all rights reserved. https://www.flickr.com/photos/alan_cressler/

Deaton Spring, Polk County

Deaton Spring, owned and managed by the Polk County Water Authority, is a primary water source that supplies roughly 70 percent of the county's drinking water. The authority operates the site alongside the adjacent Deaton Spring Water Treatment Plant and pumping station.

In 2015, the Polk County Water Authority completed an enclosure for Deaton Spring, after receiving a $1.2 million Drinking Water State Revolving Fund (DWSRF) 20-year loan with a 1.40 percent interest rate from the Georgia Environmental Finance Authority (GEFA).





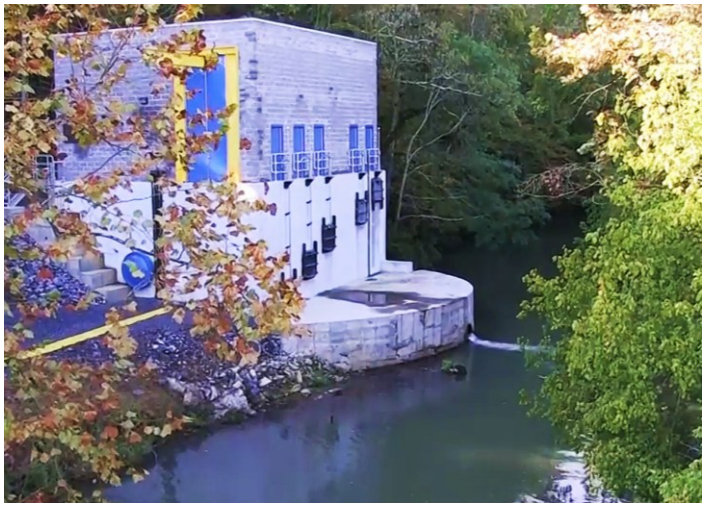


Figure 3.2.30 *Top*: Deaton Spring, pictured here in the 1970s, was subject to flooding by Euharlee Creek and generally unsafe conditions. *Left*: Spring enclosure, completed in 2015, is built of reinforced high-strength concrete and features a pumping station inside. Photographs courtesy of Georgia Environmental Finance Authority. YouTube video available at https://www.youtube.com/watch?v=pTbY5RdGC2A

3.3 Alabama

Alabama's springs are a spectacular natural resource and should be protected and preserved. These springs serve as an important water supply source for municipal, agricultural, domestic, and recreational use, as well as for contributions to the State's scenic beauty.

Improving and expanding the consistency of monitoring efforts is greatly needed to develop long-term hydrological and geochemical characteristics and allow for improved understanding of the effects of climate, land use, and groundwater withdrawal on the overall health of Alabama's springs and shallow groundwater reserves.

Smith and Guthrie, 2022
Alabama Geological Survey

The water-bearing characteristics of rocks in Alabama that govern the availability of usable and sustainable groundwater resources are diverse. Alabama can be separated into five distinct physiographic provinces (Guthrie and Bearden, 2019; Fig. 3.3.1) with internally similar hydrogeologic characteristics that affect availability of groundwater resources. These are, from north to south, the Interior Low Plateau (also referred to as the Highland Rim; e.g., see Smith and Guthrie, 2022), the Cumberland Plateau (often referred to as the Appalachian Plateaus), the Valley and Ridge, the Piedmont Upland, and the East Gulf Coastal Plain. Groundwater use is most prevalent in the Interior Low Plateau, Alabama Valley and Ridge, and East Gulf Coastal Plain provinces, and surface water is the predominant source in the Piedmont Upland and Cumberland Plateau.

The Interior Low Plateau (the Highland Rim) to the north is primarily a limestone plateau of moderate relief. The primary aquifers are comprised of Middle Paleozoic clastic and carbonate rocks, producing gently southeast-dipping ridges in the southern part and broad sub-horizontal valleys containing abundant karst features throughout the northern part. The aquifers are for the most part unconfined, fractured and karstified, and wells have the potential to produce large volumes of water, making the Highland Rim one of the most heavily used groundwater areas in the state (Smith and Guthrie, 2022). Major surface water drainage flows towards the Tennessee River throughout the province.

The Cumberland Plateau (the Appalachian Plateaus) to the south and east is comprised of sub-maturely to maturely dissected sandstone and shale synclinal plateaus with moderate relief. In the eastern part of the Appalachian Plateaus are three linear anticlinal limestone valleys (Murphrees Valley, Wills Valley, and Sequatchie Valley) characterized by resistant sandstone ridges with moderate relief. Large volumes of water are not typically produced from wells in the Cumberland Plateau and surface waters serve as the primary water source for most public supply, irrigation, and industrial users (Smith and Guthrie, 2022).

The Valley and Ridge physiographic and groundwater province in central and northeastern Alabama consists of a series of subparallel ridges and valleys trending generally northeast-southwest. The ridges are formed by sandstone and chert beds that are resistant to erosion; valleys are underlain by less resistant shale and carbonate rocks. Karst features are prominent in valleys underlain by limestones in the central part of the section. The southeastern part of the province is characterized by a wide plain of varied relief containing irregularly spaced parallel ridges and valleys. In the extreme northeastern part of the province, mountainous terrain is developed on faulted and folded sandstone and quartzite. The southwest-flowing Cahaba and Coosa Rivers are the main surface water features (Smith and Guthrie, 2022).

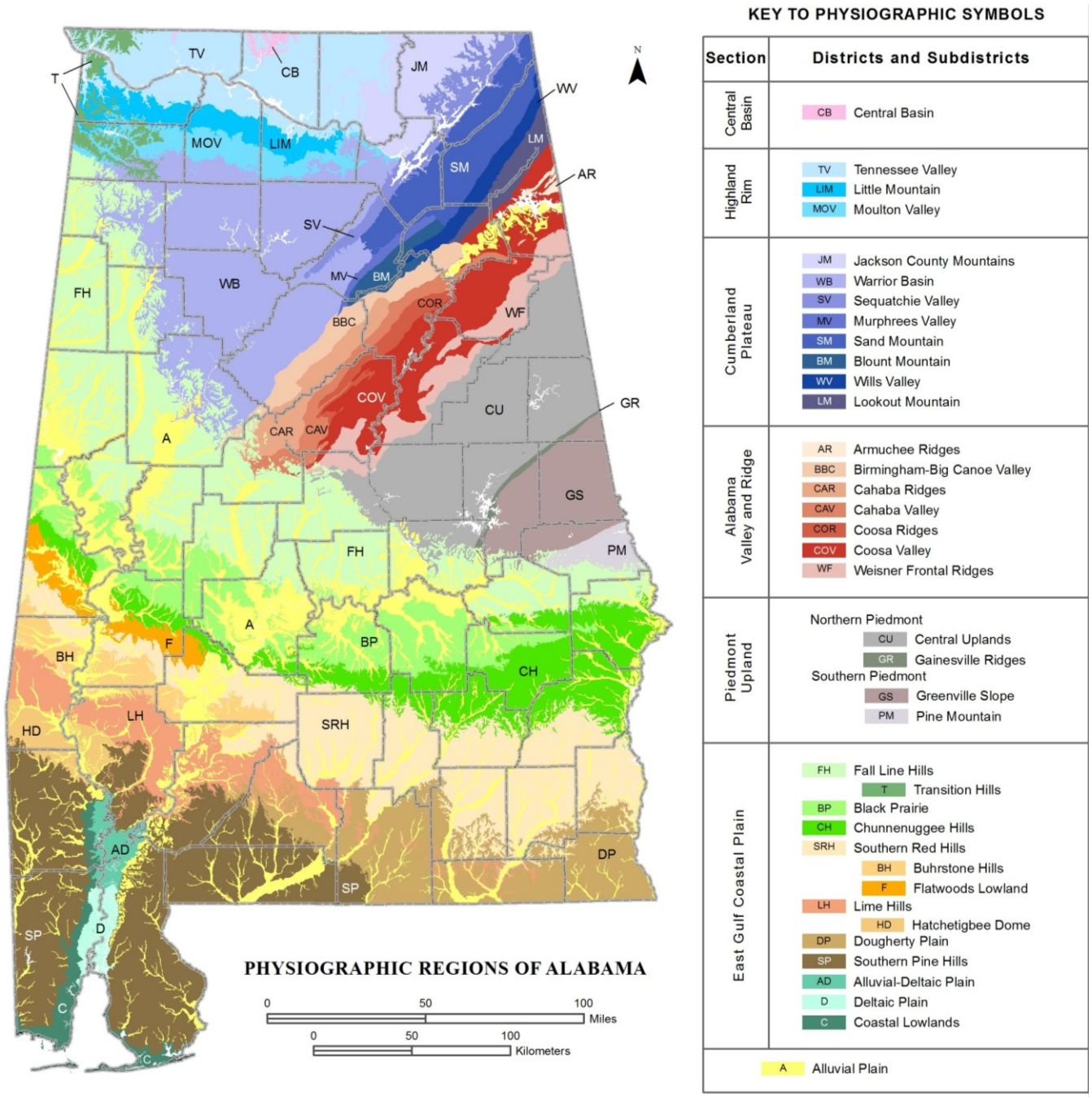


Figure 3.3.1 Physiographic map of Alabama (from Ebersole et al., 2019)

Large water volumes are being produced from carbonate aquifers in the Valley and Ridge groundwater province, which host the majority of public-supply and industrial wells, with clastic aquifers producing smaller volumes.

The smallest physiographic province in Alabama, the **Central Basin**, lies along the Tennessee-Alabama line and is primarily underlain by Ordovician limestones. The small knobby hills are capped by Devonian Chattanooga

Shale and cherty Mississippian age carbonate units. These characteristic knob hills are remnants of maturely dissected low plateaus and include the drainage area closest to the Elk River in Limestone County and small outliers in other counties (Ebersole et al., 2019).

The most common use of groundwater by volume occurs in the East Gulf Coastal Plain groundwater province. The East Gulf Coastal Plain extends from the Fall Line in central Alabama to the Gulf Coast, accounting for over 50% of the state's land area. Groundwater is used in all applications, including public supply and agricultural, industrial, and domestic uses across the region with the primary exception being the cities of Mobile and Spanish Fort, which use surface water. Aquifers in the East Gulf Coastal Plain consist primarily of Mesozoic and Cenozoic clastic, with minor carbonate, sedimentary strata that strike northwest to southeast and dip at a low angle to the southwest across the province (Smith and Guthrie, 2022).



Figure 3.3.2 Russell Cave, six miles northwest of Bridgeport in far northern Jackson County, was declared a National Monument by President John F. Kennedy in 1961 because of its historical and natural significances. It is an archeological site with one of the most complete records of prehistoric cultures in the Southeast. In the 1950s, archeologists uncovered a large quantity of artifacts representing 12,000 years of use in a single place. A short spring run that flows into the "Wet Entrance" of the cave (pictured here) originates as Dry Creek (its headwaters is Rattlesnake Spring on private property several miles north of the cave). Dry Creek loses water along the creek bed and reappears as a spring right below the Russell Cave National Monument viewing boardwalk. After passing through Russell Cave and the neighboring Montague Cave system, the water finally resurfaces couple of miles southeast of the monument at Widows Spring (also known as Widows Creek Spring). Widows Creek flows into Guntersville Lake, a dammed section of the Tennessee River near Bridgeport, Alabama. The cave is hollowed out of Mississippian carbonate layers—specifically the Monteagle Limestone, Bangor Limestone, and Pennington Formation. Layered directly on top of the limestone is the Pennsylvanian Pottsville Formation sandstone. This erosion-resistant sandstone and conglomerate prevents the entire cavern from collapsing as groundwater dissolves the limestone beneath it. Russell Cave has a mapped length of 11.61 miles and is the third longest cave in Alabama and 72nd in America. Photo copyright of Alan Cressler, all rights reserved. https://www.flickr.com/photos/alan_cressler/



Figure 3.3.3 *Left*: Stephens Gap Cave, Stephens Gap-Callahan Cave Preserve, Southeastern Cave Conservancy, Jackson County is developed in Mississippian Bangor Limestone and the underlying Monteagle Limestone. *Right*: Vahalla, 227 Foot Pit, Vahalla Cave Preserve, Southeastern Cave Conservancy, Jackson County. Jackson County holds the record for the highest concentration of caves per square mile in the United States, with more than 3,500 documented caves. That makes this corner of North Alabama one of the premier karst regions in the country. Photographs copyright of Alan Cressler, all rights reserved. https://www.flickr.com/photos/alan_cressler/.

USGS (Weary, 2008) describe the karstic carbonate rocks in Alabama shown in Fig. 3.3.6 as follows.

Gently folded and faulted Paleozoic rocks in northern and northwestern part of the State (labeled GC on map on Fig. 3.3.6) include the: Bangor Limestone, Bangor and Monteagle Limestones, undivided, Monteagle Limestone, Pennington Formation, Pride Mountain Formation and Monteagle Limestone, undivided, Pride Mountain Formation, Sequatchie Formation, Silurian rocks undifferentiated, and the Tuscumbia Limestone.

Several belts of Paleozoic carbonate rocks extend from the northeastern corner of the state to the central part of the state in the Valley and Ridge Province. Potentially karstic bedrock units in these rocks (labeled FFC) include the: Athens Shale, Bangor Limestone, Bibb Dolomite, Brierfield Dolomite, Chepultepec and Copper Shale, Gooch Branch Chert Inman Formation, Ketona Dolomite, Knox Group, Leipers Limestone, Lenoir Limestone and Athens Shale, undivided, Longview Limestone, Monteagle Limestone, Newala Limestone, Newala, and Longview Limestones undivided, Pennington Formation, Pride Mountain Formation, Sawyer Limestone Member of the Brewer Phyllite, Sequatchie Formation, Shady Dolomite, Tuscumbia Limestone, and the Tuscumbia Limestone and Fort Payne Chert, undivided.

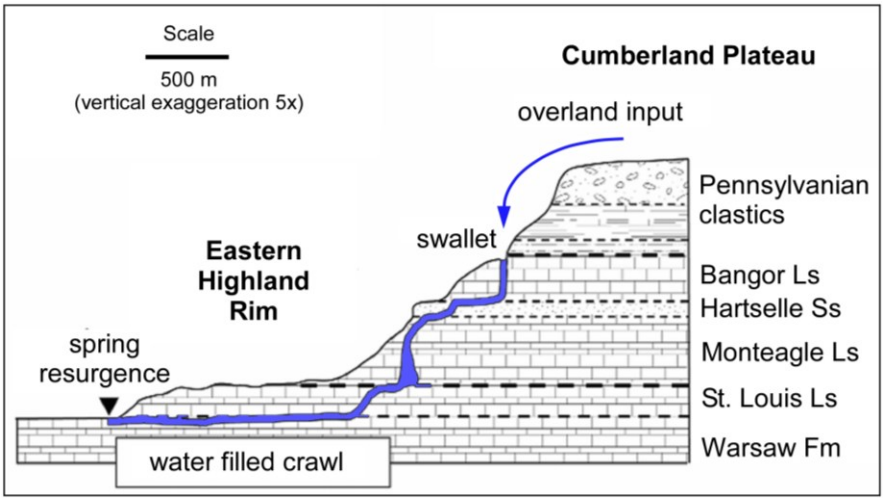


Figure 3.3.4 Schematic plateau-margin model of cave development (modified from Anthony and Granger, 2004; after Crawford, 1984). Surface streams originating on sandstone bedrock of the Cumberland Plateau flow down the escarpment and sink at the contact between sandstone and limestone. Sinking streams form cave passages in the vadose zone leading to the local water table and emerge as springs along the base of the valley wall.

In northeastern Alabama, as well as in the adjacent parts of Georgia and Tennessee (jointly referred to as the TAG region), numerous karst features are developed on two topographic surfaces of regional extent: the Cumberland Plateau and Highland Rim (Fig. 3.3.1). The more extensive and elevated of the two is the Cumberland Plateau, a rugged upland (550–610 m above sea level, asl) bounded on the east by the Valley and Ridge Province and on the west by the solutional surface (275–350 m asl) of the Eastern Highland Rim. Nearly 180 million years of differential lowering between the sandstone-capped Cumberland Plateau and the limestone surface of the Highland Rim has formed a highly dissected, eastward-retreating escarpment along the western margin of the Cumberland Plateau. The lithologic change from sandstone to limestone along the western escarpment provides an optimum hydrogeologic setting for cave and spring development. Crawford (1984) was the first to describe the "plateau-margin" model of cave development (Fig. 3.3.4). In this model, surface streams undersaturated with respect to calcite cross the sandstone caprock of the Cumberland Plateau, sink at the contact between sandstone and limestone, and form cave passage in the vadose zone leading to the local water table. Cave streams emerge as springs along the base of the escarpment or valley wall (Anthony and Granger, 2004).



https://www.flickr.com/photos/alan_cressler/

Figure 3.3.5 Wild Goat Cave in Mississippian Monteagle Limestone, Jackson County. Photo copyright Alan Cressler, all rights reserved.

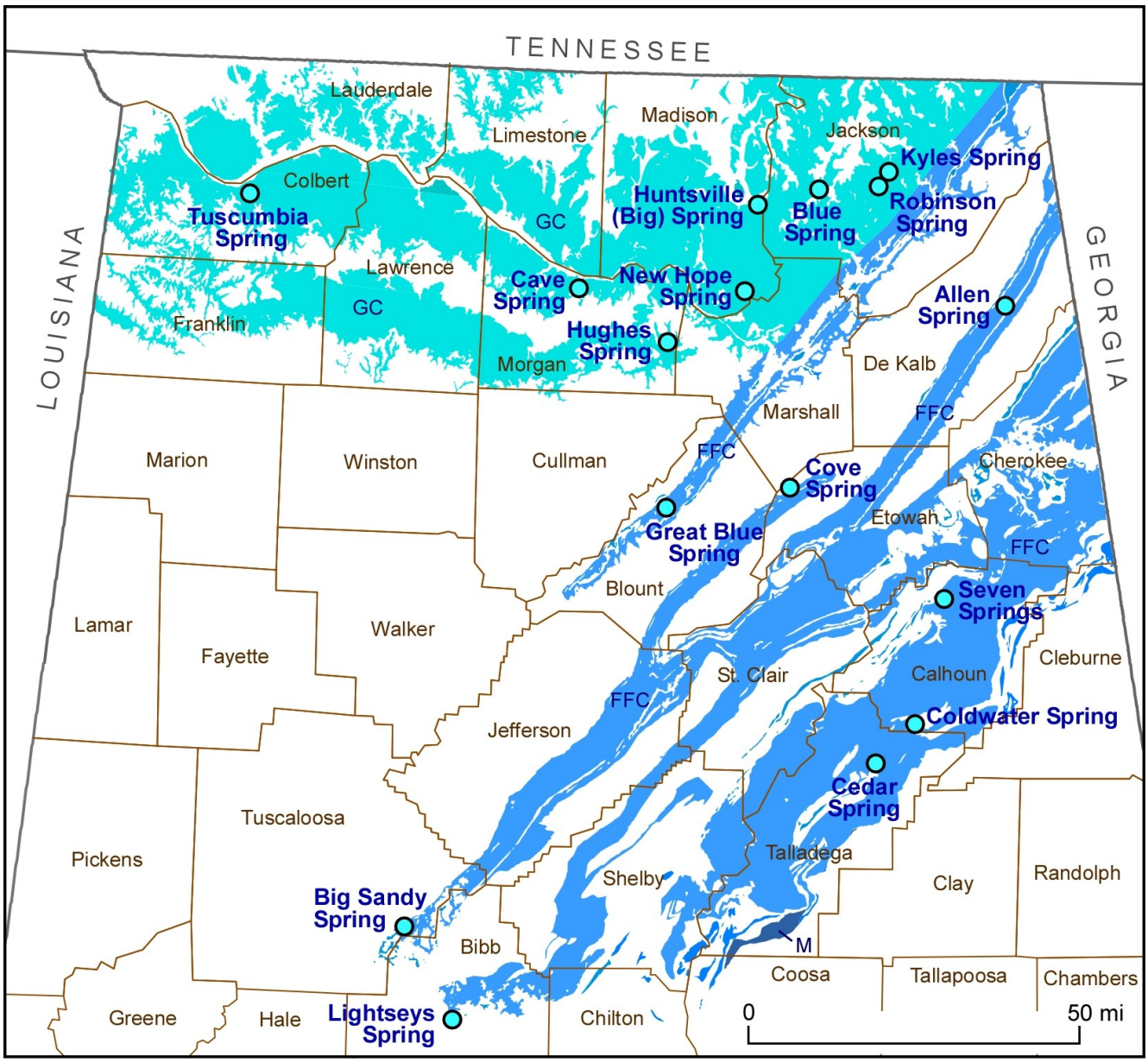


Fig. 3.3.6 Outcrops of karstic carbonate rocks in central and northern Alabama with locations of large karst springs. Karst areas from Weary, 2008. GC— Gently folded and flat-lying carbonates rocks: indurated limestone and dolomite that has not been strongly deformed. Predominantly found in interior plateaus and lowlands. Dissolution may produce solution, collapse, and cover-collapse sinkholes. Where carbonates are thick and extensive, cave systems may be long and complex. Where thin and interbedded with non-carbonates, caves are small and short. Geometry of cave passage patterns often shows stratigraphic and bedding-plane control often resulting in “branchwork" caves (Palmer, 1991). FFC— Folded, faulted carbonate rocks: Limestone and dolomite in areas flanking and in orogenic zones. May be intensely folded and faulted, commonly well jointed, commonly with cleavage. These rocks are located in the Valley and Ridge Province on this map and most are Paleozoic in age. Dissolution may produce solution, collapse, and cover-collapse sinkholes. Caves range from small and simple to long and complex systems. Geometry of cave passage patterns tend to show at least some structural control producing "network" caves (Palmer, 1991). M—Marbles and metalimestones: highly deformed carbonate rocks, usually found In long, thin, linear belts or pods. Mapped areas are often exaggerated as these rocks are usually mapped with associated, non-soluble metamorphic rocks. Dissolution may result in solution, collapse, and cover-collapse sinkholes and small, short caves.

Table 3.3.1 Large karst springs in Alabama. Based on information in Smith and Guthrie, 2022. *Provided by owner. **Blue Springs in Barbour County is south of the area shown on Fig. 3.3.6.

Spring	County	Average Discharge Rate gpm (cfs)	Aquifer	Spring Status
Tuscumbia Big Spring	Colbert	20,769 (46.3)	Tuscumbia Limestone	Municipal Supply & City Park
Cave Spring	Morgan	3,119 (6.9)	Monteagle Limestone	National Wildlife Refuge
Hughes Spring	Morgan	3,013 (6.7)	Bangor Limestone	Private
New Hope Spring	Madison	2,852 (6.3)	Monteagle Limestone	Private
Huntsville (Big) Spring	Madison	4,169 (9.3)	Tuscumbia Limestone	City Park
Kyles Spring	Jackson	9,668 (21.5)	Monteagle Limestone	Private
Robinson Spring	Jackson	9,414 (21.0)	Monteagle Limestone	Private
Blue Spring	Jackson	6,175 (13.8)	Tuscumbia Limestone	Private
Allen Spring	De Kalb	1,700 (3.8)	Monteagle Limestone	Private
Cove Spring	Etowah	1,162 (2.6)	Bangor Limestone	Municipal Supply
Great Blue Spring	Blount	625* (1.4)	Bangor Limestone	Private
Seven Springs	Calhoun	2,135 (4.8)	Newala & Longview Ls.	Municipal Supply
Coldwater Spring	Calhoun	17,610 (39.2)	Shady Dolomite	Municipal Supply
Cedar Spring	Talladega	2,737 (6.1)	Knox Group Carbonates	Private
Big Sandy Spring	Tuscaloosa	5,547 (12.4)	Knox Group Carbonates	Private
Lightseys Spring	Bibb	9,109 (20.3)	Knox Group Carbonates	Private
Blue Springs**	Barbour	2,862 (7.7)	Clayton Formation	State Park

Tuscumbia Big Spring, Colbert County

Tuscumbia Big Spring, which issues from solution openings in the Tuscumbia Limestone, is used for municipal water supply by Tuscumbia Water Department. Water is pumped directly from the spring to the Tuscumbia Water Treatment Plant, a nationally recognized facility designed by Garver that utilizes coagulation, sedimentation, filtration, chlorination, and fluoridation. The dual Ultrafiltration (UF) and Reverse Osmosis (RO) system was specifically built to counteract "hard water" stemming from the local carbonate rock layers, effectively lowering the water's alkalinity to prevent clogged home plumbing and appliances. The plant supplies up to 4 million gallons per day to over 5,000 customers in Tuscumbia. Water is also supplied to the Littleville, Spring Valley, and Colbert County Water Systems.

The overflow from the spring feeds an engineered lake constructed for the municipal park in Tuscumbia, Spring Park. The park's lake features a memorial fountain dedicated to Princess Im-Mi-Ah-Key, the wife of Chickasaw Chief Tuscumbia. Its 51 water jets shoot up to 150 feet in the air, performing timed light and music shows during holidays' evenings.

The centerpiece of Spring Park is Coldwater Falls is a man-made waterfall that is constructed with over 2,000 tons of sandstone. It stretches 80 feet wide and is 42 feet tall. Near the falls, an Indian statue, Sacred Tears, stands 12 feet in height and pays tribute to Tuscumbia's early heritage in commemoration of Native Americans.

The highly photographed waterfall is considered the world's largest man-made natural stone waterfall in existence. The waterfall was under construction for 120 days and the largest stone weighs 77,000 pounds.

The period of record for Tuscumbia Big Spring, the largest in Alabama, is from 1929 to 2018, during which time 24 discharge measurements were collected. It is the largest spring in Alabama with an average discharge rate of 20,769 gpm (46.3 cfs). The highest recorded discharge rate is 46,791 gpm measured April 12, 2018, and the lowest recorded discharge rate is 200 gpm measured August 6, 1929 (Smith and Guthrie, 2022).



Figure 3.3.7 *Left*: Tuscumbia Big Spring receiving pond in the city's Spring Park. Photo courtesy of Alea Ullerly. Available at https://huntsvillewonders.com/tuscumbia-spring-park/. *Right*: A memorial fountain in the Tuscumbia Big Spring receiving pond is dedicated to Princess Im-Mi-Ah-Key, the wife of Chickasaw Chief Tuscumbia. Its 51 water jets shoot up to 150 feet in the air, performing timed light and music shows during holiday evenings. Photo courtesy of Colbert County. Available at https://www.colbertcountytourism.org/outdoors/spring-park/.

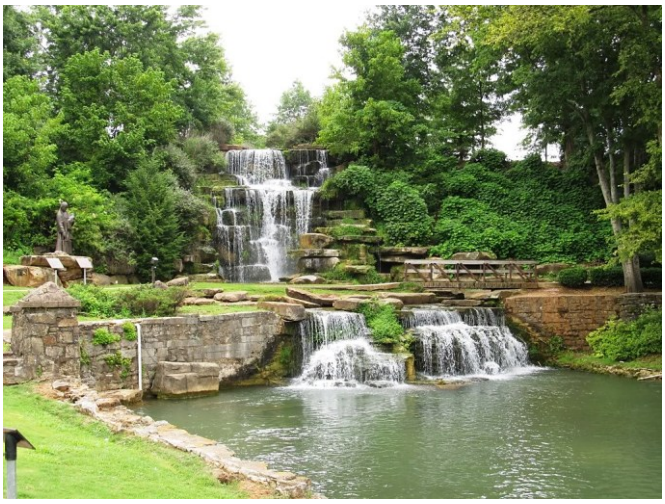


Figure 3.3.8 Coldwater Falls, the world's largest man-made natural stone waterfall to be known in existence. Photo courtesy of City of Tuscumbia. Available at https://cityoftuscumbia.org/spring-park-2/

Cave Spring, Morgan County

Cave Spring, located within the Wheeler National Wildlife Refuge in northern Morgan County, issues from a cave formed by solution channels along bedding planes and fracture zones in an outcrop of the Monteagle Limestone at the base of a hill formed by the Monteagle Limestone and Hartselle Sandstone. The spring discharges to a natural unnamed receiving channel which eventually flows to the Tennessee River.

The Cave Spring cave has been visited for thousands of years. The combination of shelter, fresh water, and abundant food has attracted humans and other wildlife to its safety. The cave's current residents include several thousand Gray Bats, an endangered species whose population stronghold is in northeastern Alabama, and the rare Cave Spring *Cave Spider*, endemic exclusively to this single cave system (https://www.gbif.org/taxon/478XZ; see also Hedin and Milne, 2023).

The period of record for Cave Spring is from 1958 to 2018, during which time 25 discharge measurements were collected. Cave Spring is a third-magnitude spring with an average discharge rate of 3,119 gpm (6.9 cfs). The highest recorded discharge rate is 17,754 gpm measured April 26, 2018, and the lowest recorded discharge rate is 0 gpm measured October 20, 1981 (Smith and Guthrie, 2022).



Figure 3.3.9 Left: Cave Spring orifice. Right: View from cave entrance towards the receiving spring run. From Smith and Guthrie, 2022.



Figure 3.3.10 Cave Spring spider relies heavily on the cave's summer residents: the federally endangered Grey Bats. The massive bat colony leaves behind guano, which supports a rich micro-ecosystem of cave flies, springtails, and millipedes. The *Nesticus jonesi* spiders build delicate webs along the cave walls to capture these insects. Photo courtesy of niemiller_nature. https://www.instagram.com/p/DGt5TA0MfMx/

Hughes Spring, Morgan County

Hughes Spring issues from a cave developed in a vertical face or bluff in an outcrop of Bangor Limestone. Bedding planes observed in the limestone outcrop suggest the cave was formed through dissolution of the limestone by groundwater movement along the bedding planes. The spring discharges directly to a natural spring pool and the receiving channel, Hughes Creek, eventually flows to Cotaco Creek, a tributary of the Tennessee River.

The period of record for Hughes Spring is from 1958 to 2018, during which time 47 discharge measurements were collected. The spring is of third-magnitude, with an average discharge rate of 3,013 gpm (6.7 cfs). The highest recorded discharge rate is 17,282 gpm measured April 26, 2018, and the lowest discharge rate is 108 gpm measured October 6, 1987. The spring is privately owned and is not currently in use (Smith and Guthrie, 2022).

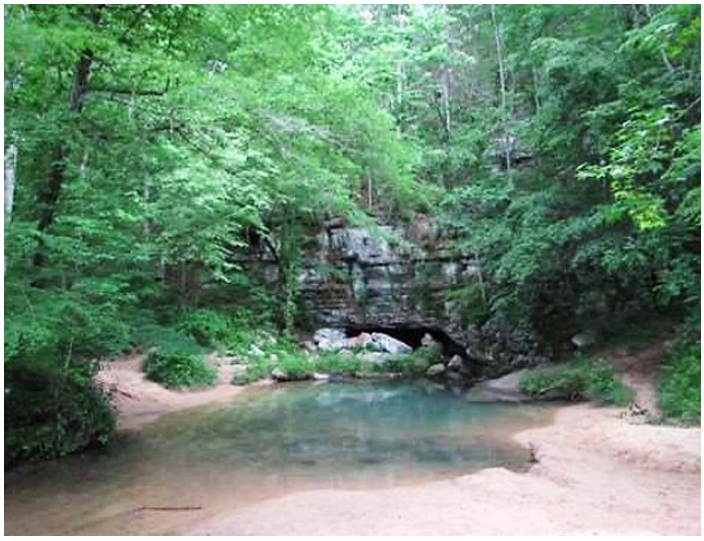


Figure 3.3.11 Hughes Spring discharge location and receiving channel. From Smith and Guthrie, 2022.

Huntsville (Big) Spring, Morgan County

Big Spring in Huntsville (also known as Huntsville Spring) issues from a bluff face formed by an outcrop of the Tuscumbia Limestone and discharges to the engineered receiving pool and stream channel within the surrounding Big Spring International Park. The Indian Creek Canal was constructed to connect this area with the Tennessee River, allowing cotton and other goods to be transported to market. Construction of the canal began in the early 1820s and was completed in 1831 (according to Alabama Historical Association, 1965 Historical Marker). The Indian Creek Canal flows to Huntsville Spring Branch, a tributary of the Tennessee River.

Big Spring is a third-magnitude spring with an average discharge rate of 4,169 gpm (9.3 cfs). The highest recorded discharge rate is 13,800 gpm measured on August 11, 1958, and the lowest recorded discharge rate is 0 gpm measured on October 4, 2000 (Smith and Guthrie, 2022).

Historically, Big Spring was utilized for the earliest public water supply in the United States west of the Appalachians, and it used cedar log pipes for water distribution. For decades during the early 20th century, the sale of this water was the largest single source of income for the city's general fund.

On the web page of the City of Huntsville, one can read that "More than 200 years ago, future U.S. Senator John Williams Walker remarked that "Huntsville is situated around the finest spring in the world," and two centuries later, it's still true. Huntsville's Big Spring Park is located at the heart of the city, just off the courthouse square, and will always be near and dear to the hearts of Huntsvillians.

In 1805, Revolutionary War veteran John Hunt chose Big Spring as the location for a new community – the 7 to 20 million gallons of fresh water the spring produces every day were an invaluable resource for the new town. Before it was Huntsville, the community was called "Hunt's Spring," in honor of the two ingredients on which it was started. Hunt built the first cabin in what would become Huntsville atop the bluff by the spring. It would be the better part of a century before Big Spring became part of Big Spring Park; the U.S. Army Corps of Engineers renovated the site of the spring beginning in 1898, under the leadership of Hiram Chittenden, who had just been involved in the early development of Yellowstone National Park."

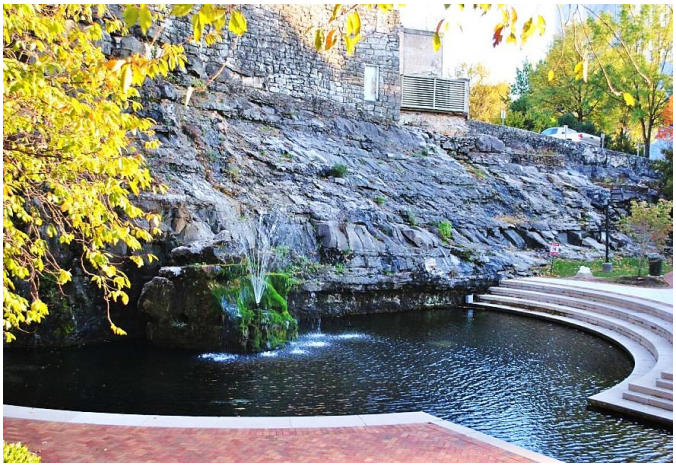




Figure 3.3.12 Big Spring in Huntsville, Alabama. *Left*: Spring orifice. Photo courtesy of the City of Huntsville. *Right*: The Indian Creek Canal. Photo courtesy of Gheorghe Ponta, Alabama Geological Survey.



Figure 3.3.13 In 1805, Revolutionary War veteran John Hunt chose Big Spring as the location for a new community. Courtesy of the City of Huntsville.

Unfortunately, the growing city used dolines and caves as natural sewer lines and garbage dumps. Eventually, the spring had to be abandoned in the mid-20th century and drinking water is now produced from other sources. Today, Huntsville relies on surface water from the Tennessee River and protected deep wells.

Before it became known globally as the "Rocket City," Huntsville was nicknamed "Cave City" due to its unique karst topography. Huntsville's city limits contain over 250 documented caves. This includes the nearby, highly protected Shelta Cave, which is managed by the National Speleological Society and is famous for harboring ancient, endangered blind cave shrimp and rare crayfish species.

Directly beneath the bustling streets of downtown sits Big Spring Cave, a massive natural cavern system that runs directly under the Madison County Courthouse and the surrounding Courthouse Square. The cave is completely closed to the general public to preserve its delicate environment and ensure structural safety. While its original natural entrances near the spring and downtown banks have been sealed off, researchers and safety units access it through a secure manhole cover located in the middle of Green Street.

When the modern courthouse was being planned, geological drillings revealed the exact path of the cave. To prevent the building from collapsing into the cavern, engineers shifted the blueprint footprint, leaving the main building intentionally off-center on the square. To reduce the total downward pressure on the thinnest section of the cave's limestone ceiling, the northern section of the courthouse was constructed shorter than the southern section. Massive concrete pillars and reinforcement beams are anchored deep inside the bedrock and directly inside the cave itself to support the courthouse foundations. These support beams are completely visible to researchers exploring the cavern below.



Figure 3.3.14 Big Spring Cave, beneath the courthouse in Huntsville, Alabama. *Left*: Part of the width of the main passage, where beds of the nearly horizontal limestone have fallen from the roof, so that the open space is now on top of slabs stacked 5 m deep. *Right*: A steel-cased, bored pile that extends through the cave and debris fill, and carries its load to stable rock beneath the cave floor. From Waltham, 2016.



Figure 3.3.15 Huntsville Grotto in the Lake Room of Shelta Cave. Photo by Eric Hammon. Shelta Cave is a historically and biologically significant 2,500-foot-long limestone cavern located entirely within the city limits of Huntsville. Designated as a National Natural Landmark in 1972, it serves as a critical nature preserve and underground laboratory owned and managed by the National Speleological Society (NSS), whose national headquarters sits directly above the cave system. Purchased in 1888 by Henry Fuller—who named it "Shelta" after his daughter—the cave was developed into a commercial public entertainment venue. Fuller installed electric lighting, built a subterranean wooden bandstand, and operated an underground bar and dance hall. Locals frequently beat the brutal Alabama summer heat by going underground for dances and boat rides across the massive subterranean lakes.

https://caves.org/preserve/shelta-cave-nature-preserve/



Figure 3.3.16 **McCrary Spring** in Jackson County is a privately owned and currently not in use. It issues from openings and solution channels formed along fractures and bedding planes in the Tuscumbia Limestone outcropping at the base of a ridge (Figure 8.45). The spring discharges directly to the receiving channel, Big Coon Creek, a tributary of the Tennessee River. The period of record for McCrary Spring is from 1971 to 2017, during which six discharge measurements were collected, with an average of 6,895 gpm. The highest recorded discharge rate is 16,000 GPM measured April 12, 1971, and the lowest discharge rate recorded is 5 GPM measured on November 10, 1971 (Smith and Guthrie, 2022).



Figure 3.3.17 **Robinson Spring** in Jackson County is a privately owned spring that is currently not in use. It issues from a cave developed in the Monteagle Limestone outcropping at the base of a hill and discharges directly to the receiving channel, Robinson Creek, a tributary of Mud Creek and the Tennessee River. The period of record for Robinson Spring is from 1971 to 2017, during which time six discharge measurements were collected Robinson Spring is a second-magnitude spring with an average discharge rate of 9,414 gpm. The highest recorded discharge rate is 20,000 gpm measured April 8, 1971, and the lowest discharge rate recorded is 750 gpm measured November 10, 1971 (Smith and Guthrie, 2022).



Figure 3.3.18 **Blue Spring** in Jackson County is privately owned and currently not in use. It issues from the Tuscumbia Limestone outcropping at the base of a ridge, as a "pool spring." The spring pool discharges to Guess Creek which flows to Paint Rock River, a tributary of the Tennessee River. The period of record for Blue Spring is from 1971 to 2017, during which time five discharge measurements were collected. An average discharge rate is 6,175 gpm. The highest recorded discharge rate is 12,200 gpm measured February 20, 1986, and the lowest discharge rate is 400 gpm measured November 10, 1971 (Smith and Guthrie, 2022).

Great Blue Spring, Blount County

Great Blue Spring in Blountsville issues from the Bangor Aquifer, with an average discharge rate of 900,000 gallons per day (1.4 cfs) as reported by the owner, Blue Spring Bottling Water company. The water is harvested and bottled directly at the spring, also historically known as the Big Blue Spring. Blue Spring Living Water fills approximately 30,000 bottles a day and distributes throughout Alabama. Water temperature of this ascending, blue hole-type spring is a constant 52 degrees Fahrenheit.



Figure 3.3.19 Great Blue Spring in Blountsville is an ascending, blue hole-type spring owned by Blue Spring Bottling Water botting company. Photo courtesy of https://bluespringlivingwater.com/.

Coldwater Spring, Calhoun County

Coldwater Spring is owned and operated by the Anniston Water Works & Sewer Board and currently used for municipal supply. It is Anniston's primary source of drinking water, utilized since the late 1800's (https://www.awwsb.org/). Coldwater spring issues from residuum at the base of a hill formed on the Shady Dolomite. The spring discharges directly from the formation into the municipal supply system's engineered containment structure where a portion of the spring's water is captured and transferred to the municipal supply system for use throughout local community. The remaining water is allowed to discharge from the containment structure into a natural channel eventually entering Choccolocco Creek, a tributary of the Coosa River.

The period of record for Coldwater Spring, the second largest spring in Alabama, is from 1928 to 2018, during which time 25 discharge measurements were collected. It is a second-magnitude spring with an average discharge rate of 17,610 gpm (39.2 cfs). The highest recorded discharge rate was measured at 23,339 gpm on May 1, 2018, and the lowest recorded discharge rate was on October 31, 2006 (7,958 gpm).

Over eighty years of military and industrial waste in the broader Anniston area caused groundwater contamination of Coldwater Springs and groundwater in its drainage area. The primary chemical of concern in the

untreated spring water is TCE, a volatile organic compound (VOC) historically used as an industrial degreaser at the Anniston Army Depot. Despite the raw groundwater being contaminated, Anniston's municipal drinking water is reportedly safe to drink and meets all federal standards (Calhoun Journal; Anniston Water Works Releases Water Quality Report - Calhoun Journal).

The Anniston Water Works & Sewer Board treats the raw spring water at the Paul B. Krebs Water Treatment Plant. In 2004, the U.S. Army funded the construction of five massive air-stripping towers specifically designed to vaporize and completely remove VOCs like TCE from the water before it ever reaches the public distribution system. The Anniston Water Works Annual Reports continue to confirm that finished municipal tap water registers zero violations.

According to U.S. Environmental Protection Agency, the U.S. Army is currently constructing upgraded, below-ground pump-and-treat systems to contain the groundwater contaminant plumes before they reach the spring. Local advisory boards continue to advocate for faster characterization of contaminant plumes and more aggressive groundwater remediation. A multi-agency task force, including the EPA, the U.S. Fish and Wildlife Service, and the Alabama Department of Environmental Management (ADEM), remains actively engaged at the site to protect the Pygmy Sculpin. This tiny fish is entirely unique to Alabama and lives exclusively in the Coldwater Spring pool and its immediate run. Because the fish lives directly in the contaminated raw groundwater, scientists continuously monitor toxicity levels to prevent the species from going extinct (U.S. Environmental Protection Agency, 2026).



Figure 3.3.20 Coldwater Spring in Calhoun County, the second largest spring in Alabama, is used for the public water supply of the City of Anniston. Top photo courtesy of Gheorghe Ponta, Alabama Geological Survey. Bottom photo courtesy of Anniston Water Works & Sewer Board.

Cedar Spring, Talladega County

A privately owned Cedar Spring issues from a cave formed along bedding planes and fractures developed in limestone of the Knox Group undifferentiated. It discharges to a natural stream channel that flows to Cheaha Creek, a tributary of Choccolocco Creek and the Coosa River. Cedar Spring is currently used for private recreation.

Historically, the spring was used to supply a tannery in the early to mid-1800s and was later the site of nationally sanctioned equestrian competitions in the 1950s and 1960s. The spring's name "Cedar Spring" was given due to the cedar log home located next to the spring. The cedar home was moved to the location in the late 1950s to save it from flooding prior to the construction of Logan Martin Lake (J. P. Whitson, November 2021, personal communication).



The period of record for Cedar Spring is from 1928 to 2018, during which time 38 discharge measurements were collected. It is a third-magnitude spring with an average discharge rate of 2,737 gpm (6.1 cfs). The highest recorded discharge rate is 3,830 gpm, collected March 13, 1975, and the lowest recorded discharge rate is 1,849 gpm measured November 8, 1988 (Smith and Guthrie, 2022).

Figure 3.3.21 Cedar Spring. From Smith and Guthrie, 2022.

Blue Springs, Barbour County

Blue Springs is in Blue Springs State Park in Clio, in the Wiregrass Region of Alabama. The park's main attractions, the swimming pools with sandy bottom, are fed by a crystal-clear spring that remains a comfortable 68 degrees Fahrenheit year-round (https://www.alapark.com/parks/blue-springs-state-park).

Blue Springs has a long history of recreational use dating back to at least the latter part of the 19th century. In 1890, the Harrison Family built the first hotel to accommodate travelers visiting the popular summer resort. The Whigham Family constructed the second hotel in 1900 and enclosed the spring with concrete walls in 1913 to stabilize the spring pool. In 1963, Blue Springs was designated as an Alabama state park.



Blue Springs discharges from the Paleocene Clayton Formation. It is a third-magnitude spring with an average discharge rate of 2,862 gpm (7.7 cfs; Smith and Guthrie, 2022).

Figure 3.3.22 Swimming pools fed by Blue Springs in the Blue Springs State Park. Courtesy of Alabama Department of Archives and History.



Figure 3.3.23 Blue Hole Spring in Bear Hollow, about 3.6 miles due east of Hytop in north Jackson County. Photograph by Samuel Lee Fields; available at https://www.facebook.com/groups/AlabamaTheBeautiful/posts/6045480318843414/

3.4 Tennessee

As explained by Bradley (2021), karst terrains are characteristic of much of the eastern two thirds of Tennessee, and include the Highland Rim (Mississippian carbonates), Central Basin (Ordovician carbonates), and Valley and Ridge (Cambrian-Ordovician carbonates) physiographic provinces (Fig. 3.4.1). The escarpments on the east and west sides of the Cumberland Plateau are also significant in the occurrence and development of karst features. To a much lesser extent, caves and karst features also occur along the Western Valley of the Tennessee River and in the Blue Ridge Mountains in East Tennessee.

Tennessee has more than 10,000 documented caves (Niemiller et al., 2016; Tennessee Cave Survey (TCS; 2020), making up more than 20 percent of the documented caves in the United States, more than any other state (Niemiller et al., 2016).

The western Highland Rim is primarily underlain by the Mississippian Fort Payne Formation and Warsaw Limestone, with the St. Louis Limestone occurring in the northern part of the western Highland Rim. The northern part of the western Highland Rim is a continuation of the Pennyroyal Plain karst region in Kentucky. The Mississippian formations generally become younger progressing to the north, with the St. Louis and Ste. Genevieve Limestones exposed along the Tennessee-Kentucky border (Kemmerly, 1982).

Most of the eastern Highland Rim is also underlain by the Fort Payne Formation and Warsaw Limestone, with the Warsaw and St. Louis Limestones occurring in the northern part of the eastern Highland Rim. To the east, the units become younger approaching the Cumberland Plateau, and the eastern Highland Rim is underlain by the Monteagle and Bangor Limestones and the Hartselle Formation (Brahana and Bradley, 1986). Continuing east, the

Mississippian carbonates are overlain by the Mississippian Pennington Formation and the Pennsylvanian sandstones and shales of the Cumberland Plateau.

The carbonate formations in the Central Basin are generally thin bedded, with intervening shale and shaley limestone. From youngest to oldest, they are the Ordovician Bigby-Cannon Formation, Hermitage Formation, Carters Limestone, Ridley Formation, and the Murfreesboro Limestone (Brahana and Bradley, 1985a).

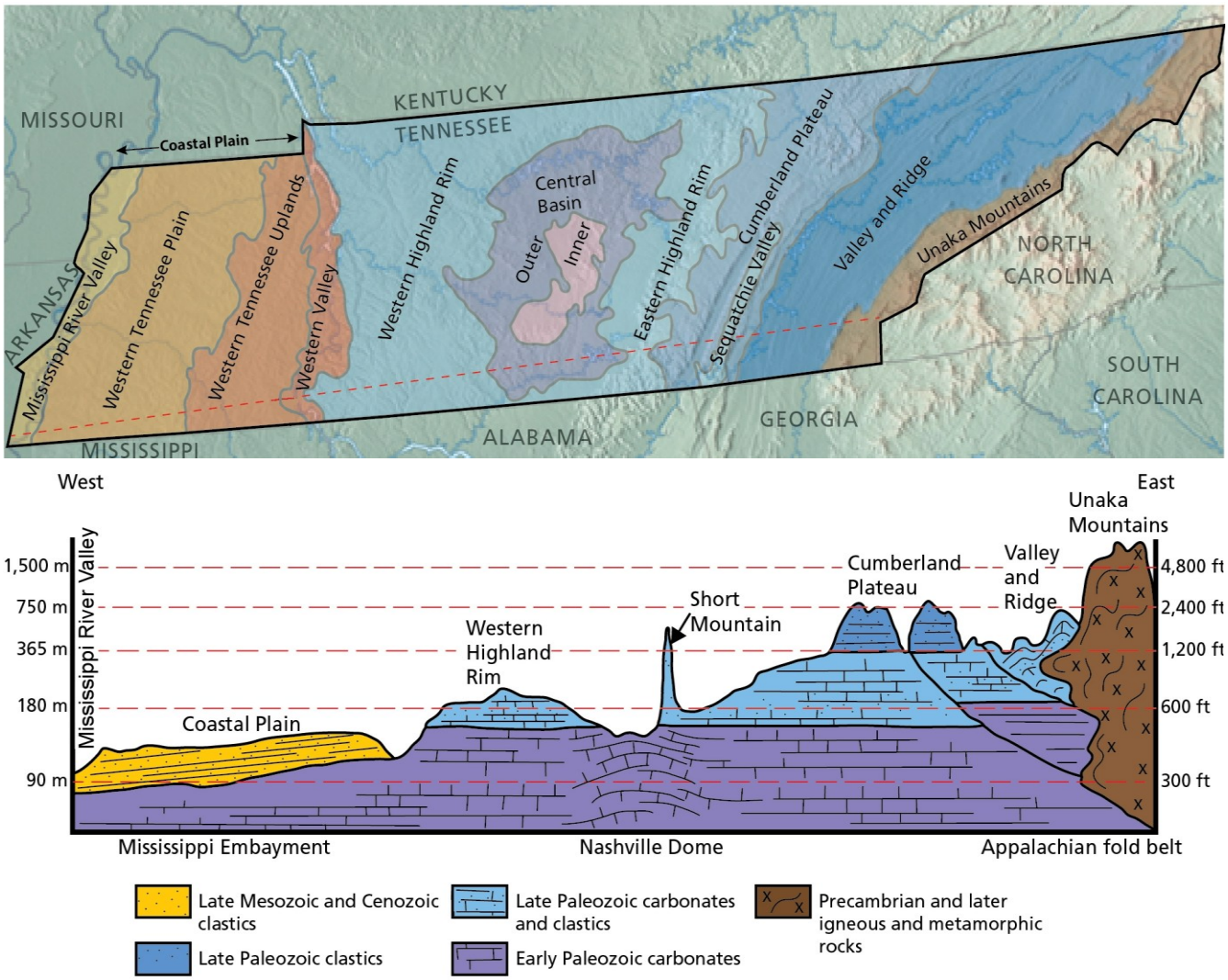


Figure 3.4.1 *Top*: Physiographic provinces of Tennessee. *Bottom*: cross section through Tennessee: From west to east, the section crosses from the low-lying coastal plain, upwards across the highland rim and into the central basin before rising further east onto the Cumberland Plateau and ultimately into the Unaka Mountains of the Appalachian Mountains. The trace of the section is marked by a red dashed line on the top map. The vertical scale is marked and nonlinear to emphasize the differences in each area's topographic expression. From Thornberry-Ehrlich, 2012; after Harris, 2012.

The Cumberland Plateau province is capped by Pennsylvanian formations, primarily sandstone, shale, and some conglomerate. The Cumberland Plateau is about 600 to more than 1,000 ft higher in elevation than the Highland Rim province to the west and the Valley and Ridge province to the east. Along the edge of the Cumberland Plateau, the underlying carbonates are exposed and eroded mechanically and chemically (Crawford, 1987). The elevation difference along the escarpments, steep hydraulic gradients, and slightly acidic water create a narrow, but

extremely important karst region with large springs and stream resurgences and a very high density of caves (Bradley, 2021).

The broad valleys of the Valley and Ridge province are underlain by limestone and shale of the Conasauga Group of Cambrian age and Chickamauga Limestone of Ordovician age. The high ridges are formed on more resistant rocks, principally cherty dolomite and limestone of the Knox Group, sandstone members of the Rockwood and Rome Formations, and other formations. The linear pattern of the geologic structure in the Valley and Ridge province, consisting of northeastward-trending parallel ridges and valleys, resulted from compressive stresses which folded and faulted the sedimentary rocks and resulted in the predominant southeasterly dip of the formations (Sun et al., 1963).

Karst aquifers in Tennessee provided close to 40 million gallons per day to public water systems in 2015 with the carbonate formations in the Valley and Ridge province of East Tennessee being the second most productive aquifer in the state, after the Tertiary Sand Aquifer System in the Mississippi River Valley and Western Plains (Bradley, 2021.) Public water systems in East Tennessee produced about 39 Mgal/d from the Valley and Ridge aquifers to supply water to about 565,000 people. Notably, however, the occurrence of caves and karst features in East Tennessee, the use of karst aquifers for public water supply, and the susceptibility of the systems to contamination has not been fully evaluated (Bradley, 2021).



Figure 3.4. 2 Deciduous trees growing within karren in Ordovician Ridley Limestone at Stones River National Battlefield northwest of Murfreesboro in Rutherford County, central Tennessee. Karren entrap organic debris and act as water conduits; this combination creates relatively deep soil that supports plant life. Soil formation and plant growth mechanically and chemically weather and widen the karren. Photograph by Trista L. Thornberry-Ehrlich in March 2009.



Figure 3.4.3 Fall Creek Falls in Fall Creek Falls State Park, Van Buren County. Exposed is Mississippian Monteagle Limestone. With a height of 256 feet, Fall Creek Falls is reportedly the highest waterfall in the eastern United States. Photo courtesy of Tennessee State Parks.

https://tnstateparks.com/parks/fall-creek-falls

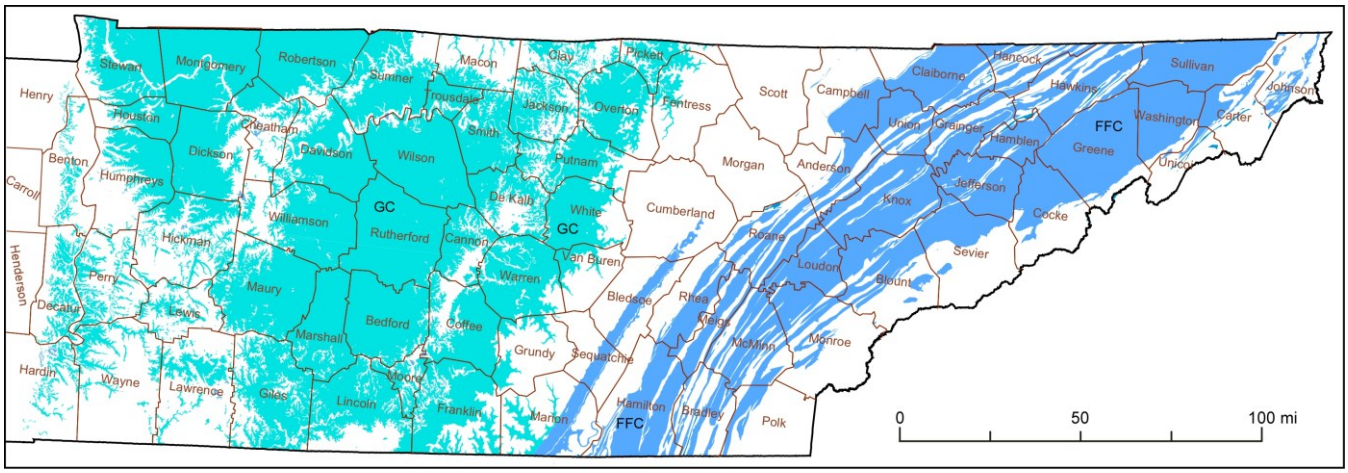


Figure 3.4.4 Outcrops of karstic carbonate rocks in central and eastern Tennessee (from Weary, 2008). GC: Gently folded and flat-lying carbonates rocks: indurated limestone and dolomite that has not been strongly deformed. Predominantly found in interior plateaus and lowlands. Dissolution may produce solution, collapse, and cover-collapse sinkholes. Where carbonates are thick and extensive, cave systems may be long and complex. Where thin and interbedded with non-carbonates, caves are small and short. Geometry of cave passage patterns often shows stratigraphic and bedding-plane control often resulting in “branchwork" caves (Palmer, 1991). FFC: Folded, faulted carbonate rocks: Limestone and dolomite in areas flanking and in orogenic zones. May be intensely folded and faulted, commonly well jointed, commonly with cleavage. These rocks are located in the Valley and Ridge Province on this map and most are Paleozoic in age. Dissolution may produce solution, collapse, and cover-collapse sinkholes. Caves range from small and simple to long and complex systems. Geometry of cave passage patterns tend to show at least some structural control producing "network" caves (Palmer, 1991).



Figure 3.4.5 Hamilton Cave in Bledsoe County. The cave is developed in the Mississippian Pennington Formation. Limestone in this formation is characterized by horizontal bedding, and breakdown is often slabby. Photo copyright Alan Cressler, all rights reserved. https://www.flickr.com/photos/alan_cressler/



Figure 3.4.6 *Left*: Grotto Cave, Marion County. This is one of Alan Cressler's favorite cave images. The cave room is about 30 feet high with a small skylight entrance in the ceiling. This provided a small amount light on the waterfall. *Right*: Lost Creek Cave, White County. Photographs copyright Alan Cressler, all rights reserved.
https://www.flickr.com/photos/alan_cressler/



Figure 3.4.7 Cumberland Caverns in McMinnville, Warren County is Tennessee's longest show cave, spanning over 27 mapped miles, and is a U.S. National Natural Landmark. It holds a legendary place in American music history as the original home of the Emmy-winning PBS series Bluegrass Underground. Photo courtesy of Cumberland Caverns.

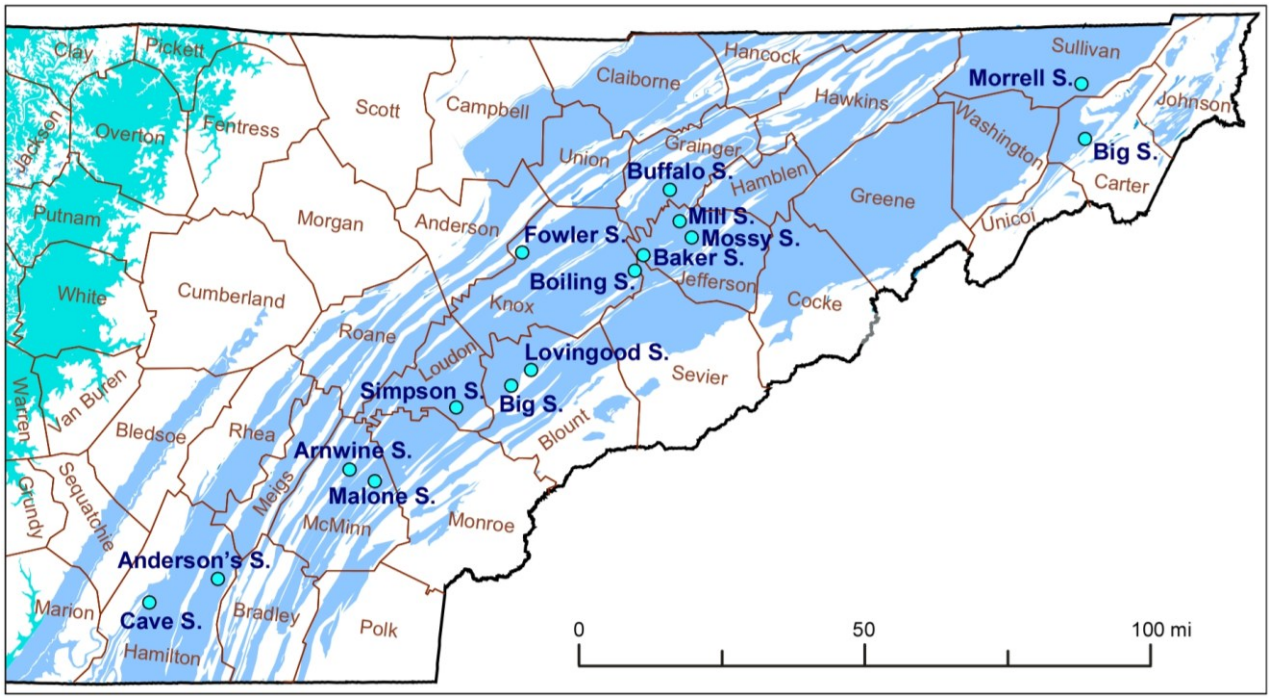


Figure 3.4.8 Locations of karst springs with an average discharge rate greater than 2,000 gpm (5.3 cfs) in East Tennessee, based on information in Sun et al., 1963. Outcrops of karstic carbonate rocks are from Weary, 2008; see also Fig. 3.10.54. Note that on this map, the Sequatchie Valley (see Fig. 3.10.51) is included in the "folded, faulted carbonate rocks", whereas Sun et al. place it outside the Valley and Ridge province.

Table 3.4.1 Large karst springs in Eastern Tennessee with an average discharge rate greater than 2,000 gpm (5.3 cfs). Based on information in Sun et al., 1963.

Spring	County	Average Discharge Rate gpm (cfs)	Aquifer	Spring Status
Big Spring	Blount	3,040 (8.1)	Knox Group Carbonates	Private
Lovingood Spring	Blount	2,130 (5.7)	Knox Group Carbonates	Private
Big Spring	Carter	3,370 (9.0)	Knox Group Carbonates	Municipal Supply
Buffalo Spring	Grainger	5,070 (13.6)	Knox Group Carbonates	Wildlife Management Area
Anderson's Spring	Hamilton	3,380 (9.0)	Knox Group Carbonates	Private
Cave Spring	Hamilton	9,640 (25.8)	Knox Group Carbonates	Municipal Supply
Baker Spring	Jefferson	2,660 (7.1)	Lenoir Limestone	Private
Mill	Jefferson	2,210 (5.9)	Knox Group Carbonates	Private
Mossy Spring	Jefferson	13,300 (35.6)	Knox Group Carbonates	Municipal Supply
Boiling Spring	Knox	4,180 (11.2)	Lenoir Limestone	Private
Fowler Spring	Knox	2,080 (5.6)	Knox Group Carbonates	Municipal Supply
Simpson Spring	Loudon	3,480 (9.3)	Knox Group Carbonates	Private
Arnwine (Cagle) Spring	McMinn	2,460 (6.6)	Knox Group Carbonates	Private
Malone Spring	McMinn	2,660 (7.1)	Knox Group Carbonates	Private
Morrell Spring	Sullivan	5,120 (13.7)	Knox Group Carbonates	Private

The last comprehensive study of a select 84 larger springs in east Tennessee was conducted by Sun et al. in 1963, preceded by a study of more than 960 springs in east Tennessee performed by De Buchananne and Richardson in 1956. Both studies were focused on the springs in the Appalachian Ridge and Valley province in East Tennessee. No similar publications, by either the USGS or the Tennessee state agencies, exist for quite a few significant springs in other karst regions of the state.

Based on a series of measurements, Sun et al. observed that the discharge of 84 larger springs in east Tennessee was as follows: 2 averaged less than 100 gpm; 16 ranged from 100 to 450 gpm; 62 ranged from 450 to 4,500 gpm; 4 ranged from 4,500 to 45,000 gpm. None averaged more than 45,000 gpm. Table 3.10.4 includes 15 springs which had an average discharge rate greater than 2,000 gpm (5.3 cfs) based on monthly measurements for each spring made during the period of record. As pointed out by Sun et al., these averages are fairly representative, as they were determined through both wet and dry seasons, but are perhaps lower than normal due to the period of record being during the moderate drought of 1951-54. Importantly, the data on average discharge are based on the period of monthly measurements only and may not be representative of the true karstic nature of the springs.

Most of the springs described by Sun et al. issue from solution openings in formations of the Cambrian-Ordovician Knox Group, Chickamauga Limestone, or limestones of the Conasauga Group. Of the 15 largest springs included in Table 3.10.4, thirteen discharge from the Knox Group dolomites and two from the Lenoir Limestone of the Ordovician Chickamauga Group.

3.4.1 Springs of East Tennessee

Big Spring, Carter County

Big Springs, located approximately 2 miles south of Elizabethton on Gap Creek Road, issues from fractures under a bluff formed in Knox Group carbonates. It is captured and protected from surface runoff by a concrete enclosure. As reported by Sun et al. (1963) its average discharge rate is 3,370 gpm, with the minimum and maximum of 871 gpm and 8,660 gpm respectively. The spring is a key component of the region's infrastructure, supplying roughly 24% of the drinking water for the City of Elizabethton, primarily serving the Milligan and Central areas. Previously utilized for a private trout hatchery, the facility was re-purposed in 1981 as a major component of Elizabethton's Comprehensive Water Plan.

The spring water is treated at the treatment plant that uses two 10' x 37' horizontal pressure filters that force the water through a variety of media to remove any impurities. The plant treats approximately 1,600 gallons per minute or approximately 1.5 million gallons per day and supplies 24% of the water for the City of Elizabethton. A state certified lab was also built at the site to allow the city to conduct its own testing of water samples system wide. https://www.elizabethton.org/departments/utilities/water_resources/water_treatment/big_springs.php

Buffalo Spring, Grainger County

Buffalo Spring is in Wildlife Management Area (WMA) owned by the Tennessee Wildlife Resources Agency and located near Rutledge. It issues from the Copper Ridge dolomite of the Knoix Group and is utilized by a fish hatchery, one of nine operated by the Tennessee Wildlife Resources Agency across the state. Water is piped from the spring head to the hatchery and is distributed inside the hatchery building and to the outside production raceways. Trout are hatched inside the hatchery building and reared to a length of about 3 inches. At this stage,

they are moved to the outside production raceways where they are grown for up to 14 months to reach the desired size. Buffalo Springs Hatchery delivers around 65,000 trout to the Erwin Trout hatchery for grow out. Approximately 30,000 trout are given to the City of Gatlinburg for grow out and use in their trout program. In 2018, Buffalo Springs Hatchery stocked 135,835 pounds representing 473,808 fish (Roddy, 2018).

The land surrounding the spring was originally purchased by Grainger County to develop a Civilian Conservation Corps (CCC) Camp in 1935 with plans to create a game propagation program. The facilities included quail and wild turkey hatcheries, a brooder building, and growing pens. By 1938 the facility was known as the Buffalo Springs Fish and Game Preserve. Buffalo Springs is one of the oldest wildlife management areas within the state of Tennessee.





Buffalo Creek runs directly through the WMA and is stocked weekly with rainbow trout. It operates under delayed harvest regulations during specific fall and winter months, making it a popular catch-and-release fly fishing destination. Buffalo Creek is accessible for a stroll along the dirt road and is a pleasant place for a morning birding or another outdoor outing. There are no specific trails for hiking. Common woodland birds are present in season, including Acadian Flycatcher (spring/summer), Louisiana Waterthrush (spring/summer), Eastern Tufted Titmouse, Carolina Chickadee, and Scarlet Tanager (spring/summer). White-tailed deer and Wild Turkeys may be seen. The WMA is surrounded mostly by privately owned agricultural fields.

Figure 3.4.9 Top: Buffalo Spring, captured for supply of Buffalo Springs Hatchery. Photo courtesy of Tennessee Wildlife Resources Agency. https://www.facebook.com/tnwildlife/videos/behind-the-scenes-at-buffalo-springs-tn-wildcast-406/1273416790739854/ *Bottom*: A man-made waterfall is located just under a bridge below the Buffalo Springs Hatchery. There is a spring pipe that is located right next to the waterfall, which provides water for public use. Photo Courtesy of Tennessee Wildlife Resources Agency.

Cave Spring, Hamilton County

Cave Spring, located approximately 13 miles north of downtown Chattanooga, within the suburban community of Hixson, is the second largest spring in Tennessee. It issues from a cave beneath a footwall in the Newman Limestone, between two regional thrust faults where fracturing is extensive. The Newman Limestone, the overlying Copper Ridge Dolomite, and the carbonates of Chepultepec, Longview, and Newala Formations, constitute the geologic framework for the Cave Springs drainage system (Bradfield, 1992, and Pavlicek, 1996).

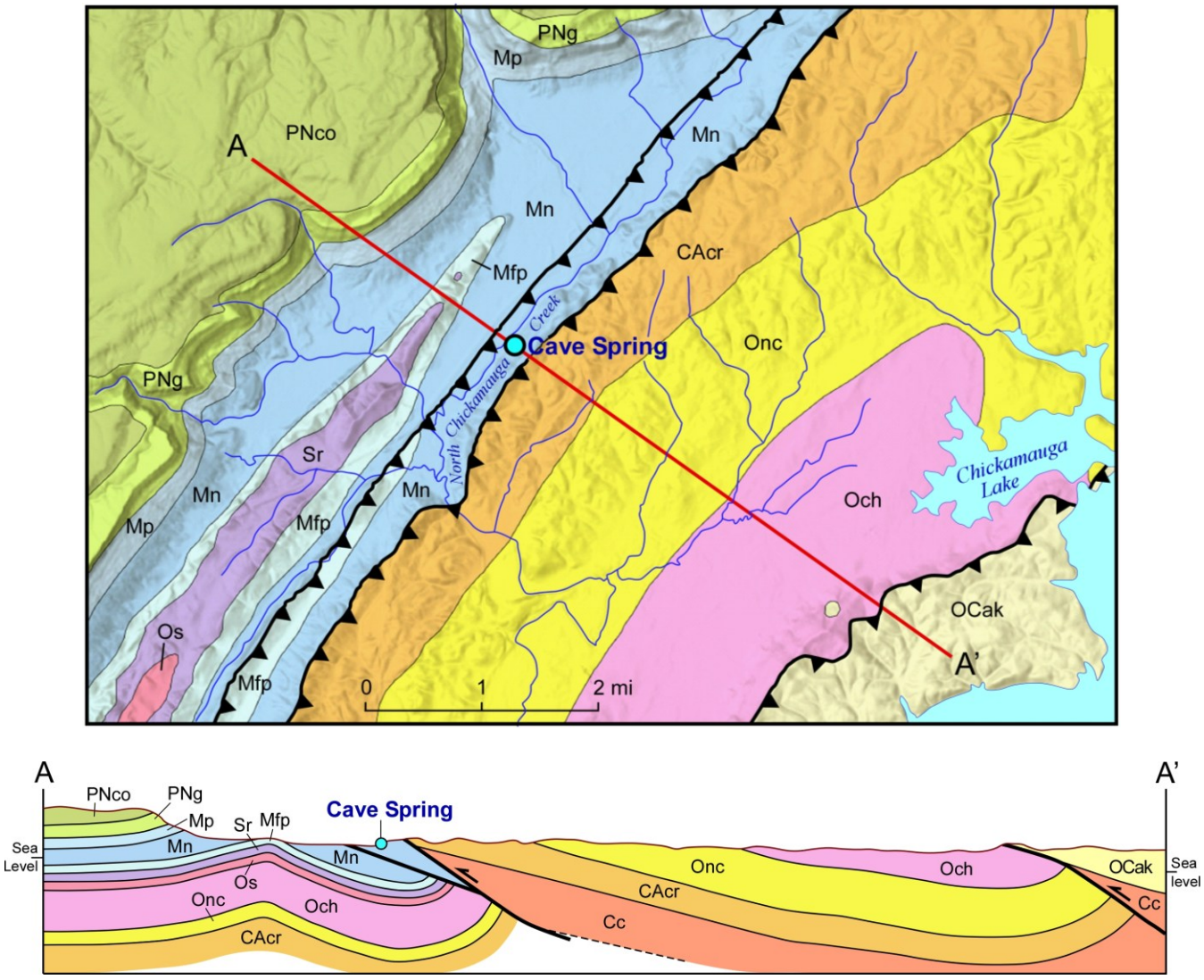


Figure 3.4.10 Geologic map and cross section of Cave Spring. Geologic units, from oldest to youngest: Cc: Cambrian Conasauga Group mudstone, shale, and limestone. CAcr: Cambrian Coper Ridge Dolomite of Knox Group. Onc: Lower Ordovician Chepultepec cabonates, Newala Limestone and Longview Dolomite of Knox Group. Och: Ordovician Chickamauga Limestone. Os: Ordovician Sequatchie Formation limestone, shale, and siltstone. Sr: Silurian Rockwood Formation shale, siltstone, and sandstone. Mfp: Mississippian Fort Payne Formation chert, shale, and minor limestone. Mn: Mississippian Newman Limestone. Mp: Mississippian Pennington Formation shale, siltstone, and minor dolomite and limestone. Png: Pennsylvanian Gizzard Group shale, siltstone, sandstone, and conglomerate. PNco: Pennsylvanian Crab Orchard Mountain Group conglomerate, shale, sandstone, and siltstone. Based on The Cooperative National Geologic Map v2.0.0 by USGS (Cooperative National Geologic Map | NGMDB), and Pavlicek, 1996.

Based on the wider topographic drainage area, average annual long-term precipitation, and runoff records, the amount of water available for recharge to Cave Springs is 11.8 cubic feet per second (cfs). The mean annual long-term discharge of Cave Springs is 16.4 cfs which leaves 4.6 cfs of recharge unaccounted for. As determined by low-flow stream discharge measurements, recharge along losing reaches of North Chickamauga Creek may be an important source of unaccounted-for recharge to the Cave Springs Basin (Pavlicek, 1996).

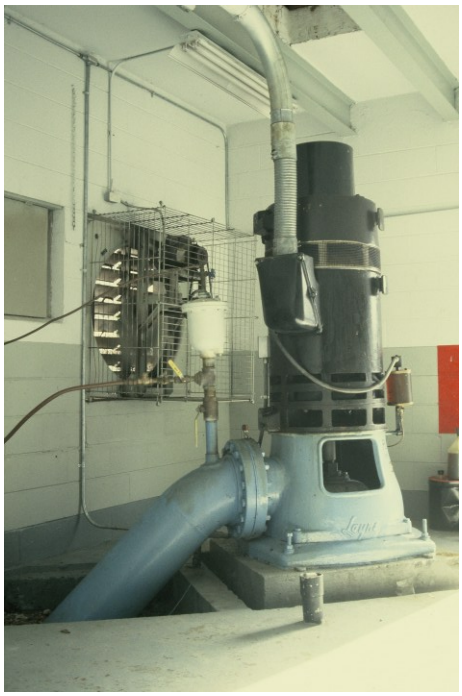


Figure 3.4.11 Powerful line-shaft turbine pump at one of the Hixson Utility District water supply wells that intercept an extensive cavernous interval 65-70 ft below ground surface, close to Cave Spring.

Fracture and cavernous porosity characterize the Cave Springs area. Fractures enlarged by solution have been observed in the field along Cave Springs Ridge above Cave Springs where regolith-free Newman Limestone crops out. Geophysical logs from wells throughout the basin commonly indicate cavernous porosity in most of the carbonate formations. Wells 1 and 2 at the Hixson Utility District (HUD) pumping facility, located about 150 ft northeast of Cave Springs, intercepted an extensive cavernous interval 65 to 70 ft below land surface. The full extent of this submerged cave is not known. There is also a vadose cave (a cave occurring above the water table) southeast of the pumping facility that trends approximately 260 ft along strike (Pavlicek, 1996).

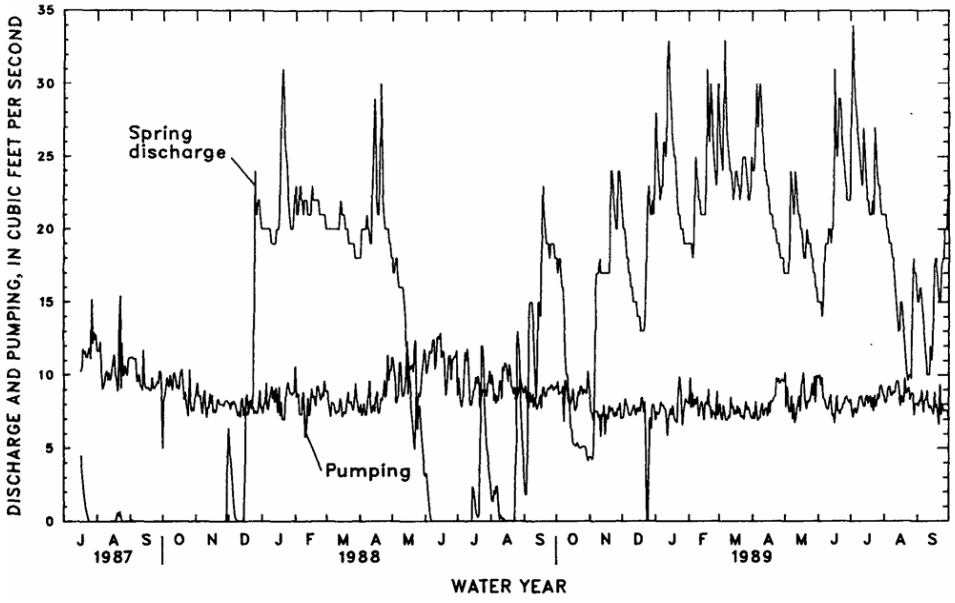


Figure 3.4.12 Daily mean spring discharge and total daily withdrawal by pumping from Cave Spring, July 1987 through September 1989. From Bradfield, 1992.

As part of a comprehensive hydrogeologic study of the Cave Spring drainage area, USGS drilled numerous wells including near the HUD pumping facility. A number of these wells intersected additional water-bearing zones beneath the large solution opening supplying water to the utility district. Aquifer tests in which three wells at Cave Springs were pumped at a combined rate of 9,000 gallons of water per minute documented drawdowns of less than

3 feet. Aquifer tests conducted at five test wells in the study area generated specific-capacity values ranging from 4.1 to 261 (gal/min)/ft of drawdown (Bradfield, 1992).

Cave Spring was a well-known source of water for local residents during periods of drought before public water supplies were established in the area. Cave Springs was also a stopping point for steam engines and passenger trains before land and water rights to the spring were acquired by the Hixson Utility District (HUD) in 1952. The following excerpts from an article on the Chattanooga History webpage illustrate some of the historic facts about this extraordinary karst spring (https://chattanoogahistory.com/cavespringstn).

In 1904, the Cincinnati Southern Railway developed picnic grounds adjacent to its tracks, 13 miles north of Chattanooga. The area featured an abundant freshwater spring, boating, fishing, baseball field, and a dancing platform. It quickly grew in popularity as organizations began hosting group events with attendees numbering into the hundreds.

The railroad company has supplied the grounds with swings and seats and it has the appearance of being a pleasure park in a large city. There is an excellent water supply from a large spring, and the place bids fair to be one of the most popular resorts for picnics anywhere around...

Chattanooga News June 5, 1904

Today the area has returned to a wilderness with no signs of its former and brief recreational glory. Only the railroad tracks remain – following the same route that so many arrived via chartered train cars, traveling to and from the Central Station Depot downtown.

Epilogue

In early 1909, the land containing the bountiful springs on the east side of the tracks was purchased by John A. Patten, Z. C. Patten, and other investors eager to bottle and sell healthy 'table water' under the name Gladstone Springs. Picnics continued on the developed grounds west of the tracks. It's not clear when the excursions ended.

Growing access to automobiles likely expedited the end of its appeal and recreational use.



HIXSON TO DISPLAY PUMPING STATION

Water District to Show New Facilities at Open House Afternoon of Dec. 30

BY FRED SCHNEIDER

The Hixson Utility District will hold open house the afternoon of Dec. 30 to celebrate completion of its new pumping station project, carried out at a cost of $154,000, Ira P. Jones, president of the district commission, announced yesterday.

From 1 p.m. to 5 p.m. that day, residents of the area and others interested are invited to visit the utility office in the Hixson business center, the pump house at Cave Spring, the spring and cave and the 500,000-gallon reservoir atop Cave Ridge.

The cave and spring, popular many years ago as a picnic site and the mecca for railway train excursions from as far away as Cincinnati, is located about five miles north of Hixson and a mile or two from the Boy Scout Camp Road.

The modern electric pumping station is completely automatic in operation. It is located on the hill-

Here is a view of mouth of Cave Spring, long ago a popular picnic area, located about five miles north of Hixson. The new pumping station draws water from an underground stream below spring.

Figure 3.4.13 Historic newspaper article featuring Cave Spring. Chattanooga Daily Times, Sun, Dec 21, 1952.



Figure 3.4.14 Cave Spring in December 2021. Courtesy of Chattanooga History. Available at https://chattanoogahistory.com/cavespringstn

Mossy Spring, Jefferson County

Mossy Spring, less than a mile east of the historic downtown Jefferson City, discharges from the Lower Ordovician Mascot Dolomite of the Knox Group. It is the largest spring in Tennessee, utilized for water supply of Jefferson City since 1940s when the TVA's construction of the Cherokee Dam/Reservoir flooded the city's water supply intake on the Holston River. In 2013, the water treatment plant treating raw water of Mossy Spring was upgraded to a 7.5 MGD submerged membrane filtration plant, installed in the existing gravity filter boxes, one of the few projects of this type in the country.

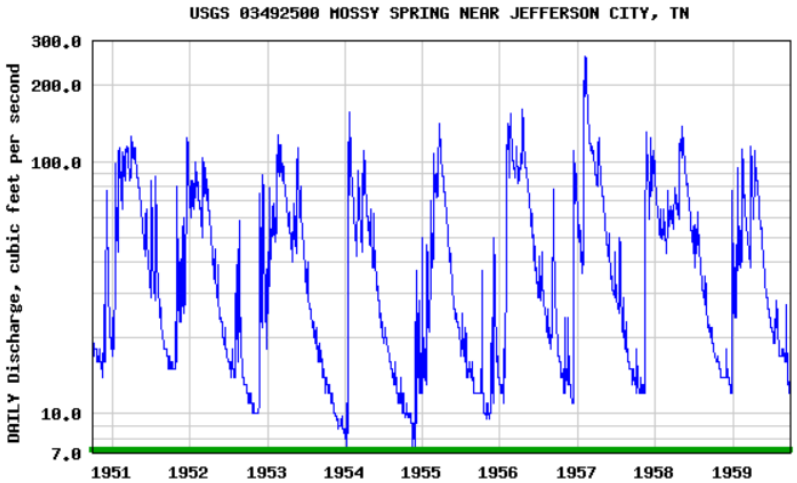


Figure 3.4.15 Daily discharge rate of Mossy Spring near Jefferson City, the largest spring in Tennessee, for the period of record. Average is 43.8 cfs, minimum is 7.4 cfs, maximum is 261 cfs. Index of Variability is 35.3.

The overflow from the enclosed Mossy Spring continues as Mossy Creek, which historically earned its name from the lush, vibrant green moss carpeting its bed and banks. When Revolutionary War veteran Adam Peck and his wife Elizabeth arrived from Virginia in 1788, they discovered Mossy Creek and its powerful headspring. The steady water flow soon started powering Adam Peck's original gristmill and nearby iron works, establishing the economic engine that drew nearly 100 pioneer families to the immediate four-mile radius by the late 1790s (https://www.jeffersoncitytn.gov/government/history.php).



Figure 3.4.16 *Top*: A beautiful stretch of Mossy Creek as it cuts through the campus of Carson-Newman University in Jefferson City. Courtesy of Carson-Newman University. *Bottom*: This aerial view shows the Mossy Creek Water Trail winding through green fields and trees in Jefferson City. Courtesy of The Mossy Creek Water Trail Project (https://www.floatthemossy.com/).

Morrell Spring, Sullivan County

Morrell Spring is located 2.7 miles southeast of Bluff City via TN-44 N / Dry Branch Road and Timber Ridge Road. It is the outlet for water of an underground karst network, over 37,000 feet of which were mapped as passages across multiple levels of Morrell Cave, better known as Worley's Cave in the caving world.

Much confusion has arisen over the years about the proper spelling of the name of both the spring and the cave. The cave has been called Morrell, Morrill, Morrils, Morrels, Mirrells (a local by the name of John Morril led many explorations), as well as Worley's Cave after the original landowner Elias S. Worley. The issue was resolved in 1980 by the U.S. Board on Geographical Names when it approved the name Morrell Cave. The current official USGS name for the spring is Morrell Spring, whereas in the older USGS reports it was called Morrill Spring (e.g., see Sun et al., 1963).

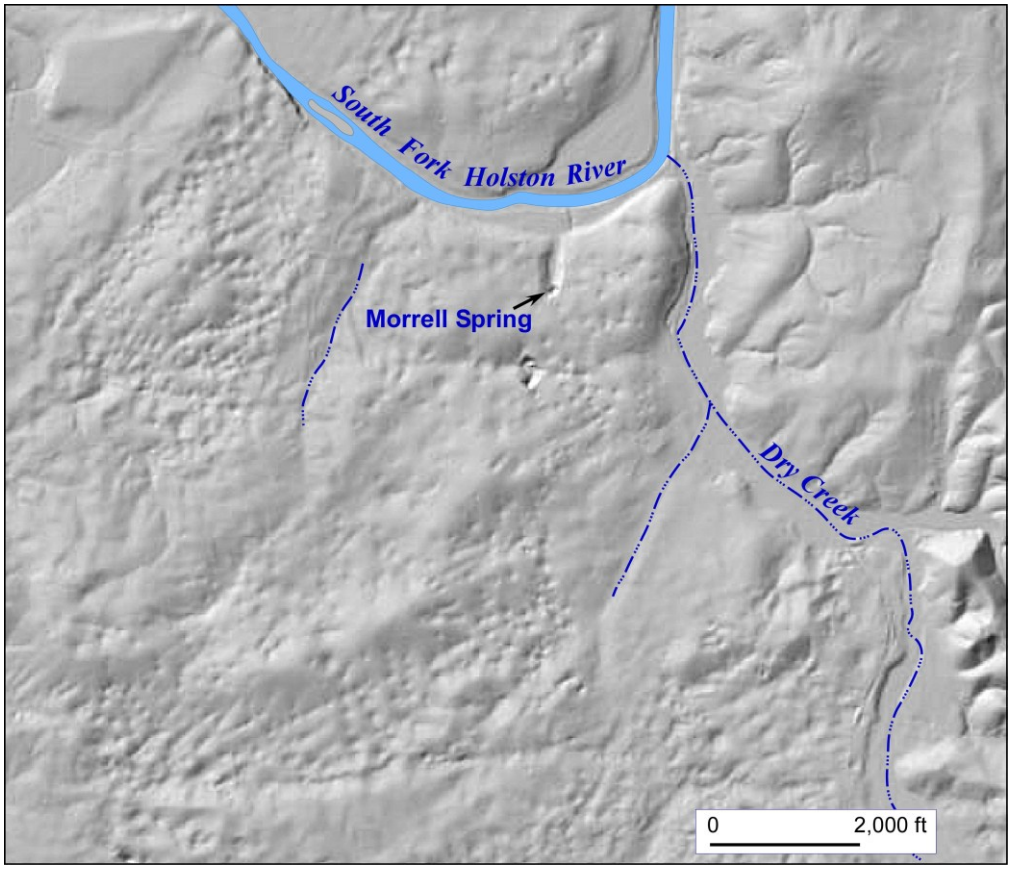


Figure 3.4.17 Most of the drainage area of Morrell Spring is highly karstified, with countless sinkholes developed in the Knox Group carbonates. Note a virtually complete absence of flowing surface streams south and west of the spring on this high resolution shaded relief map from USGS National Map Viewer (https://apps.nationalmap.gov/viewer/).

Two dye tracing experiments were conducted in the spring and fall of 2012 to identify recharge sources, delineate the springshed, and to interpret structural controls for groundwater flow. The experiments confirmed that allogenic recharge from the northern slopes of Holston Mountain enters the karst system through swallets and flows to the northwest following dominant joint trends that transect local folds. When the groundwater reaches Morell Cave, the flow is redirected northeast and parallels a shallow thrust fault, along which Morell Cave has developed, before resurging at Morell Spring. Using a joint-path flow model, groundwater velocities ranged from 0.04–0.007 m/s, which is consistent with typical groundwater velocities in karst systems (Burnham et al., 2016).



Figure 3.4.18 Morrell Spring, center left, and the dry entrance to Worley's Cave (center right). Worley's Cave, which is how the feature is called in the caving world, is named after original landowner Elias S. Worley. The lower level of the cave features a perennial flowing creek populated by fish, white crayfish, and salamanders, feeding the hydrological system that surfaces at the spring (Burnham et al., 2016). Photo by Tim Shep of Knoxville, Tennessee. Descent Caving Group | Another awesome trip to Worleys Cave | Facebook



Figure 3.4.19 Worley's Cave contains over 5.5 miles of surveyed, unlit multi-level passages, making it one of the longest cave systems in East Tennessee. Photo courtesy of Worley's Cave Facebook page. The cave is owned by Watson family, which allows public visits with proper registrations and a nominal parking fee. Every visitor must fill out a release form any time before coming to the cave. https://www.worleyscave.co/

https://www.facebook.com/WorleysCave/photos

3.4.2 Sequatchie Valley and Cumberland Plateau Springs

The Sequatchie Valley is the defining geographic feature between Cumberland Plateau in the west and Valley and Ridge physiographic province in the east. Stretching roughly southwest-to-northeast through the southeastern Cumberland Plateau, it is one of the longest continuous valleys in the eastern United States. Marion County forms the valley's southern end; Sequatchie, Bledsoe, and Cumberland counties lie to the north (see Figs. 3.4.4 and 3.4.8).

The Mississippian limestone that underlies the Sequatchie Valley and much of the plateau is the host for one of the most striking karst areas in the country—the landscape of sinkholes, disappearing streams, springs, and caves. The springs that rise at the Sequatchie Valley floor, including the Head of Sequatchie in Cumberland County to the north and Blue Spring and Owen Spring in Marion County to the south, are karst springs carrying water that entered the plateau through sinkholes miles away.

Karst drainage in the area does not respect surface watersheds as shown in the USGS Scientific Investigations Report 2024-5089 which mapped karst flow paths in the Little Sequatchie and Pryor Cove watersheds in Marion County and confirmed that the two systems are hydrogeologically linked beneath the valley floor. Another example is where the valley's karst plumbing reaches beyond individual counties: the Sequatchie River itself rises from karst, where surface water sinking in Grassy Cove, an enclosed basin at the head of the valley, travels for miles beneath the mountains and resurfaces at the Head of Sequatchie as confirmed by a dye test conducted in 1961 (https://mctnhistory.com/geography/sequatchie-river).

Two rivers shape Marion County which has the densest concentration of karst features in the valley. The Tennessee River defines the county's southern boundary for 26 miles, cutting through the Cumberland Plateau in the “Grand Canyon of Tennessee.” The Sequatchie River runs the length of the valley and joins the Tennessee River at Kimball. The Marion County reach of the Tennessee has been dammed twice (Hales Bar in 1913, and Nickajack in 1967); the Sequatchie River remains entirely free flowing.

Martin Spring, Marion County

Martin Spring, the headwaters of Battle Creek, is a spring located on the east side of Battle Creek Valley at the mouth of Cave Cove, near the small community of Martin Springs. It discharges from a cave developed in the Mississippian St. Louis Limestone, at an estimated rate of 6,500 gpm, although official measurements of any kind are lacking.

In July 1958, members of the Florida Speleological Society explored the cave with diving gear and documented an underwater passage about 15 feet in diameter running some 250 feet from the spring entrance into a room roughly 50 feet across and 40 feet high. The cave is known for about 550 feet of passage and reaches depths of about 50 feet. No progress was made beyond this area (https://mctnhistory.com/communities/martin-springs).

Martin Springs is one of a small number of documented Cherokee removal campsites in Marion County. On October 11, 1838, John Bell began escorting a group of roughly 660 Cherokee, members of the so-called "Treaty Party" who had accepted the 1835 Treaty of New Echota, westward from their gathering camp near Fort Cass (in present-day Bradley County) toward Evansville, Arkansas. The detachment's route, known as the Bell Route, passed through the Sequatchie Valley and over the Cumberland Plateau.

During 1915-1927 Dixie Hwy (Hwy 41) was being constructed and it went right by the spring. Thornton Herbert Martin saw potential in the year-round 60 degree spring and purchased it. He soon thereafter opened Martin



Springs Tourist Camp which offered cabins, a boardinghouse and he also advertised the spring water as having healing properties. In the mid 60's, Interstate 24 was built and like many pop-up attractions along Hwy 41, the interstate bypassed them and the tourist camp eventually closed

Figure 3.4.20 Martin Spring, the headwaters of Battle Creek in Marion County. Martin Spring is privately owned and the owners do not welcome visitors to the site. Photo courtesy of Kelly Smallwood and Jason Hardy, TAG Cavers. Very Informative posts, photographs, and information about the TAG (Tennessee-Alabama-Georgia) caving region from Kelly and Jason can be found at their social media pages:
https://www.facebook.com/undergroundearthcaving/
https://tagcaver.wixsite.com/undergroundearth



Figure 3.4.21 Historic photograph of Martin Spring. Courtesy of Kelly Smallwood and Jason Hardy.



Figure 3.4.22 **Long Spring** near Whiteside, Marion County. Long before European settlers arrived, the area surrounding the spring was a Cherokee town established in the late 18th century, known as Running Water. The spring was an essential lifeline for the settlement before the community's forced removal via the Trail of Tears in 1838. Photo copyright Alan Cressler, all rights reserved.

https://www.flickr.com/photos/alan_cressler/



Figure 3.4.23 **Sequatchie Cave Spring** in Marion County. Sequatchie Cave is a 133-acre biologically significant natural area located where Owen Spring Branch flows from the mouth of the cave at Sequatchie Cave Park. The cave and its cold spring water support three federally and state-listed animal species, three other species of state concern, and many other aquatic and cave species. This is one of two sites where the federally endangered Royal Snail (Marstonia ogmorhaphe) is known in the world. Both are in Marion County. This is also the site where the rare Sequatchie Caddisfly (Glyphopsyche sequatchie) was first described, making it the type locality for this species. The caddisfly is reported only from three other spring-fed streams, all in Marion County. The site is a former Tennessee Department of Transportation roadside park and was later managed by Marion County and its County Highway Department before it was designated as a state natural area in 2001. While the public still enjoys the roadside park, the Division of Natural Areas manages the site for the benefit of the rare species that occur in Owen Spring Branch. The cold spring water supply at Owen Spring is in part why the community of Sequatchie was first settled. The mix of ecological, cultural, and historical values makes Sequatchie Cave a unique area. (https://www.tn.gov/environment/natural-areas/what-we-do/sna/sv/sequatchie-cave.html). Photo courtesy of https://www.southeasttennessee.com/southeastern-aquatic-diversity-splendor-at-sequatchie-cave-state-natural-area/

Head of Sequatchie Spring, and Devilstep Hollow Cave, Cumberland County

Devilstep Hollow Cave is the underground conduit and "overflow valve" for the water that feeds the Head of Sequatchie Spring. Together, they represent a textbook example of a complex, interconnected karst hydrogeological system. The connection works through an intricate subterranean conduit network. The main recharge of water is roughly nine miles away at Grassy Cove, which is North America's largest sinkhole (Kambesis, 2014). Grassy Cove is an equivalent to a typical, large-scale, closed depression with internal drainage called "polje" in the classic Dinaric Karst of former Yugoslavia, Europe. "Polje" is the official international term for such depressions in karst.

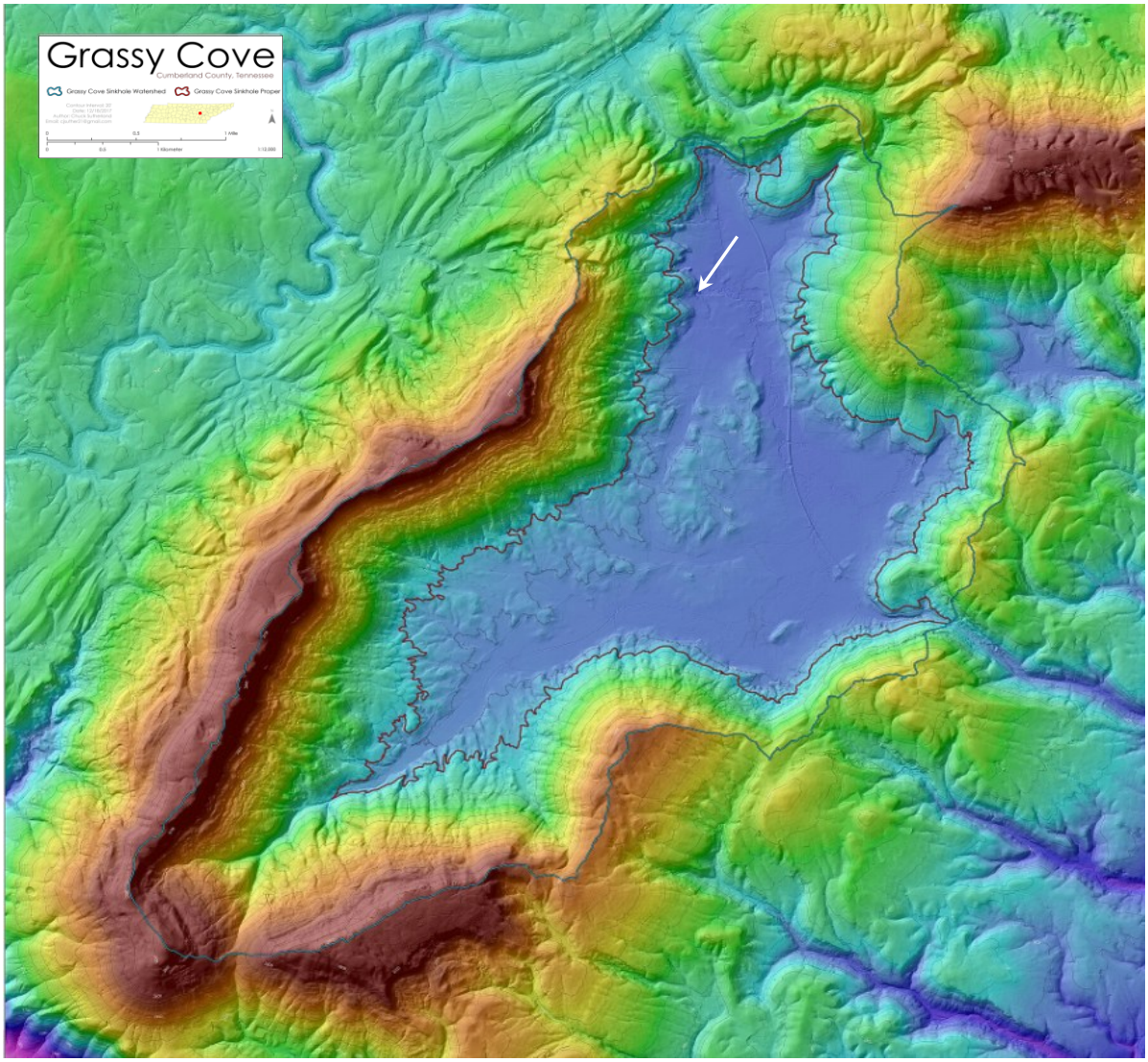


Figure 3.4.24 An elevation map, 6.4 miles across, of Grassy Cove in Cumberland County. Elevation difference between the flat bottom of the cove and the surrounding rim is about 840 ft. Mill Cave is denoted with arrow. Image created by Chuck Sutherland. Available at https://commons.wikimedia.org/wiki/File:Grassy_Cove_Sinkhole_elevation_map.jpg

When it rains in Grassy Cove, all surface water drains down into a cave called Mill Cave. This massive volume of water flows entirely underground, cutting through the limestone beneath Brady Mountain. The underground stream finally reemerges at the valley floor to form the Head of Sequatchie Spring. Devilstep Hollow Cave sits immediately behind and above this spring. It serves as a direct window into the underground river, carrying the

main stream inside its passages. Under normal conditions, the water pools at the mouth of Devilstep Hollow without visible flow. During heavy rains or high-flow events, Devilstep Hollow Cave acts as the primary atmospheric "overflow valve," allowing the surging underground river to spill out of its massive 125-by-150-foot mouth. Because of this seamless connection, the pool at the mouth of Devilstep Hollow Cave and the Head of Sequatchie Spring jointly mark the literal birthplace of the Sequatchie River.

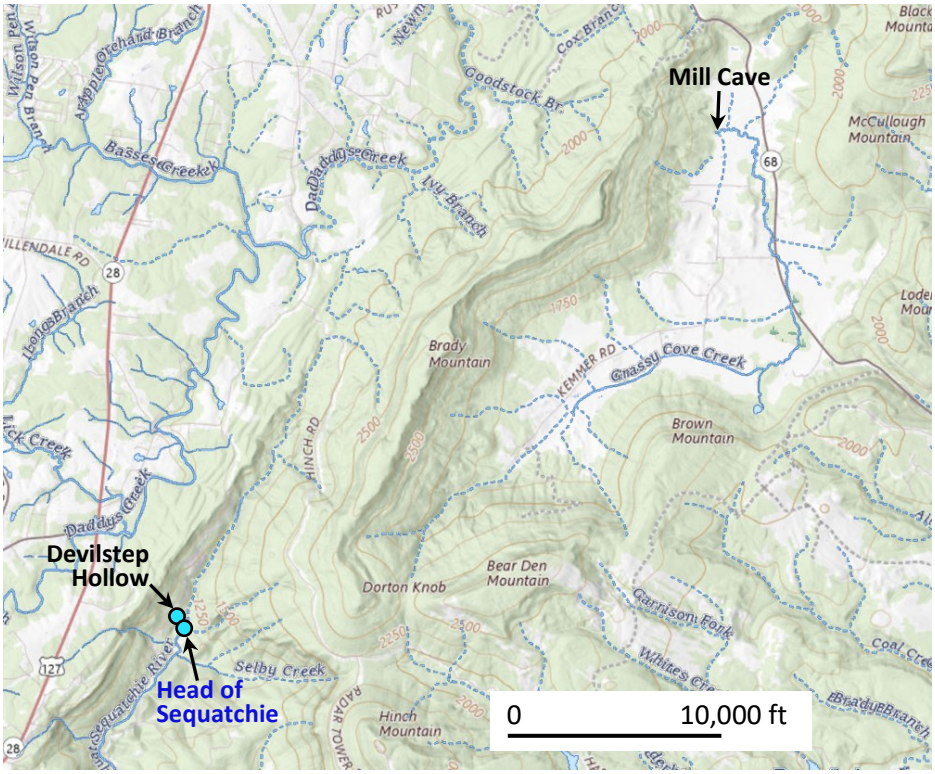


Figure 3.4.25 USGS Topographic map of the Grassy Cove and Head of Sequatchie hydrogeologic karst system.



Figure 3.4.26 Head of Sequatchie Spring in The Justin P. Wilson Cumberland Trail State Park near Pikeville, Cumberland County. The spring discharges from Monteagle Limestone. Photo courtesy of Tennessee State Parks.



Figure 3.4.27 The entrance to Devilstep Hollow Cave. One of the best and most significant examples of Indigenous dark zone cave art in the southeastern United States is found in Devilstep Hollow, where images made a thousand years ago adorn what seems to be a complete ceremonial space. The panels of petroglyphs, pictographs, and mud glyphs in Devilstep Hollow tell a story related to the religious beliefs of the Mississppian people in much the same way that artwork in a modern church aims to shape the experience of visitors and open their hearts to a larger spiritual experience. Mississippian peoples divided the universe into three realms: an upper realm of sky creatures and sky spirits like the thunderbirds, a middle realm of earth on which we live with all the other terrestrial flora and fauna, and an underworld beneath. The underworld spirits controlled life and death and provided a pathway through which the souls of the dead were led on their journey to the stars. Woodpeckers served as the guides who ushered dead souls along that path. The cave is strictly off-limits to the general public to protect the fragile archeological art and respect the sacred nature of the site. Text and photo courtesy of Ancient Art Archive. This photo and a nice video are available at https://www.ancientartarchive.org/mural-of-america/devilstep-hollow-cave-tennessee/

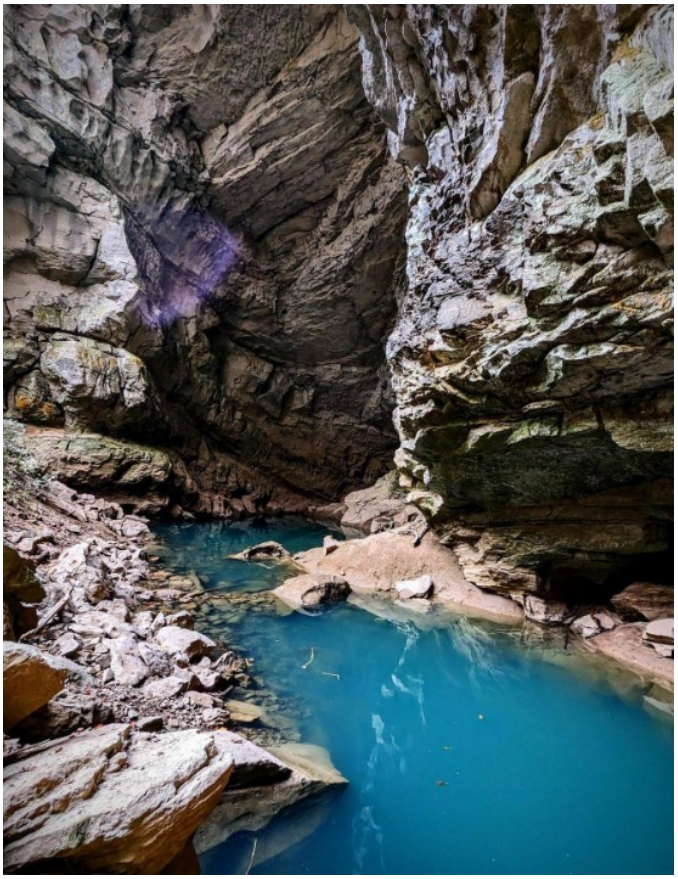


Figure 3.4.28 Devilstep Hollow. To this day, Devilstep Hollow Cave/Head of Sequatchie Spring remains one of the favorite conservation projects of TennGreen Land Conservancy. This Tennessee treasure was brought to TennGreen's attention more than a decade ago by former Board member, Bob Brown. Although the land was far outside of TennGreen's price range, Bob insisted that they pursue it—suggesting that it was so valuable, so historic, and so scenic that it should be a national park. In 2007, the owners of Devilstep Hollow Cave donated a conservation easement and sold their property to TennGreen Land Conservancy. The property is currently managed by Tennessee Department of Environmental Conservation as part of the Justin P. Wilson Cumberland Trail State Park. Photo courtesy of TennGreen
https://www.instagram.com/p/DY2I_W6EjJ_/
https://tenngreen.org/project/devilstep-hollow/



Figure 3.4.29 **Big Spring at Caney Fork** is located in Scott's Gulf Wilderness Area, a recently designated Tennessee state park in White County that spans over 9,500 acres of state property with public access. The spring can be accessed on foot. It discharges from the Mississippian Monteagle Limestone and feeds the Caney Fork River. This is one of the larger springs in Tennessee (see person on right side for scale). Text and photo courtesy of Amy M. Hourigan.



Figure 3.4.30 **Jasper Blue Spring** is in Jasper, Marion County. The spring is on private property and used for community water supply. This large spring is formed in Mississippian Monteagle Limestone, on the Eastern Escarpment of the Cumberland Plateau. Jasper Blue Spring is currently the second longest underwater cave in Tennessee. Text and photo courtesy of Amy M. Hourigan.



Figure 3.4.31 **Virgin Falls Spring** is in Virgin Falls Natural Area located in White County. The natural area is named for Virgin Falls, which is formed by an underground stream that emerges from a cave, then drops over a 110-foot-high cliff before disappearing into another cave at the bottom of the sink. Virgin Falls Spring Cave is over 3,000 feet long and ends in a massive breakdown. The huge passage is 30 ft wide and 45 ft high, and rather easy to visit. The spring and the falls are only a trickle in dry season, late summer and early fall. In the wet season, winter and early spring, they become a raging torrent and the cave is. not accessible. The area is noted for its unique geological features and several additional waterfalls including Big Laurel, Sheep Cave Falls, and Big Branch Falls. Due to white nose syndrome, all caves in the area are closed to recreational use. The sinkholes at Virgin Falls, such as Virgin Falls Sink and Sheep Cave Sink, are characteristic of karst features found on the Cumberland Plateau. The Caney Fork River and its tributaries drain the area and contribute to the formation of the gorge.
https://www.tn.gov/environment/natural-areas/what-we-do/sna/cu/virgin-falls.html



Figure 3.4.32 Lost Creek State Natural Area in White County is a diverse area situated on the western flank of the Cumberland Plateau. Its scenic highlight is the beautiful Lost Creek Falls, geologically similar to its nearby cousin, Virgin Falls. The creek also emerges from a large spring, or collapsed cave on top, drops over the 40-foot falls, and disappears underground again. On the opposite side of this large sink is the spectacular entrance to Lost Creek Cave. Because these Falls and Cave open into this large sink, or bowl, with no surface drainage, cold air is trapped in the hottest and most humid times of summer, essentially wicking the water from the humid air and coating the rocks and vegetation in the bottom of the bowl with moisture. This increased moisture helps to stimulate rich ferns, flowers, and liverworts in the bottom of the sink in the late Spring and Summer. The beauty of this area attracted the Walt Disney Corporation in 1994 to film several scenes from the “Jungle Book” at the area, utilizing both the beautiful Falls and the Cave entrance. The cave is also home to several rare species, including the federally protected Indiana bat. Because of the population decline of cave-dwelling bats, the cave is closed during the hibernation and swarming time of bats.
https://www.tn.gov/environment/natural-areas/what-we-do/sna/cu/lost-creek.html

The Boils, Jackson County

As described by Gardner, Hart, and Sutherland (Gardner et al., 2018), The Boils is a major karst spring in Jackson County, downstream from the Roaring River State Scenic River and Spring Creek State Scenic River. These two streams contribute no surface flow to their confluences at base flow; they are sinking streams, and their base flow is transmitted through conduits. As part of the study, the authors focused on karst features in the Ordovician limestone of the Leipers and Cathey's Formations in the drainage areas of the streams and performed quantitative dye traces to identify their contributions to The Boils. The average discharge of The Boils was approximately 2.1 m^3/sec (74 cfs) for the calendar year 2015, with storm discharge reaching as much as 14 m^3/s (494 cfs) making it among the highest discharge springs in Tennessee.



Figure 3.4.33 The Boils, located in The Boils Wildlife Management Area (the main entrance is five miles southwest of Gainesboro, via TN-56, Dodson Branch Highway, and Roaring River Road). Photo by Chuck Sutherland. From blog post The Boils. Available at https://chuck-sutherland.blogspot.com/2017/01/the-boils.html

The dye trace revealed a direct connection to the Boils from a sink located 10 km away (straight-line distance), with a travel time of about 12 h. A second trace at another sink covered a straight-line distance of 1.5 km in 4 h. The rapid travel times suggest that this aquifer is dominated by conduit flow.

Under these conditions, potential contaminants entering the surface streams in the basin would remain concentrated and be transmitted through the system quickly. The shallow carbonate aquifer is highly susceptible to point and non-point source contaminants such as pesticides, fertilizers, and bacteria. During the storm event the conductivity and temperature decrease similarly, showing the flood pulse as it mixes with the existing base flow. Flood pulses from rain events in the basin adversely impact the water quality at The Boils, by adding a large amount of sediment to the system (Gardner et al., 2018).



Figure 3.4.34 A swallet in Spring Creek, Overton County. Photo courtesy of Chuck Sutherland.

Berlin Spring, Marshall County

Berlin Spring, also known as Big Spring, is the headwaters of Cedar Creek which eventually feeds into the Duck River. It was the literal heart around which the community of Big Springs grew in the early 19th century. The community changed its name to Berlin from "Big Springs" because another Tennessee town already held the name. Today, the spring is preserved as a quiet local park managed by the county.

Long before the Civil War, Berlin was a bustling, nearly self-sufficient village that was larger in population than the county seat of Lewisburg. The local geography formed a perfect natural amphitheater around the wide spring cave mouth, shaded by a massive, towering elm trees. Because of this unique acoustic and scenic landscape, it became one of 19th-century Tennessee's premier hubs for "stump speaking" and massive political rallies, including campaign speeches by prominent figures like James K. Polk and Andrew Johnson. Famous *Berlin Rock* was placed by the spring as a speaker's platform (https://freepages.rootsweb.com/~bethlehemcommunity/school-alumni/berlintable.html).



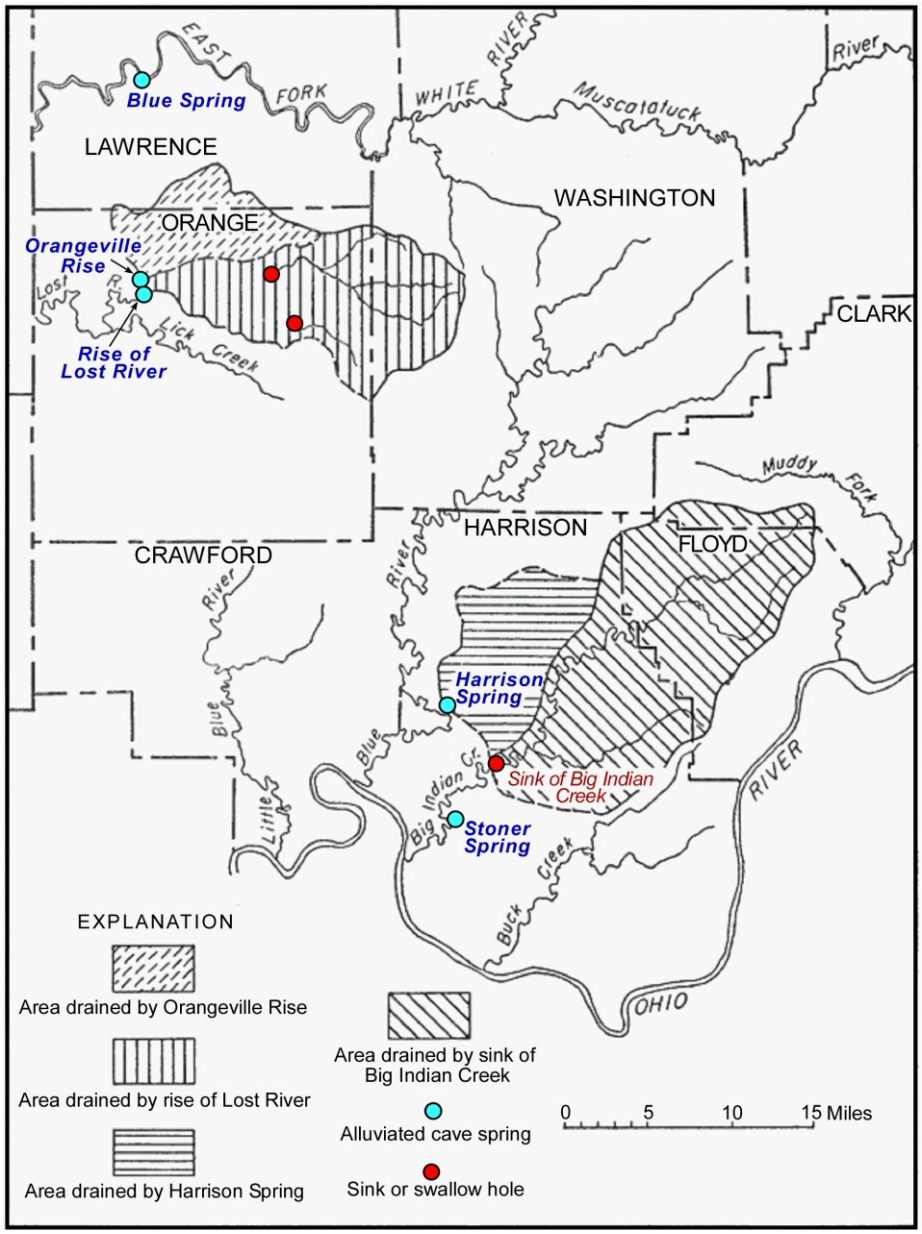
Figure 3.4.35 Berlin Spring discharges from the Ordovician Ridley Limestone aquifer of the Inner Nashville Basin. Measured minimum, median, and maximum discharge rates of the spring are 0.04 cfs, 1.6 cfs., and 7.8 cfs respectively (Knight and Kingsbury, 2007). Photo courtesy of Marshall County. https://marshallcountytn.gov/berlin-springs-pavilion



Figure 3.4.46 Drawing of Berlin Spring featuring the famous Berlin Rock by John William Lunn. From *A Visit to Berlin Tennessee's Big Spring* by William Andrews, The Daily Herlad, July 17, 1976.

3.5 Indiana

As explained by Powell (1963), most karst springs in Indiana are simple gravity-flow tubular or cave springs. Donaldson Cave in Spring Mill State Park and Boone's Cave in Owen County are examples. In contrast to these cave springs which flow by gravity, the largest karst springs in the State are alluviated artesian springs or rises; they are characterized by well-like openings through which groundwaters from cavern passages ascend under hydrostatic pressure. Alluviated cave springs have been buried by accumulations of alluvial sediment in a previously deeper valley. They are found along major streams that are tributary to the Ohio River and the East Fork White River. The valleys of both streams are known to contain deep bedrock channels. The U.S. Corps of Engineers discovered bedrock approximately 270 feet above sea level or 114 feet below the normal pool elevation of the Ohio River about one mile upstream from Blue River.



Harrison Spring

Harrison Spring, one mile north of White Cloud in Harrison County, is the largest spring in Indiana. It was designated a U.S. National Natural Landmark in 1980, and it is situated on private land. The spring consists of a subcircular pool about 120 feet long and 95 feet wide. It sits in a bend of the Blue River. The depth of the pool ranges from a few feet at the base of the steep sides to 35 or 45 feet at the bottom of the well-like opening or rise conduit fed by the Mississippian Blue River and Sanders Group Aquifer System.

Figure 3.5.1 Map showing the areas drained by Harrison Spring, sink of Big Indian Creek, Orangeville Rise, and rise of Lost River. From Powel, 1963; modified for clarity.

A low rim or levee, consisting of clays and silts, surrounds the spring on all sides except at the outlet. The outlet stream follows the bed of the abandoned meander to its junction with Blue River half a mile southwest of the spring. Although the stream flows within the flood plain, the alluvial sediments are thin in several places, and limestone bedrock is exposed in the stream bed immediately downstream from the rise—indications of a lateral-planation bench between the bedrock valley and the present valley wall.

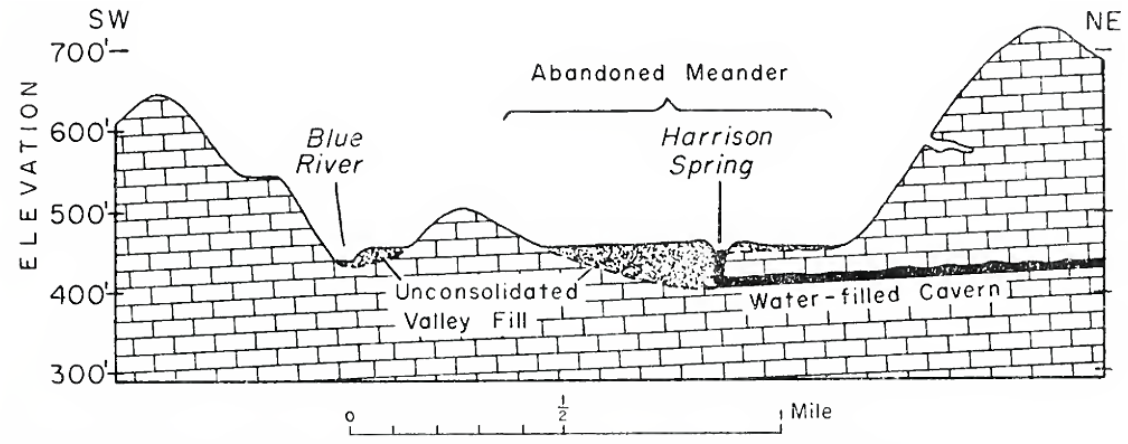


Figure 3.5.2 Idealized cross section through Harrison Spring and Blue River. From Powell, 1963.

According to Powell (1963), Harrison Spring, as well as perhaps most other alluviated cave springs, was formed where a former meander of the stream turns in an updip direction and deeply dissects the strata (Fig. 3.5.2). Pohl (1936) observed that resurgences of subterranean drainage "are found where the meanders of a surface stream are convex in an updip direction." Harrison Spring occupies a meander that crosses the axis of a broad shallow syncline, which covers an area of more than 25 square miles between the spring and Big Indian Creek. The sink of Big Indian Creek lies updip from Harrison Spring. The hypothetical gradient between this sink and Harrison Spring would be approximately 21 feet per mile, or adequate to permit subsurface drainage from the sink to Harrison Spring. The spring described by Ashley and Kindle as the rise of Indian Creek (Stoner Spring) was not flowing at the time when the low flow of Big Indian Creek was entering the sink. If Big Indian Creek upstream from the sink is a tributary to Harrison Spring, part of the waters of more than 200 square miles could be added to the drainage area of Harrison Spring. Dye tests and analysis of hydrographs have shown that water can move underground from the Sinks of Indian Creek to Harrison Spring, a surface distance of over four miles, as quickly as one hour. The average flow of Harrison Spring has been estimated at 18,000 gpm (Unterreiner, 2006).



Figure 3.5.3 Harison Spring, the largest spring in Indiana. Photo courtesy of NPS.

Harrison Spring was once part of a large 600-acre farm owned by United States President William Henry Harrison, from whom it gains its name. The spring produced enough water to run a gristmill and sawmill downstream which began operating in 1807, making it one of the first in the state.

For all future spring enthusiasts and brave cave divers, here are several fun facts about Harrison Spring for kids from their Kiddle Encyclopedia (https://kids.kiddle.co/Harrison_Spring):

Scientists who explore caves, called cavers, have found something interesting. They map Binkley's Cave, which is the longest known cave in Indiana. Their maps show that water in one part of Binkley's Cave seems to flow under Indian Creek. This water then comes out at Harrison Spring.

Tests using special dyes have also shown this connection. Water that sinks into holes in the ground near Corydon flows through parts of Binkley's Cave. It then travels underground beneath Indian Creek. Finally, it comes out at Harrison Spring and flows into the Blue River.

It's possible there's a direct link between Harrison Spring and Binkley's Cave. However, exploring this link would mean very long underwater cave dives. No one has tried a dive like that in Indiana yet. If this connection is found, it could make both caves much longer! Binkley's Cave is already about 44 miles long. It is the longest cave in Indiana and the seventh longest in the United States.

Brave cave divers have explored Harrison Spring itself. They have mapped thousands of feet of cave passages. All of these passages are deep underwater.

Orangeville Rise, and Lost River Rise

The Orangeville Rise, located in the town of Orangeville in Orange County, about 7 miles west of Orleans, is the state's third largest karst spring and a key resurgence point for the Lost River system. Acquired by the Indiana Karst Conservancy (IKC) in 1999, this protected site was designated National Natural Landmark in 1972, and state-dedicated nature preserve in 1975. The spring issues from openings in Late Mississippian Ste. Genevieve Limestone. It has a highly variable flow rate that responds rapidly to rainfall, often within 24 hours. According to historical measurements and USGS studies, the discharge rates typically fall within the following ranges: low/base flow: approximately 9 cubic feet per second (cfs); bank-full stage: approximately 185 cfs; peak/flood flow: estimated at 200 cfs (Bayless et al., 2014; USGS).



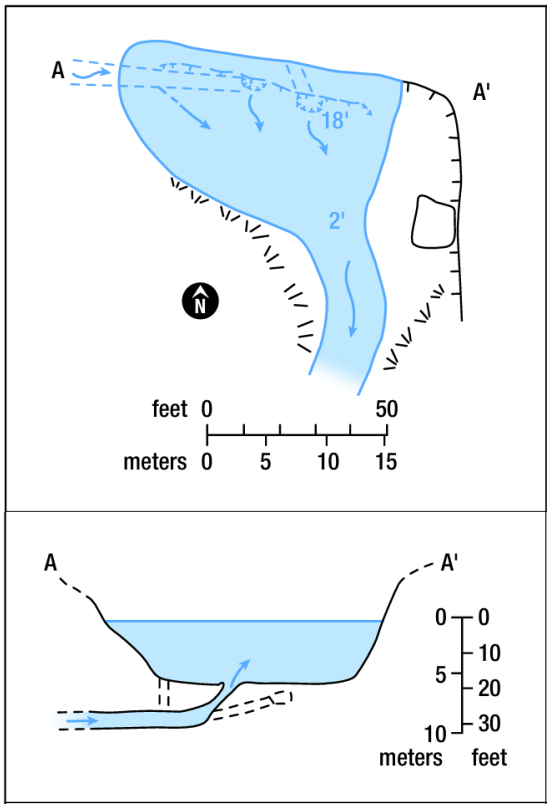
Figure 3.5.4 The third-largest spring in Indiana, the Orangeville Rise is part of the Lost River system, one of the largest subterranean streams in the country. It was dedicated as a National Natural Landmark in 1972 and has been a state-dedicated nature preserve since 1975. The property consists of a little over three acres of land within the town of Orangeville and may be visited at any time. The main pull off for viewing is on the northeast side of the preserve. Photographs courtesy of Indiana Karst Conservancy (https://ikc.caves.org/orangeville-rise).

USGS study indicates that there are limits on the hydraulic capacity of the conduits feeding the Orangeville Rise of roughly 200 cfs, when the underground system becomes overwhelmed (Fig. 3.5.5). The excess water then overflows onto the surface, as well as below surface to other outlets such as the Mather's stormwater rise.



Unlike the main "Rise of the Lost River" (the "True Rise"), which connects to the primary 23-mile long subterranean channels, the Orangeville Rise acts as a major tributary of Lost River, discharging water from a separate 30-to-48-square-mile karst basin as shown by dye tracing.

Figure 3.5.5 Orangeville Rise during flood conditions in 2011. Photograph taken by Ginger Korinek, Indiana Department of Natural Resources,



The Orangeville Rise, which is fed by some 30 square miles of drainage north and northeast of Orangeville (Fig. 3.5.1), is on the south side of Orangeville at the head of perennial Lost River. It is the more picturesque of the two rises and has long been mistakenly considered by many local people to be the (true) Rise of Lost River.

Malott (1932) stated: “The Orangeville rise issues from a semicircular rock-walled pit 110 feet across, and the waters rising from it flow southward in a mud-banked channel 15 feet deep and 40 to 50 feet in width for about 150 yards before entering Lost River. The waters rise some 15 or 20 feet as a great artesian spring from a water filled cavern the mouth of which is apparently 70 feet in width.”

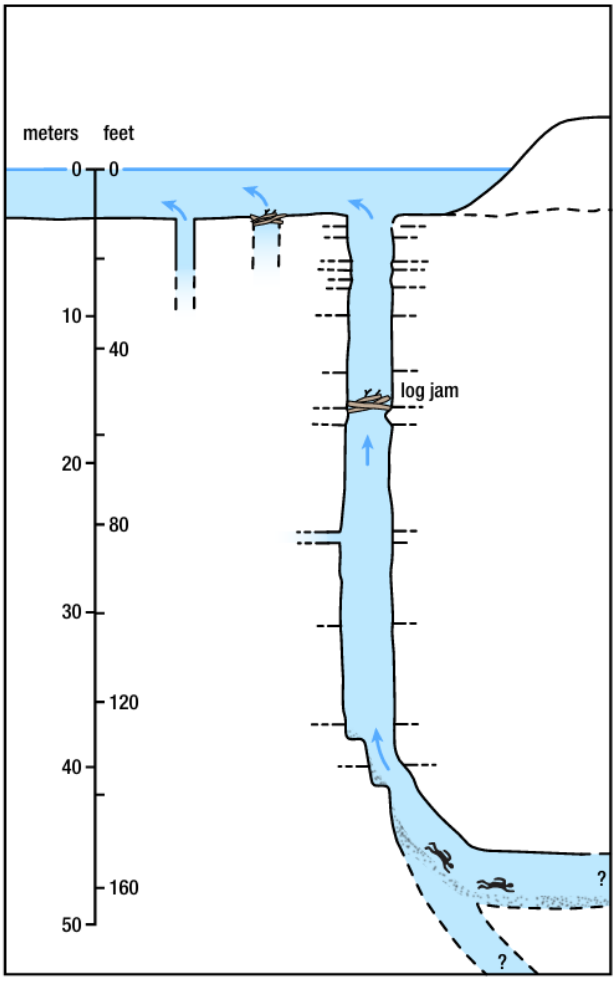
Figure 3.5.6 Sketch map and cross section of the Orangeville Rise by Steven Maegerlein (Quinlan et al., 1983, p. 76). From *Lost River Field Trip for the Indiana Water Resources Association* by Richard L. Powell.

The Rise of Lost River, the second largest spring in Indiana, marks the resurgence of more than 80 square miles of surface drainage that has been diverted underground. It lies about three quarters of a mile southwest of Orangeville. It is on private property and not open to the public. Water emerges from a massive, 165-foot deep

submerged cave system into a 220-foot diameter pit, forming a primary tributary of the Lost River. The channel enters Lost River within 50 feet of a rise pit.

The stream from the Orangeville Rise is only a few feet deep, but downstream from the (true) Rise of Lost River the water reaches several times greater depths than those upstream from the junction (Malott, 1932; Powel, 1963).

The Orangeville Rise and the Rise of Lost River are alluviated cave springs. The present channel immediately downstream from the Orange ville Rise does not reach bedrock, but farther downstream the channel crosses a buried bedrock bench. The Rise of Lost River lies in a flat part of the valley, and no bedrock is exposed either at the rise or in close proximity to it. The cavernous routes and their exits into the buried bedrock valley lie 30 to 50 feet below the top of the present valley fill.



Various karst hydrographers such as Swinnerton (1932), Piper (1932), Gardner (1935), and Malott (1938 and 1952) have indicated that caverns are formed at or near the water table or base level by the diversion of surface water or by the sapping of groundwater from carbonate uplands adjacent to deeply dissected valleys through subterranean routes. Because most artesian karst springs are found along deeply filled bedrock valleys of pre-Kansan age, it logically follows that they are buried cave springs that predate the filling of the valleys, which took place during Kansan, Illinoian, and Wisconsin ice ages (Mallot, 1931).

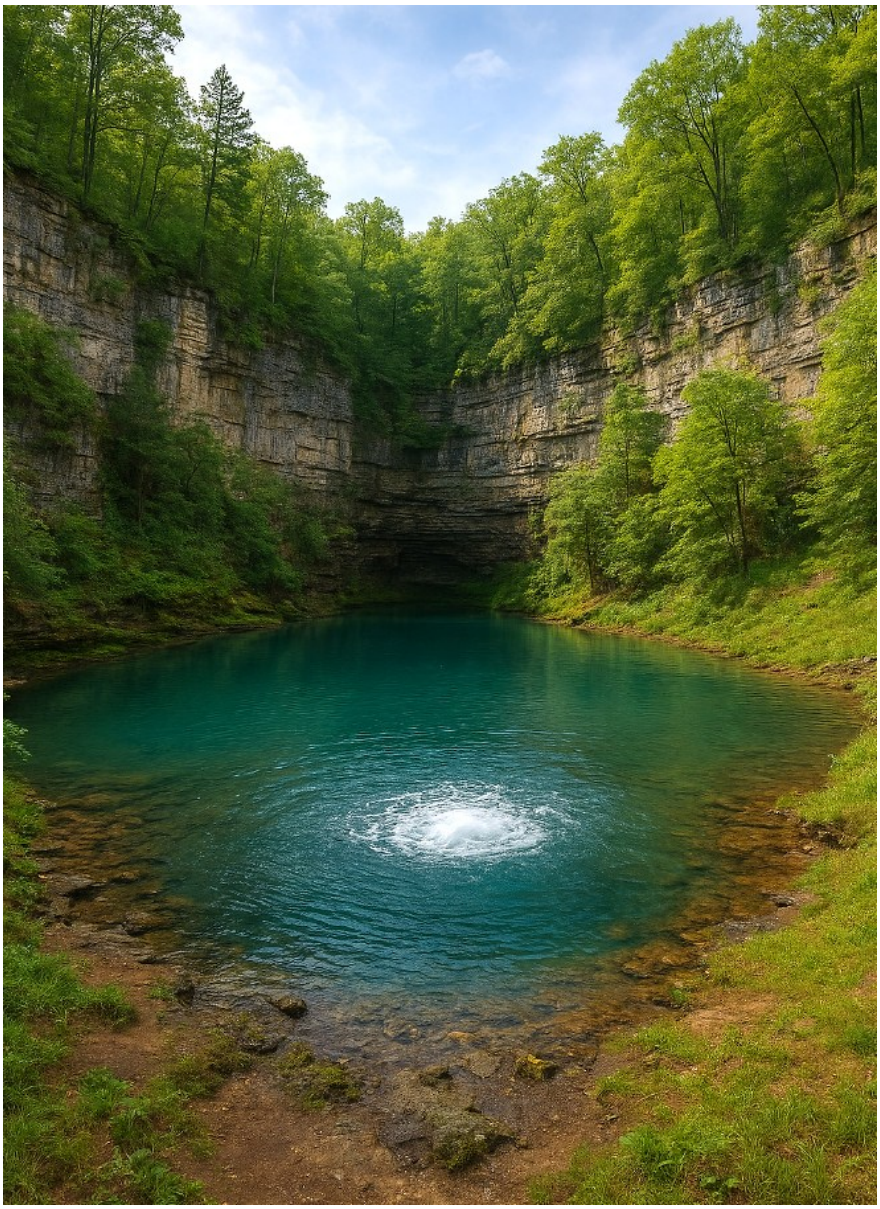
Figure 3.5.7 Sketch cross section showing the Rise of Lost River by Steven Maegerlein (Quinlan et al., 1983, p. 77). From *Lost River Field Trip for the Indiana Water Resources Association* by Richard L. Powell.

The Lost River is about 87 miles long, and its name is derived from the fact that at least 23 miles of the primary course of the river flows completely underground. It begins as a normal river in Washington County, but soon after it flows over a series of sinkholes and sinks into a karstified limestone bed for several miles until the stream bed turns dry. The sinkholes into which the river flows are progressively the Stein Swallow Hole, then Turner Swallow Hole, and, by far the largest, the Tolliver Swallow Hole which is a significant National Natural Landmark in Orange County, serving as a key point where the Lost River loses water to a karst conduit system.

The river then flows underground to the National Natural Landmark Wesley Chapel Gulf (Fig. 3.5.8; see also Fig. 1.34) and forms a box canyon with 30-to-100-foot-high bedrock walls, where the river briefly appears before once again disappearing below the surface. It finally rises at (the true) Rise of Lost River, merges with the short tributary originating from The Orangeville Rise, and continues as a permanent stream until the confluence with the East Fork White River.

The following text and the exceptional photograph in Fig. 3.5.8 are from webpage https://www.frnwh.com/2025/10/wesley-chapel-gulf-and-the-lost-river-in-indiana/

One of the best places to appreciate the Lost River's underground life is Wesley Chapel Gulf, a 187-acre site managed by the U.S. Forest Service. From above, the Gulf appears as a vast sinkhole basin, with steep limestone walls plunging as much as ninety-five feet in some spots. It is both dramatic and quiet, a secluded bowl of earth where water and stone tell stories millions of years old. Wesley Chapel Gulf has been recognized as a National Natural Landmark since 1972, a designation that highlights its significance as one of the best examples of karst topography in the Midwest. Unlike many underground rivers that remain hidden, the Gulf offers a surface window into this subterranean world. It is, in essence, a stage where the river occasionally reveals its secret performance.



Perhaps the most fascinating feature of Wesley Chapel Gulf is Boiling Spring, a rise pool where water from the underground Lost River emerges. On a normal day, the spring may look calm, a quiet pool nestled in the depression. After heavy rains, however, the spring surges dramatically, sending up roiling bursts of water—the so-called "boils" that inspired its name.

Figure 3.5.8 Boiling Spring: the heartbeat of the Wesley Chapel Gulf; available at https://www.frnwh.com/2025/10/wesley-chapel-gulf-and-the-lost-river-in-indiana/

Blue Spring on East Fork White River

Blue Spring in Lawrence County is the discharge point for Bluespring Caverns. The spring itself discharges into the East Fork of the White River from a submerged canyon-like cavity approximately 40 feet deep. The entire cave system, including the discharge point at Blue Spring, is situated on privately owned land with no public access. Historically, the property was owned by the Colglazier family, who allowed explorers on their land for decades before leasing it for commercial use.

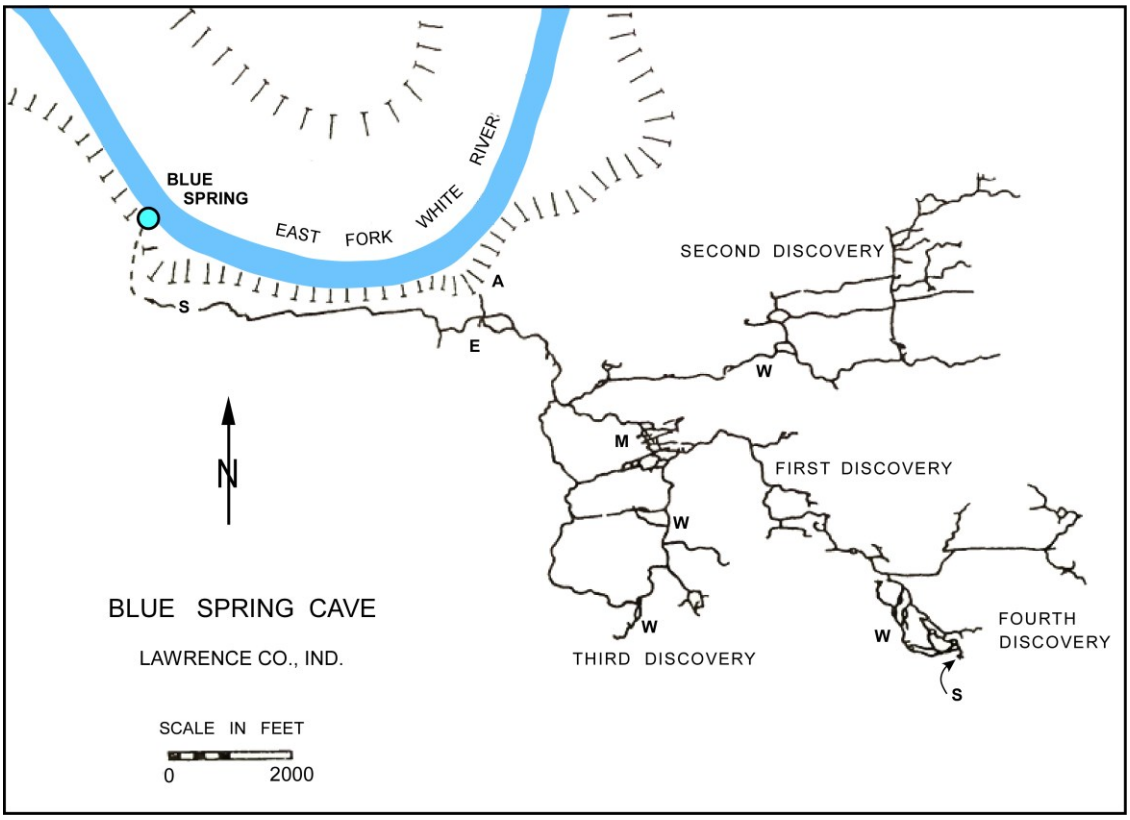


Figure 3.5.9 Map of Bluespring Caverns. E: entrance; S-S: course of main stream through cave; M: Maze; A: abandoned spring alcove; W: waterfalls. The main stream passage (S-S) carries a low flow in summer and fall of about 500 gpm. and an observed peak flow of 300,000 gpm during a period of combined snow melt and heavy rainfall. From Palmer, 1968; modified for clarity.

Bluespring Caverns are developed primarily within Middle Mississippian Salem Limestone and the basal St. Louis Limestone. Passage development is largely guided by the principal fracture sets in the Salem Limestone, following a dendritic pattern where smaller tributary streams coalesce into a large main trunk. The cave features at least three distinct levels, formed as the East Fork of the White River entrenched deeper into the plain over millions of years (Palmer, 1968).

Located southwest of Bedford on the Mitchell Plain (also known as the Mitchell Plateau), the cave system actively drains approximately 15 to 18 square miles of sinkhole-dominated land. The high variability of the Blue Spring discharge and a flashy response to rainfall events is due to rapid recharge through thousands of sinkholes in the Mitchell Plain. Because approximately 80% of the cave is wet, the "Myst'ry River" (main conduit of the system) can rise rapidly, sometimes closing the cave to boat tours during high-water events.

The cave system of Bluespring Caverns contains 21 miles of surveyed passages and is most notable for having the longest known subterranean river in the United States with approximately 3 miles of navigable subterranean channel. It has an average water depth of about 8 feet, with some spots reaching 21 feet deep. The cave remains a constant 54 F (14 C) temperature throughout the year. Access to the cave is managed by Bluespring Caverns Park (https://www.bluespringcaverns.com/), a commercial corporation. The park founders originally secured a lease from George and Eva Colglazier in 1973 to develop the site for public tours.



The Bluespring Caverns cave system was first discovered in the 19th century. Before 1913, the entrance served as the outflow of a spring that discharged into the White River. However, a dam construction on the White River in 1913 effectively blocked this access point. In 1940, a supplementary entrance was constructed in response to a severe storm in the vicinity. Overnight, a small pond on George Colglazier's farm transformed, disappearing and giving way to a sinkhole, which now serves as the main entrance for commercial cave tours.

Figure 3.5.10 Kayak tours of the Myst'ry River are popular way to explore the longest known subterranean river in the United States with approximately 3 miles of navigable channel. Photo courtesy of Bluespring Caverns.

The following nice description of touring the Bluespring Caverns is from Tourist Secrets website, https://www.touristsecrets.com/destinations/hidden-rivers-beneath-indianas-blue-spring-caverns/

Have you ever wondered what lies beneath the surface of Indiana? ***Blue Spring Caverns*** *offers a glimpse into a hidden world of underground rivers and stunning rock formations. Located in Lawrence County, these caverns are home to one of the longest navigable underground rivers in the United States. Visitors can embark on boat tours that take them through winding passages, revealing the natural beauty and geological wonders that have formed over millions of years. Whether you're a geology enthusiast or just looking for a unique adventure, Blue Spring Caverns provides an unforgettable experience. Ready to explore the mysteries below? Let's dive in*

The heart of Blue Spring Caverns lies in its intricate network of underground rivers. These waterways carve through the limestone, creating stunning formations and hidden passages. Known for its crystal-clear waters, **Myst'ry River** *winds through the caverns, offering a serene and otherworldly experience. The gentle flow and reflective surface create a mesmerizing atmosphere. Named for the echoes that bounce off its walls,* **Echo River** *provides a unique auditory experience. The sounds of dripping water and distant currents add to the cavern's mystique.*



Figure 3.5.11 Blue Spring Caverns. Photo courtesy of https://www.touristsecrets.com/destinations/hidden-rivers-beneath-indianas-blue-spring-caverns/.

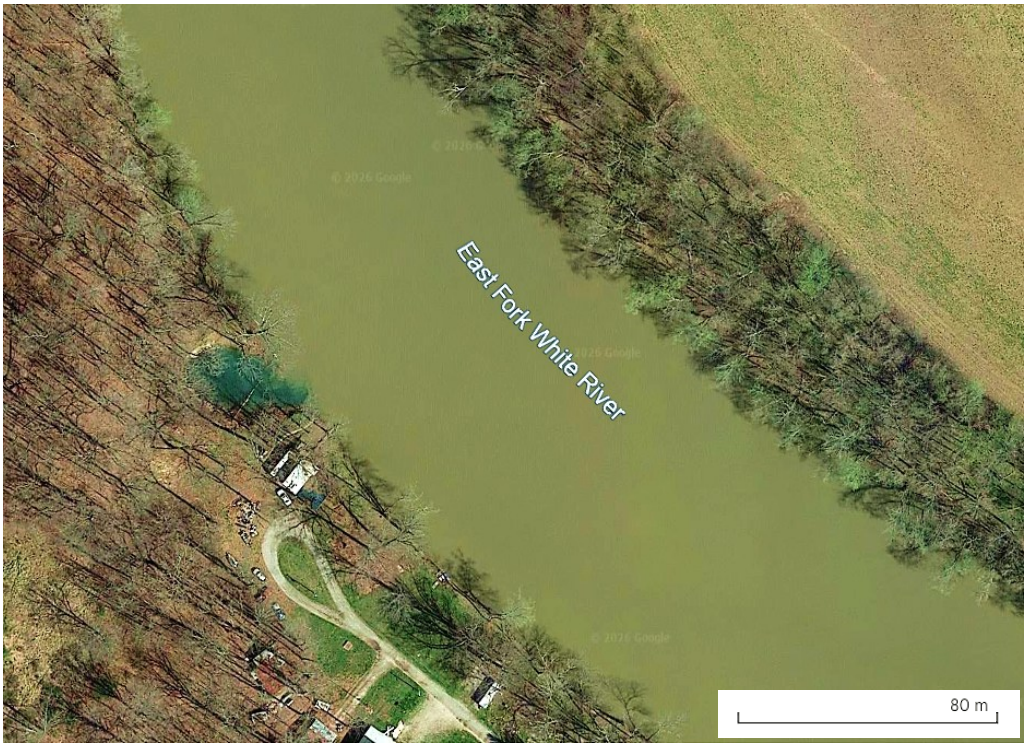


Figure 3.5.12 Google Earth image of Blue Spring (blue pool in center left) acquired 3/19/2016. ©2026 Google. Note that while the river itself is held in public trust by the State of Indiana for recreational use (such as boating or fishing), the banks and the specific spring vent are private property. Landing a boat at the spring or traversing the bank without permission is considered trespassing.

Springs of Spring Mill State Park

Spring Mill State Park (https://www.in.gov/dnr/state-parks/parks-lakes/spring-mill-state-park/) in Lawrence County, three miles east of the town of Mitchell, is in the Mitchell Plateau physiographic region, which, with its abundant dissolution features, is one of the best examples of karst topography in the world. Within the park, the sinkholes number more than 100 per square mile and reach a known maximum of 1,023 in a square mile near the town of Mitchell. There are two large cave springs in the park, Donaldson Cave, and Hammer Cave, and an exemplary karst window of Bronson Cave and Twin Caves (Fig. 3.5.13).

Many of the large cave passages with active streams, including the entrances to Hamer and Donaldson Caves, occur within the Mississippian Salem Limestone. The overlying formation is the St. Louis Limestone. Finer grained and thinner than the Salem, the St. Louis includes thin layers of shale, dolostone, and gypsum with very few fossils. The upper cave passages and nearly all the sinkholes are within the St. Louis Limestone.

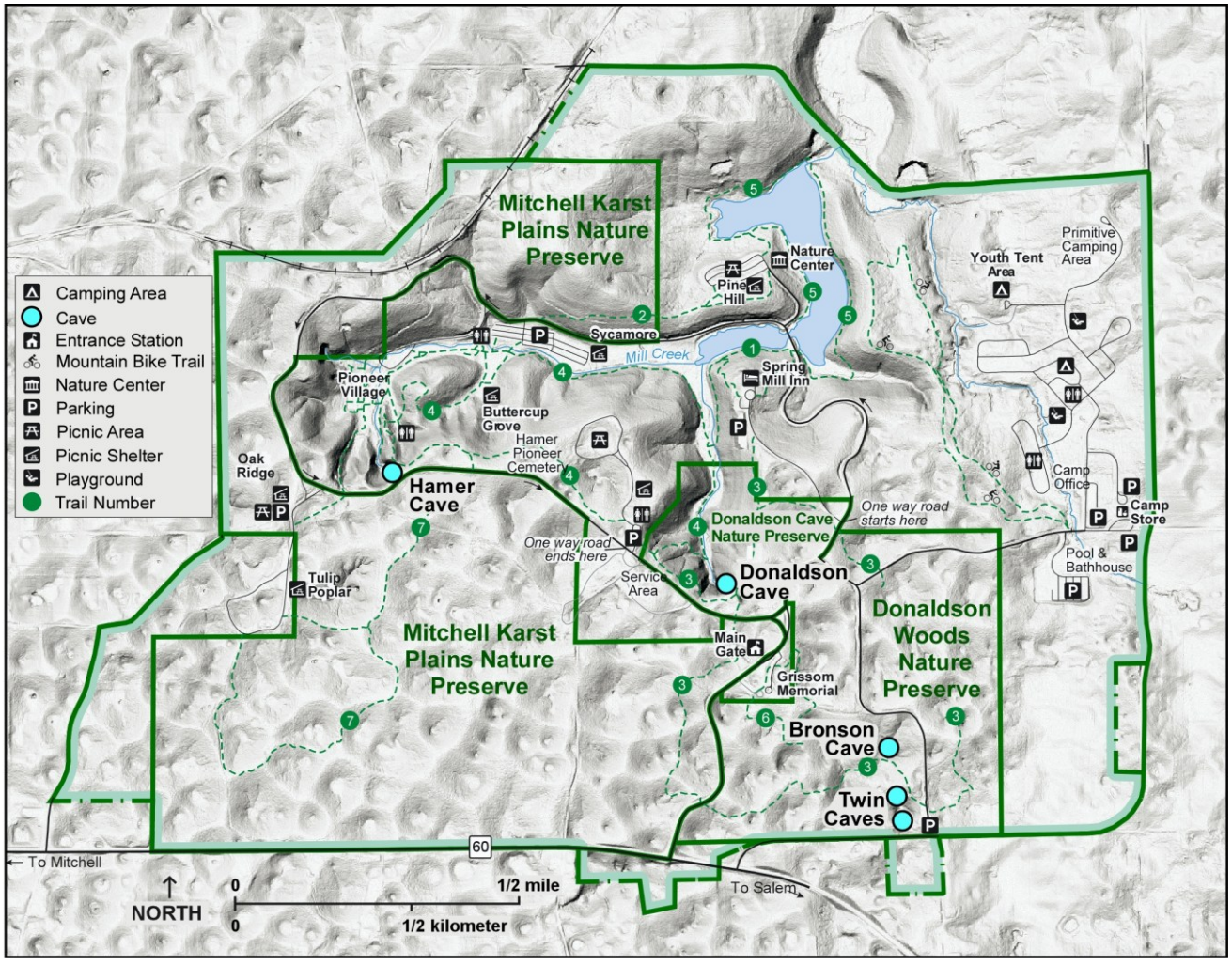


Figure 3.5.13 Map of Spring Mill State Park. Modified from *Geologic Story of Spring Mill State Park* by Indiana State Geological and Water Survey (2019).

Donaldson Cave System and Hamer Cave are two major caves in the park. Located on the southern portion of the loop road, both caves emerge as springs at the head of steep-walled valleys. Their entrances were formed by the collapse of the cavern roof and erosion of fallen debris. It is possible the collapse may have started below the

junction of Hamer and Donaldson Branches of Mill Creek. As the water dissolved the rock layers and the caves continued to collapse farther upstream, weathering and surface erosion widened and smoothed out the valleys where the lake and Pioneer Village are located. To the south along Trail 3, the karst window of Bronson Cave and Twin Caves formed when a cavern roof collapsed and exposed karst groundwater to the surface. Both of these cave entrances provide a glimpse of the stream that flows northwest through Twin Caves and Bronson Cave and exits at Donaldson Cave (Indiana Geological and Water Survey, 2019).

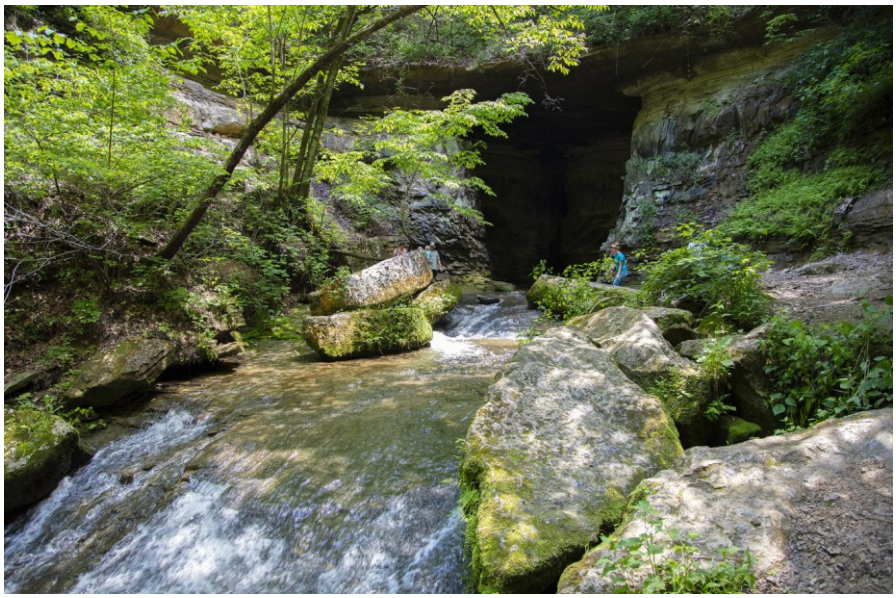


Figure 3.5.14 Donaldson Cave Spring (the cave is also called Shawnee Cave, or Donaldson/Bronson Cave.) The blind Hoosier cavefish, an endangered species and type of Northern cavefish, can be found in the Donaldson Cave ecosystem. Photo courtesy of Visit Indiana.
https://visitindiana.in.gov/blog/post/donaldson-cave-spring-mill-state-park/

Water flows through the entire length of the Donaldson Cave. The cave can easily flood, and it is advised not to enter the cave when there is a chance of significant rain, or during periods of rapid snowmelt. There are no seasonal restrictions on trips into this cave. Visitors should familiarize themselves with all the rules that regulate visits to the cave system at Spring Mill State Park and make necessary arrangements for the visit. The access to the caves is controlled by the Indiana Department of Natural Resources.

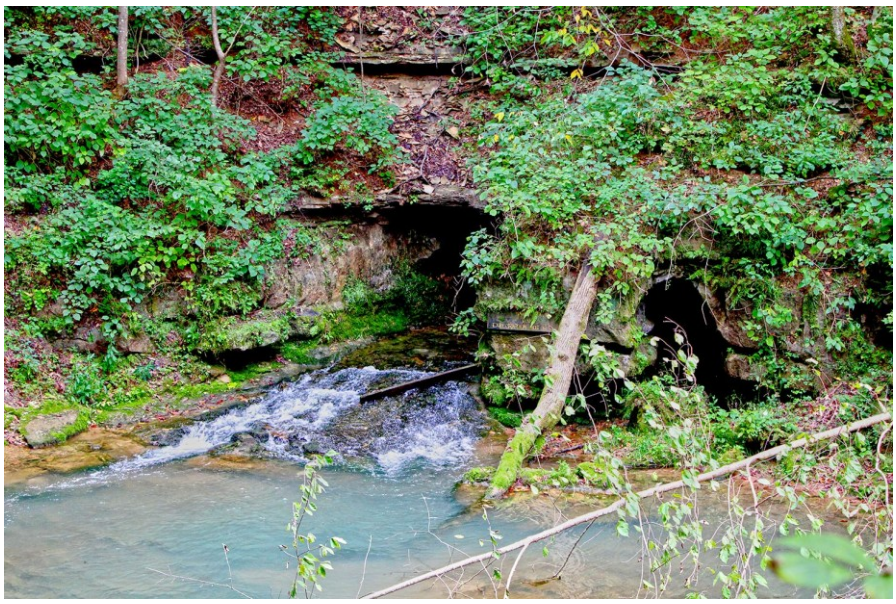


Figure 3.5.15 Hammer Cave Spring in Spring Mill State Park. The stream flowing from Hamer Cave has been harnessed in the past for regional commerce, and its water is still used to this day by The Lehigh Cement Company water for cooling purposes.

3.6 Ohio

Springs of Bellevue-Castalia Karst Plain

The Bellevue-Castalia Karst Plain occupies portions of northeastern Seneca County, northwestern Huron County, southeastern Sandusky County, and western Erie County (Fig. 3.9.16). The area is underlain by up to 175 feet of Devonian carbonates (Delaware Limestone, Columbus Limestone, Lucas Dolomite, and Amherstburg Dolomite) overlying Silurian dolomite, anhydrite, and gypsum of the Bass Islands Dolomite and Salina Group.

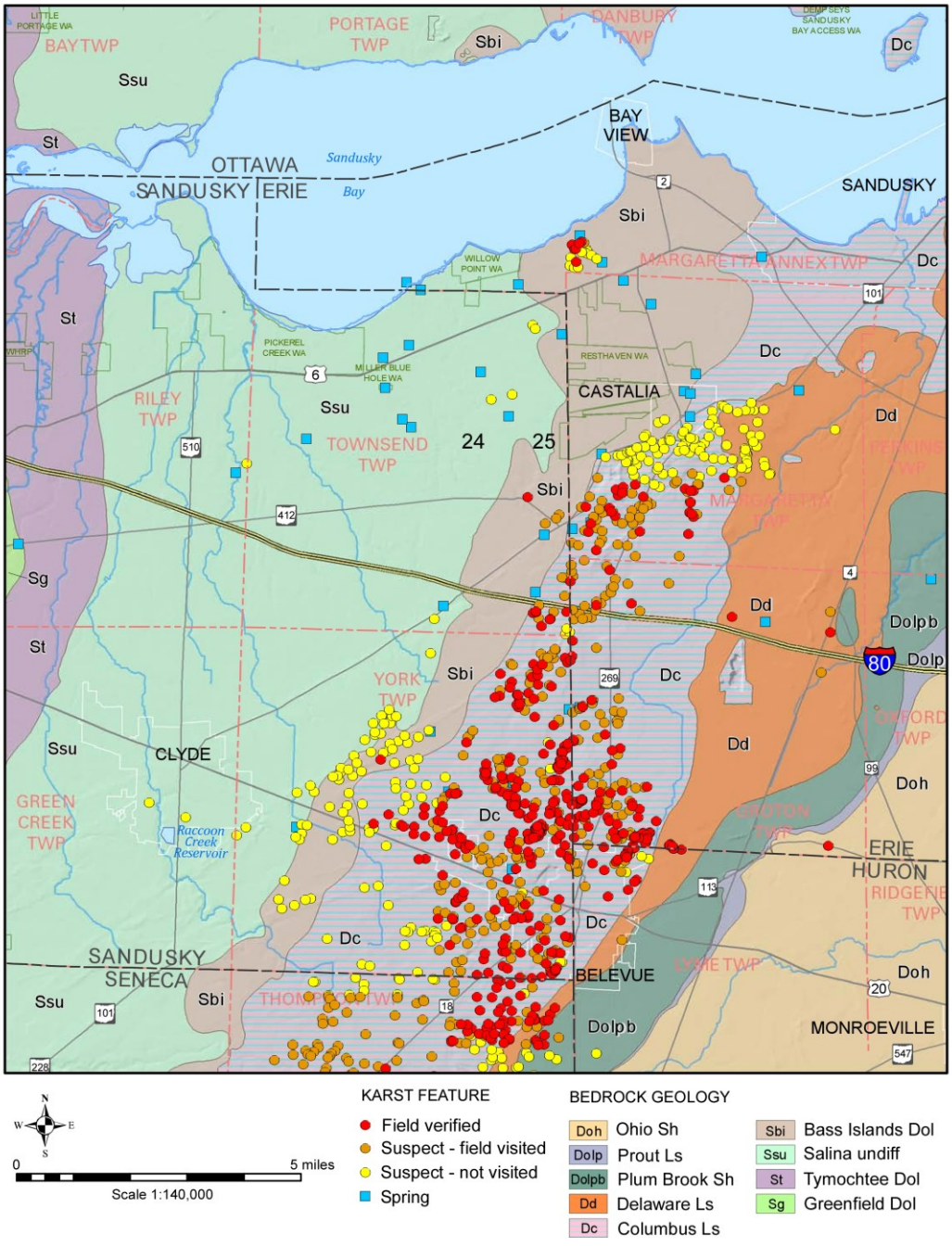


Fig. 3.6.1 Bedrock map and karst features of part of the Bellevue-Castalia Karst Plain. Modified from Aden and Martin, 2013, Ohio Department of Natural Resources, Division of Geological Survey.

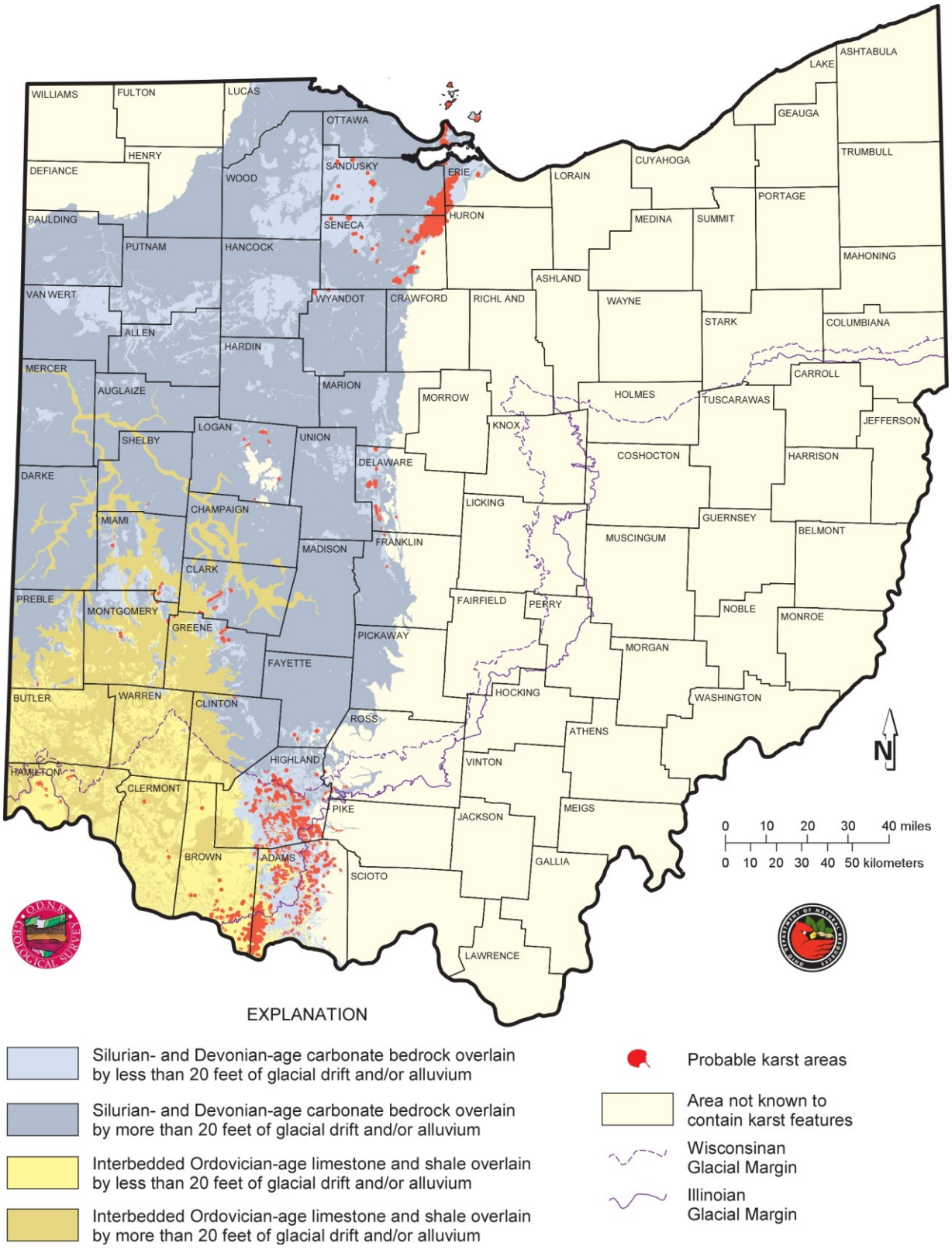


Figure 3.6.2 Map of Ohio karst areas. The Bellevue-Castalia Karst Plain is in the north. Modified from Ohio Division of Geological Survey, 1999.

The Bellevue-Castalia Karst Plain is believed to contain more sinkholes per square mile than any of Ohio's other karst regions (Fig. 3.6.2). Massive, irregularly shaped, closed depressions up to 270 acres in size and commonly enclosing smaller, circular-closed depressions 5 to 80 feet in diameter pockmark the land between the village of Flat Rock in northeastern Seneca County and Castalia in western Erie County (Ohio Division of Geological Survey, 1999). Ohio's four largest karst springs are draining the Bellevue-Castalia Karst Plain.

Surface drainage on the plain is very limited, and many of the streams which are present disappear into sinkholes often locally referred to as swallow holes. Karst in the Bellevue-Castalia and Lake Erie islands region is due to collapse of overlying carbonate rocks into voids created by the dissolution and removal of underlying gypsum beds. According to Verber and Stansbery (1953, Ohio Journal of Science), groundwater is introduced into Salina Group anhydrite (CaSO4) through pores and fractures in the overlying carbonates. The anhydrite chemically reacts with the water to form gypsum (CaSO4•2H2O), undergoing a 33 to 62 percent increase in volume in the process. This swelling lifts overlying strata, thereby opening fractures and creating massive passageways for conduction of greater volumes of groundwater through the Silurian Bass Islands Dolomite and into underlying Salina Group strata. Gypsum, being readily soluble in water, is dissolved, creating large voids. Overlying carbonates then collapse or break down, leaving surface depressions similar to those resulting from roof failure of an underground mine (Ohio Division of Geological Survey, 1999.)

The dissected Niagara Escarpment of southwestern Ohio includes the largest single area of karst terrain in the state and the greatest number of surveyed caves. It also is estimated to include the second-largest number of sinkholes in the state. However, it does not host large karst springs primarily due to fine compartmentalization of the water-bearing Silurian and Devonian carbonate rocks by the interspersed shale strata.

Mineral Springs

Mineral Springs in the village of Green Springs, situated at the border of Seneca and Sandusky Counties, is recognized as one of the country's largest mineral springs, known for its high sulfur content. It drains a confined Silurian-Devonian carbonate aquifer with an average flow rate of 8 million gallons per day (15 cfs). The massive overflow from the spring runs into Green Creek, eventually traveling to Sandusky Bay and Lake Erie. The spring is also monitored as a USGS water site under the name *S-34 St. Francis Spring*. Silurian anhydrite and gypsum of the Salina Group at the base of the aquifer is the source of mineralized water that discharges at Mineral Springs.



Figure 3.6.3 Mineral Springs in the town of Green Springs, located on the border of Seneca and Sandusky Counties. Photo courtesy of Remarkable Ohio. 7-72 Seneca Indian Reservation at Green Springs / Mineral Spring at Green Springs - Remarkable Ohio

The Green Springs area was originally inhabited by the Kaskaskia and Miami Nation. On September 29, 1817, the Seneca who had been displaced from their native lands in New York signed the Treaty of Fort Meigs, which established the 40,000-acre Seneca Indian Reservation including the springs, and a $500 annuity. Beginning in 1830, with a policy of Indian removal developed by the administration of Andrew Jackson, tribes east of the Mississippi River were pressured to move to reservations in the West. The Seneca Indians moved to northeast Oklahoma in 1831. Afterwards, the Mineral Springs, which remains at a constant 50 degrees Fahrenheit year-round, became a great source for "curing all ailments." In 1868, local entrepreneur Robert Smith had the spring water analyzed for mineral content and found it high in calcium sulphate and magnesium sulphate. The area was developed to include hotels and spas, and people from many parts of Ohio and elsewhere came to be near the water. The water was also bottled and sold until the 1930s (7-72 Seneca Indian Reservation at Green Springs / Mineral Spring at Green Springs - Remarkable Ohio).

Blue Holes in Town of Castalia

Castalia Blue Hole in Castalia, Erie County, about six miles southwest of Sandusky, is widely considered the state's most famous spring. It is the largest of the Castalia artesian springs located in the Bellevue-Castalia Karst Plain. The average flow rate of the Castalia Blue Spring is approximately 7 million gallons per day (13 cfs), and the temperature is nearly constant 46° to 51° Fahrenheit.

The following extensive excerpts are from exceptional work by Karl Ver Steeg and George Yunck, professors at College of Wooster at the time (1932). This scientific article is available through Knowledge Bank of the State University of Ohio at The Blue Hole of Castalia.

The earliest historical record of the springs at Castalia is that in the report of Major Robert Rogers of New Hampshire. After the fall of Quebec, Major Rogers left Montreal to take over the western forts held by the French and Indians. At Presque Isle he met Pontiac and was escorted to Detroit. Having secured the post at Detroit, Rogers returned by way of the Sandusky and Tuscarawas Trail which passed near the head of Cold Creek where the Castalia springs are located. In his observations of September 13, 1760, he remarks, "there is a remarkable spring at this place rising out of the side of a small hill with such force that it boils out of the ground in a column three feet high. I imagine it discharges ten hogsheads of water a minute." This area was frequently occupied by the Ottawa and Wyandot Indians, the latter establishing a village on the present site of the town of Castalia. The springs furnished a plentiful supply of clear, cold water and Cold Creek leading from them, in its natural course, flooded much level land which was a paradise for muskrats, otter and mink. Deer and wild turkey were also numerous.

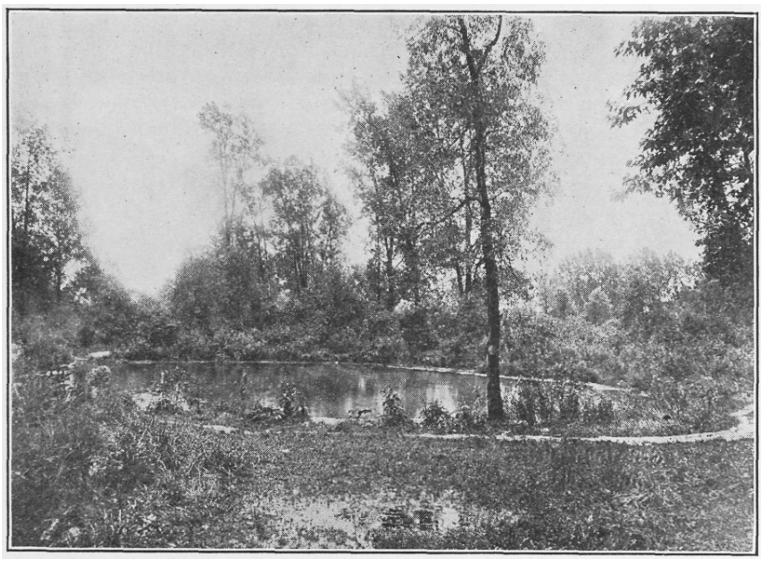


Figure 3.6.4 Historic photograph of Castalia Blue Hole from the 1932 scientific article by Karl Ver Steeg and George Yunck published in The Ohio Journal of Science.

Sandusky and Castalia are located on the Onandaga (Columbus and Delaware) limestone of Middle Devonian age which is underlain by the Monroe limestone of Upper Silurian (Cayugan) age. The Monroe limestone is a typical dolomite, about one hundred feet thick and it is in this horizon as well as the Columbus and Delaware formations that the under ground streams in the region about Castalia have carried on their work.

The Castalia springs are four in number and discharge into a pond a few acres in extent, located in the central and east portions of the village. About twenty-five thousand gallons of water are supplied to the pond per minute. This volume formerly flowed across the prairie on the north and through the marsh southeast of Bay Bridge by means of a stream, now extinct. This creek flowed northeast four miles from the shore of Sandusky Bay, at a point one and one-fifth miles east of Bay Bridge and joined the old Sandusky River a quarter of a mile upstream from Mill's Creek near Johnson's Island. With the advent of man, the prairie to the north and west of Castalia was too wet for trees. This area has been artificially drained by canals, leading the water north and northeastward into two branches of a creek flowing into the bay at Venice. The entire stream course has been known as Cold Creek.

The great marl beds used for cement by the Sandusky Portland Cement Company at Bay Bridge were formed in the flooded area north of Castalia, from the spring waters which contain a high percentage of calcium carbonate. The abundance of tufa at the surface makes it impossible to plow the land, which can be used for pasturage only. The marl bed area has always presented dismal agricultural prospects and it required little persuasion for the owners to sell their land to a "sporting club organization."

The Blue Hole is not more than one hundred and ten years old; it came into being about 1820 when the pressure caused by the rising of the water of the upper pond in Castalia, as the result of a dam, weakened the strata above the Blue Hole and occasioned its collapse into the cavernous depth. This dam was located in front of the church in the center of the village where the pond emptied into the outlet stream. The new spring has since had a sympathetic relationship with the larger and less beautiful pond to the south. Undermining has proceeded since the original collapse, for early in 1914 another cave-in occurred leaving the Blue Hole with its present dimensions, roughly circular, averaging seventy-five feet in diameter. The Blue Hole did not gain wide publicity until about 1879, because it was inaccessible except by boat. The organization of the Cold Creek Trout Club, brought about the banking of the marshy edges of the Blue Hole so that one could walk about the orifice. Today the area to the south and less to the east and west is still very moist and few trees of any size can grow there.

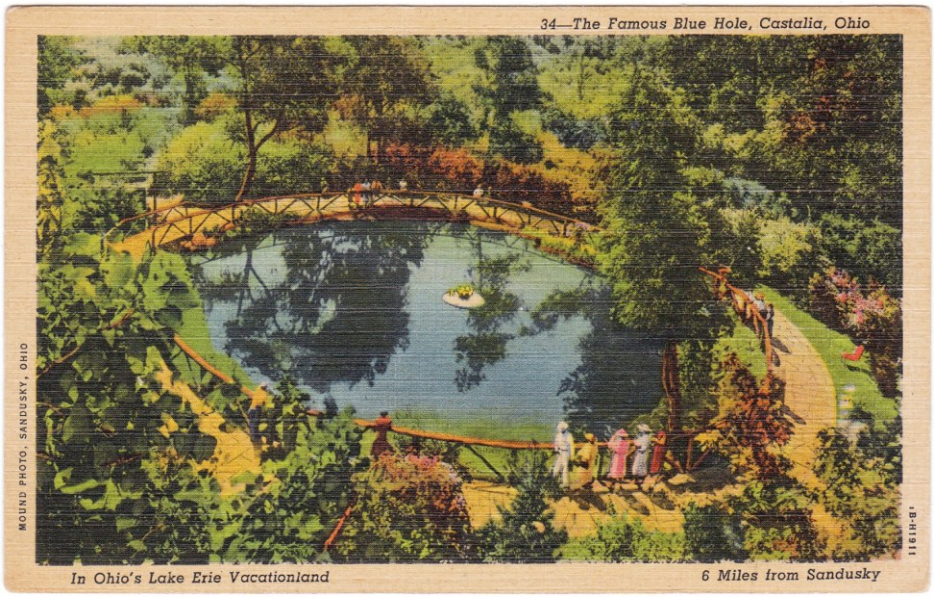


Figure 3.6.5 1920s postcard of "The Famous Blue Hole, Castalia, Ohio". While the original tourist attraction closed in 1990 and is now on private property, a nearly identical blue hole fed by the same aquifer can be viewed at the nearby Castalia State Fish Hatchery (Fig. 3.6.6).

Contrary to prevalent belief, the depth of the Blue Hole is not unknown, but has been sounded and found to be about forty-three to forty-five feet deep. The deepest point is near the south margin, where on a sunny day one may follow the descent of a small object through the limpid water to the mysterious depths below. The sun must be shining in order to penetrate the depths, for the surface otherwise acts as a mirror. Therefore the summer time is the best season in which to fully appreciate the vast, quiet beauty of the Blue Hole. The surface remains undisturbed, even though there is a constant volume of water coming from below. About five thousand gallons of water per minute escapes from the Blue Hole, through two outlets, over artificial cascades made to aerate the water which is lacking in free oxygen, Trout cannot live in the Blue Hole because of the lack of free oxygen. The volume of water and its temperature remain remarkably constant throughout the year.

During and after the drought of 1930 the Blue Hole showed no noticeable volume change. The temperature of the water does not vary appreciably during summer and winter; the maximum fluctuation is about 5° Fahr., that is from 46° to 51°. This fact, and the huge volume of water supplied by all the springs, prevents Cold Creek from freezing during the winter. Consequently, mills were established at an early date along the five-mile length of Cold Creek to Sandusky Bay. The constant source of power throughout the year was of great value to the early pioneer. The Blue Hole and other springs at Castalia send out thirty thousand gallons of water per minute into the canals which extend north a mile and a half to the club house of the Castalia Sporting Club, where they join in a single straight channel, the length of which extends an equal distance to the northeast.



Fig. 3.6.6 Blue Hole at Castalia State Fish Hatchery. Average flow rate is 2,500 gpm.
Courtesy of Ohio Department of Natural Resources, photo by David Roorbach, February 2023.

The Castalia Blue Hole—a famous tourist attraction from the 1920s to 1990—is now on private property owned by the Castalia Trout Club and off-limits to the public. Its water is anoxic (devoid of oxygen) and diverted to a raceways system of the State Hatchery where it is aerated and used to raise rainbow trout and steelhead.

An almost identical blue hole, with the average discharge rate of 2,500 gpm, is on the grounds of the nearby Castalia State Hatchery and open for public viewing (Fig. 3.6.6; https://ohiodnr.gov/go-and-do/plan-a-visit/find-a-property/castalia-fish-hatchery.)

The third large Castalia blue hole is a 5-acre Duck Pond located in the center of the village where 3 submerged vents discharge from the same karst aquifer. The Pond is a birding hot spot and owned by the Castalia Trout Club Its water also flows downstream to the State Hatchery's raceway system (Fig. 3.6.7).

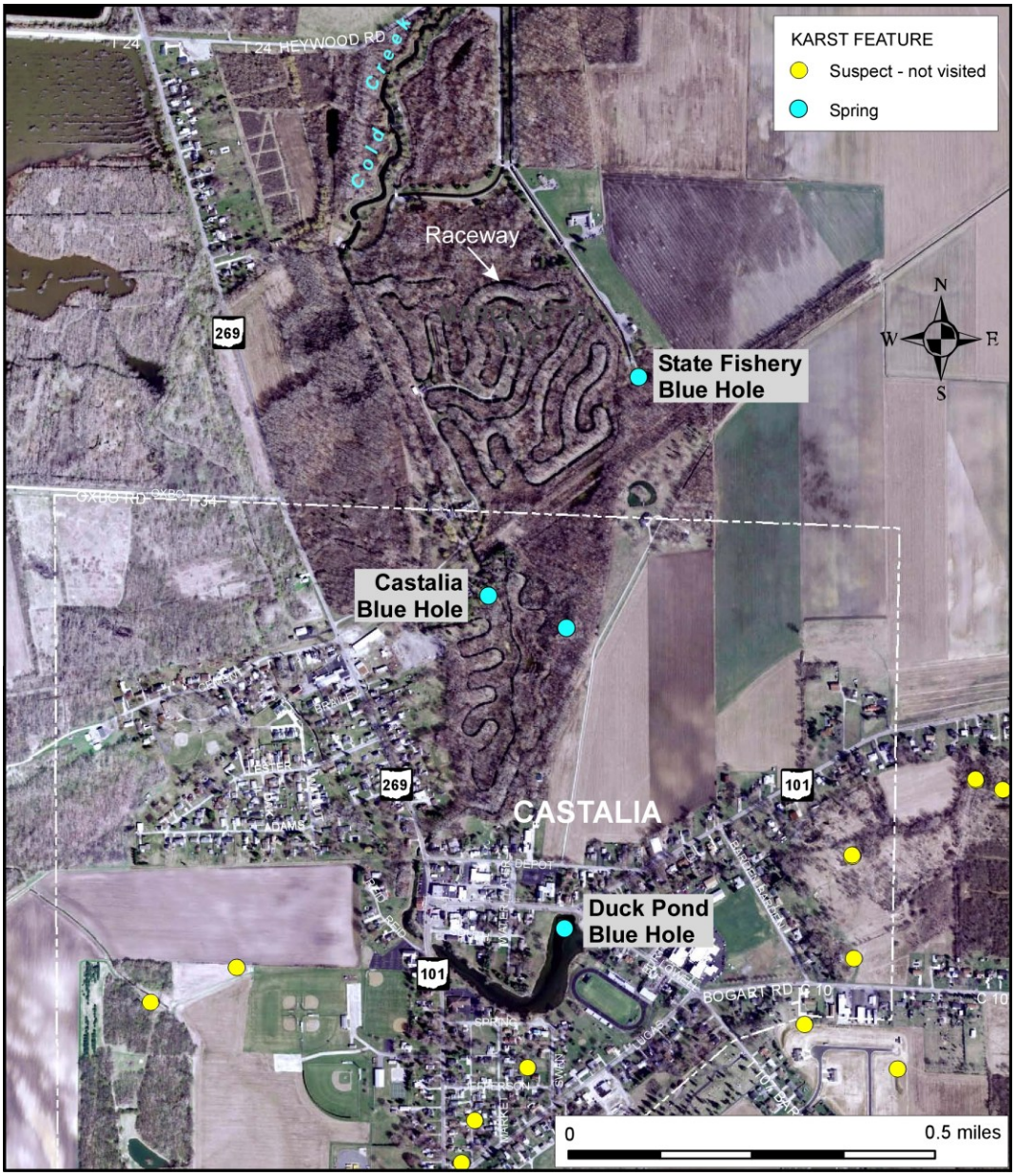


Figure 3.6.7 Locations of blue hole karst springs in the Town of Castalia, Eire County. Modified from Aden and Martin, 2013, Ohio Department of Natural Resources, Division of Geological Survey (parts of Tiles 21 and 27).

3.7 Kentucky

Most of the large springs of Kentucky are in the Pennyroyal karst region (Fig. 3.9.23) where the Mississippian Plateau limestone formations are thick and underlie a wide area. The principal formation giving rise to large springs in the Mississippian Plateau is the St. Louis Limestone of Late Mississippian (Meramec) age. The overlying Ste. Genevieve Limestone, also of Late Mississippian (Meramec) age, similarly supplies large quantities of groundwater to springs. Formations below the St. Louis, such as the Warsaw Formation of Late Mississippian (Meramec) age, the Fort Payne Chert of Early Mississippian (Osage) age, and the Laurel Dolomite of Silurian age contain less important spring horizons. Large springs are less abundant in the Blue Grass region, where the limestone strata are much thinner and are commonly interbedded with shale formations. In the Inner Blue Grass area, nearly all of the large springs issue from the Benson Limestone, a part of the Lexington Group of Ordovician age (Van Couvering, 1962).

Large springs are typical features of the drainage in the limestone areas of central and southwestern Kentucky. The use of large springs in these areas has declined, and few now power water wheels compared to the number that formerly provided energy to small industries. Towns that grew up around powerful springs from which they could draw their water have since come to depend on deep wells and surface reservoirs because the spring water was periodically of poor quality, because of population growth, and because of improved drilling and engineering techniques which had the appeal of providing what were considered more modern water supplies (Van Couvering, 1962).

Name	County	Discharge Rate, gpm		Water-bearing formation
		Min	Max	
Big Spring	Allen	900	40,000	Laurel Dolomite
Calvert Spring	Allen	310	11,000	Laurel Dolomite (?)
Bluff Spring	Caldwell	230	50,000	Ste. Genevieve Limestone
Harpending	Caldwell	670	6,200	St. Louis (?) Limestone
Town Creek Spring	Clinton	280	57,000	St. Louis Limestone
Smotherman Spring	Logan	130	30,000	St. Louis Limestone
White Mills Spring	Hardin	1,100	29,000	St. Louis Limestone
Puckett	Livingston	270	25,000	St. Louis Limestone
Schenley Spring (Head of Doe Run)	Meade	1,800	50,000	St. Louis Limestone
Arow Spring	Simpson	315	17,000	Warsaw Limestone
Town Spring	Todd	670	3,100	St. Louis Limestone
Garnett Spring	Trigg	730	10,300	St. Louis Limestone
Martin Spring	Trigg	610	48,000	Ste. Genevieve Limestone
Mill Stream Spring	Trigg	650	80,000	St. Louis Limestone
Spring Station Spring	Woodford	220	9,800	Benson Limestone

Discharge measurements and chemical analyses of select large springs in Kentucky were made periodically from 1950-60. The springs all issue from solution openings in Paleozoic limestones and generally discharge much larger amounts of water in winter than in summer.

Table 3.7.1 Information on large karst springs in Kentucky compiled from Van Couvering, 1962.

The spring water is of the bicarbonate type, but it shows radical and apparently rapid changes in chemical quality within certain limits. The timing of the measurements was selected to record seasonal trends in discharge. Measurements made during the dry season indicate the minimum flow fairly accurately; during the wet season, however, many of the springs discharged so much water that measurements were difficult to make. Maximum flows

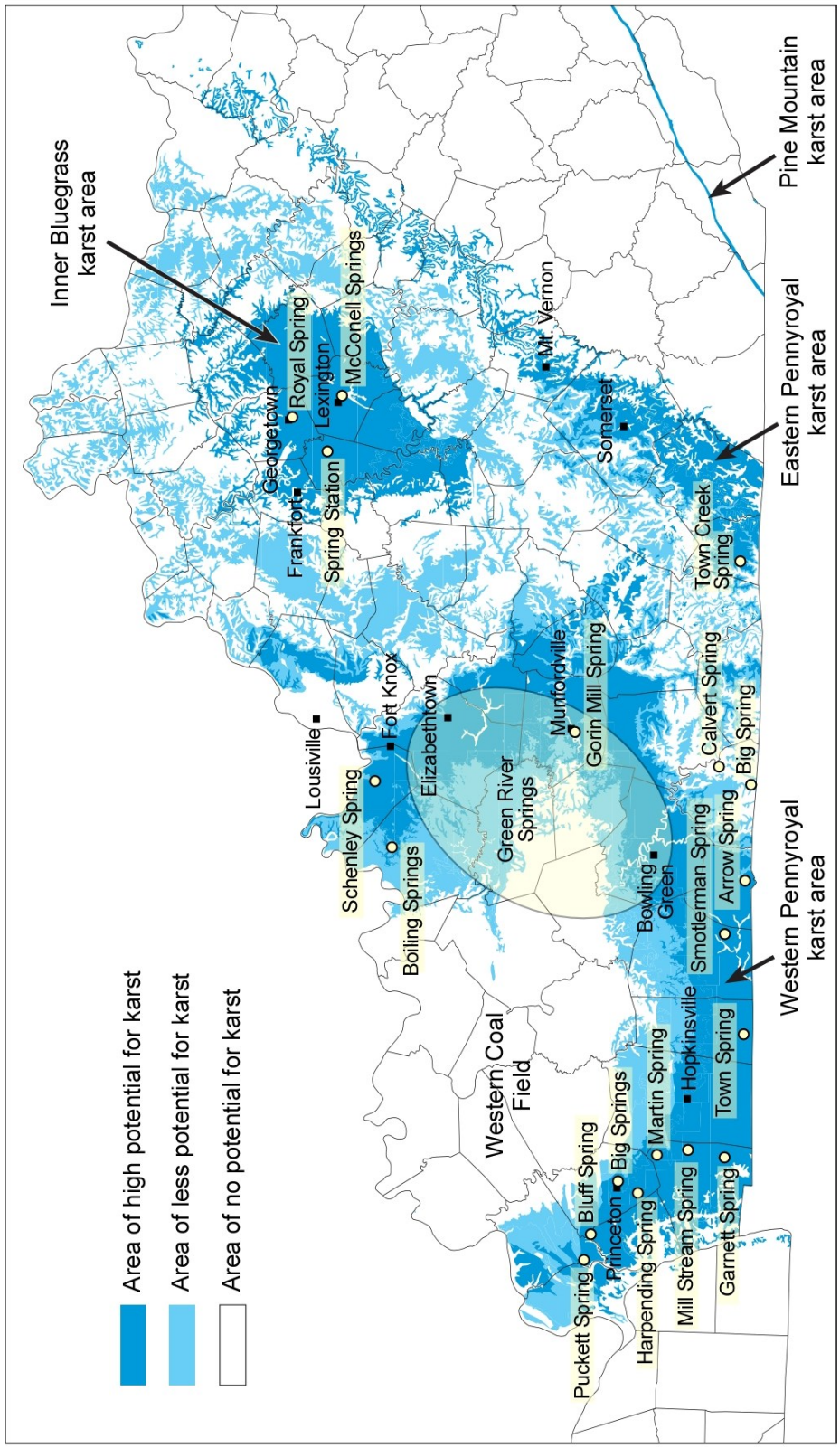


Figure 3.7.1 Map of Kentucky karst areas with locations of large and notable karst springs. Detailed map of Green River springs is provided in Fig. 3.7.2. Map compiled using information in Blair et al., 2012; Ray et al., 2005; and Van Couvering, 1962. Base map showing karst areas from Currens, 2002.

were seldom measured, because of hazardous conditions and because the peak flows at most of the springs are of short duration. In addition, many of the springs probably discharge the greatest amounts at times when the outlets are covered by flood water. The accuracy of many measurements was significantly reduced by excessively turbulent or slow currents, and obstructions or irregularities in the channel (Van Couvering, 1962).

As pointed out by Van Couvering, none of the springs described in this report are first magnitude. The largest, such as Schenley Spring and Mill Stream Spring, may rank low in the second magnitude, but the majority appear to have average discharges between 1,000 and 3,000 gpm, or in the upper range of third magnitude springs. The discharge of many of the springs, however, probably exceeds 100 cubic feet per second, about 45,000 gpm, several times each year. The springs described are those for which measurements of flow and quality of water were available for a period of 5 or more years. Van Couvering recognized that there are other large springs in Kentucky that were not included in the study; good examples are Royal Spring used for the water supply of Georgetown, Gorin Mill Spring in Hart County, the largest in Kentucky, and Boiling Springs in Breckinridge County. These and several other springs not described by Van Couvering are included on the maps in Figs. 3.7.1 and 3.7.2.

Since the work by Van Couvering, there were no reports by the Kentucky Geological Survey or USGS attempting to gather and present information on all large karst springs in Kentucky. Instead, larger springs are sometimes mentioned in reports on groundwater resources of various counties or described in reports of regional scope such as those of Ray et al. (2005), and Blair et al. (2012).

Green River Basin Springs

The Green River rises in Lincoln County and flows generally west-northwest to its confluence with the Ohio River north of the city of Henderson in Henderson County. The Green River is approximately 400 miles long and drains more than 9,100 square miles in Kentucky and Tennessee. In Kentucky alone the Green River drains more than 8,800 square miles - approximately 20% of the state. The Green River watershed drains portions of two major physiographic regions; the Mississippian Plateau and Western Coal Field.

Groundwater flow in the Green River basin varies according to local geology. After initial runoff of precipitation, groundwater provides base flow to surface water streams, thereby sustaining stream flow during periods without rain. Principal tributaries are the Barren River, Nolin River, Rough River and the Pond River. The largest impoundments are Green River Lake, Barren River Lake, Nolin Lake, Lake Malone, and Rough River Lake, all of which are operated by the Army Corps of Engineers.

The Mississippian Plateau, also known as the Pennyroyal or Pennyrile, is characterized by flat lying Mississippian-age carbonate rocks, primarily limestone with some dolostone. Well-developed karst drainage occurs in this region with an abundance of sinkholes, caves and influent streams. Groundwater flow is primarily through solutionally enlarged conduits, but fracture flow and flow along bedding planes also occurs and can be locally important. In general, yields from wells vary widely according to the size of any enlarged water-filled conduits encountered by the well-bore and can range from less than one gallon per minute (gpm) to more than one hundred gpm. Springs developed on these thick and generally pure carbonate sedimentary rocks tend to have larger discharges than in other areas within the watershed, with base flow discharges measured up to 24 cubic feet per second (cfs). The Mississippian Plateau is very sensitive to contamination from surface activities (Blair et al., 2012).

Well-developed karst drainage on the Mississippian Plateau occurs primarily in the Ste. Genevieve and St. Louis limestones of the Meramecian Series of the Mississippian System. These limestones were deposited mainly in shallow seas. One of the springs, Mill Spring, occurs in the Reelsville Limestone of the Chesterian Series of the Mississippian System. The purity and high solubility of the limestones make the terrane highly susceptible to karst

development. Long-term bedrock dissolution of these limestones has strongly influenced the Mississippian Plateau's characteristic flat-lying to undulating topography, which contains numerous shallow sinkholes and caves, losing and sinking streams, dry valleys, intermittent lakes, and large springs (Blair et al., 2012).

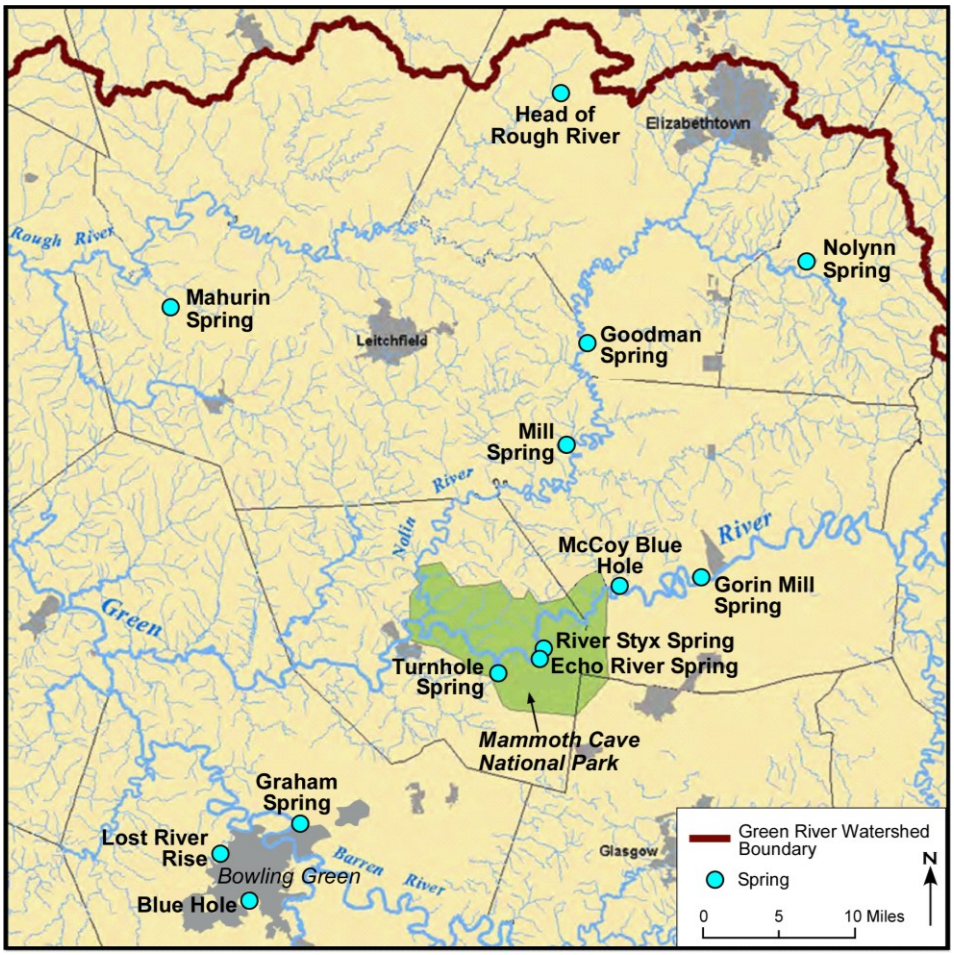


Figure 3.7.2 Map of large and notable karst springs in the watershed of Green River. Modified from Blair et al., 2012, additional springs added.

Spring Name	AKGWA	County	Base Flow (ft^3/s)	Basin Area (mi^2)	Geologic Formation
Gorin Mill Spring	0793	Hart	24.0	152.4	Ste. Genevieve LS
Graham Spring	0051	Warren	19.8	122	Ste. Genevieve LS
McCoy Bluehole	0792	Hart	12.7	34.1	Ste. Genevieve LS
Lost River Rise	0054	Warren	12.4	58.8	Ste. Genevieve LS
Skees Karst Window #1	1398	Hardin	6.4	27.5	Ste. Genevieve LS
Nolynn Spring	2673	Larue	4.6	56.4	St. Louis LS
Goodman Springs	0230	Hardin	4.6	14.7	Ste. Genevieve LS
Mill Spring	1193	Grayson	3.0*	7.1	Reelsville LS
Head of Rough River	1011	Hardin	4.0	17.7	Ste. Genevieve LS
Mahurin Spring	0202	Grayson	2.1*	25.3	Ste. Genevieve LS**

Table 3.7.2 Green River springs assessed in Blair et al., 2012. * Based upon limited data. ** Stratigraphic position questionable – complicated by faulting. AKGWA – spring identification number in KY Department of Environmental Protection (DEP) databases. Note: Mill Spring is named "White Mills Spring" in Van Couvering, 1962.

Gorin Mill Spring in Hart County is on the Rush Island Bottoms portion of the Green River State Natural Area which protects over a mile of frontage on the Green River. This section of the Green River is habitat for several rare mussel species such as fanshell, clubshell, rough pigtoe, northern riffleshell, catspaw, pink mucket, ring pink, and sheepnosein. The spring is not mapped on the USGS topographic or geologic maps. Due to limited access, Rush Island, which is on the south bank of Green River 2.8 miles below Munfordville, is not currently open to the public except by boat. Paddling access is available at Thelma Stovall Park in Munfordville.

Gorin Mill Spring discharges from the Ste. Genevieve Limestone as a moderate-sized bluehole with a spring run that flows approximately 50 feet to the Green River. Tracer data show that this spring has a groundwater basin area of 152.4 mi^2 and high-flow connections to numerous overflow springs along the Green River. This basin encompasses the towns of Cave City and Horse Cave and includes the massive Hidden River groundwater subbasin, which makes up over 80% of the total area. Gorin Mill has the largest base flow of any known spring in Kentucky at 24.0 ft^3/s (Blair et al., 2012).



Figure 3.7.3 *Left*: Gorin Mill Spring, the largest spring in Kentucky. Courtesy of Hart County Tourism Facebook page (https://www.facebook.com/HartCounty); photo by Norman Warnell. *Right*: View from bluff above spring looking down at blue hole and spring run to the Green River; from Blair et al., 2012.

A water mill was constructed at the Gorin Spring by Major James H. Gorin. It was a two-story weather-boarded mill sitting on the top of a cliff and operated by a steel line and turbine water wheel located at the foot of the cliff. By the 1960's the old mill was reportedly torn down and used for firewood.

Just above the spring an old road once ran from Munfordville, crossing the river, and into 'Epes' Bend. This was a strategic location for a water mill which furnished most of the residents of Munfordville with corn meal for many years.

In 2021, ten new national recreation trails were designated in eight states, including Kentucky's Green and Nolin Rivers Blueway. On its path through Hart County, the Green River includes stretches of springs, blue holes and the dramatic 300 Springs Waterfall, which is only accessible by boat.

Graham Spring Karst Window (KW), located in Warren County, is part of a large karst distributary that has traditionally been called the **Graham Springs system** (Ray and Currens, 1998). Graham Spring KW is in the southeastern portion of the Bowling Green North 7.5-minute Quadrangle, but is not mapped on the USGS topographic or geologic maps. Groundwater rises from the Ste. Genevieve Limestone to form a large bluehole at Graham Spring KW and is then discharged into a cave that feeds Wilkins Bluehole, approximately 750 feet to the west. During excessively wet periods, Graham Spring KW will overflow to a surface channel it shares with the adjacent Tooley Overflow Spring. Three smaller overflow springs connected to this system are located on the banks of the Barren River and the spring run. In base flow conditions, water is discharged to the surface solely via Wilkins Bluehole, forming a spring run approximately 1000 feet long down to the Barren River. Base flow at Wilkins Bluehole has been measured at 19.8 ft^3/s and tracer data show that it drains an area of 122 mi^2 (Blair et al., 2012).



Figure 3.7.4 Graham Spring—rise pool and sink point of Graham Spring Karst Window; photograph from Blair et al., 2012.

McCoy Bluehole is located in Hart County in the northeastern corner of the Mammoth Cave 7.5-minute Quadrangle, but is not mapped on the USGS topographic or geologic maps. McCoy Bluehole discharges from a near-vertical conduit in the Ste. Genevieve Limestone, forming a large pool at the base of a cliff. The spring flows a short distance to the Green River. Base flow at McCoy Bluehole has been measured at 12.7 ft^3/s and tracer data show that its groundwater basin is 34.1 mi^2 (Blair et al., 2012).



Figure 3.7.5 **McCoy Blue Hole** is located directly on the Green River in Hart County within the WKU Green River Preserve. Photo courtesy of Western Kentucky University, available at https://www.wku.edu/greenriver/

Lost River Rise is located in Warren County in the northwestern portion of the Bowling Green South 7.5-minute Quadrangle but is not mapped on the USGS topographic or geologic maps. This spring discharges from an opening approximately 20 feet wide, beneath a low bluff formed in the Ste. Genevieve Limestone. It is the ultimate resurgence of the Lost River Cave Valley karst system that begins several miles south of Bowling Green and flows underneath a portion of the city. **The Lost River Bluehole** emerges within the city and flows into **Lost River Cave**, where visitors can purchase a boat ride through a section of the cave (this is a privately-owned attraction). The spring run for Lost River Rise flows about 750 feet to its confluence with Jennings Creek. Tracer data show that Lost River Rise drains an area of 58.8 mi^2 and discharge measurements indicate a base flow of 12.4 ft^3/s (Blair et al., 2012).



Figure 3.7.6 *Left*: Lost River Rise which is connected with Lost River Cave as determined with dye tracing inside the cave. *Right*: View of a short stream created by the Rise which joins Jennings Creek, a tributary to the Barren River. Photographs courtesy of Nenad Marić.

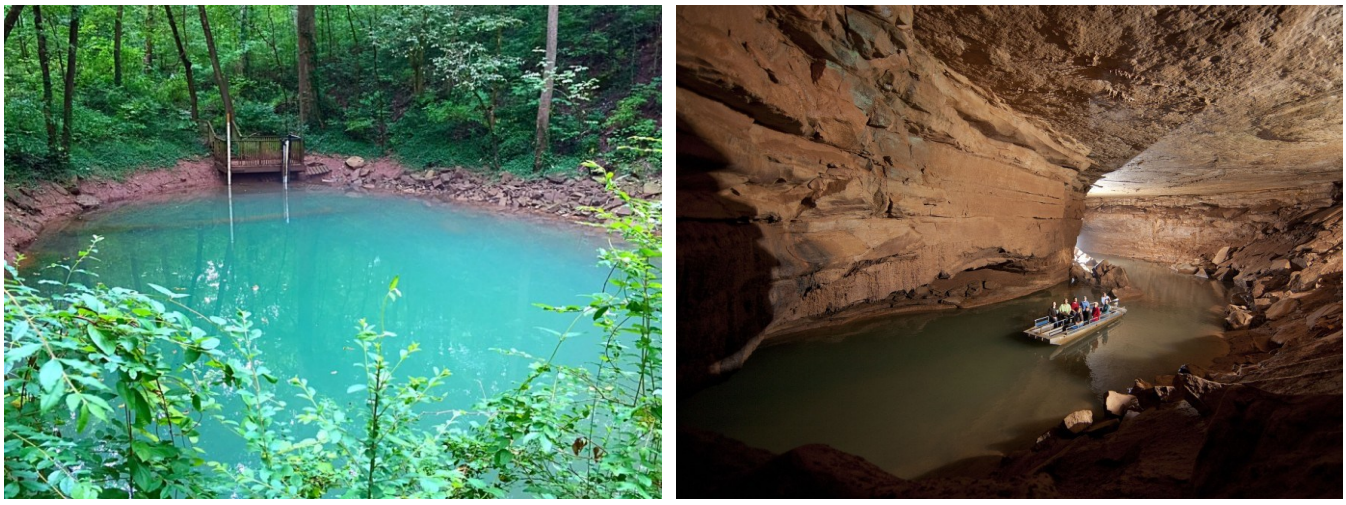


Figure 3.7.7 *Left*: The Lost River Bluehole emerges within the city of Bowling Green and, after flowing several hundred feet, disappears into Lost River Cave**.** Lost River Cave is one of only a few caves in the country that offer boat tours. Photo courtesy of MHS Jennie, available at https://www.motherhoodsupport.com/2015/09/lost-river-cave-underground-boat-tour/. *Right*: Photo courtesy of Lost River Cave, managed by the Friends of the Lost River, Inc., a non-profit 501(c)3 organization; https://www.lostrivercave.org/

Goodman Springs is located in Hardin County in the northeast corner of the Millerstown 7.5-minute Quadrangle, but is not mapped on the USGS 1:24,000 topographic or geologic maps. Goodman Spring is a perennial distributary. Spring water issues from multiple orifices in an outcrop of the Beaver Bend and Paoli Limestone, although the majority of this groundwater basin is formed in the Ste. Genevieve Limestone. The discharges occur across a single bedding plane horizon spanning approximately 150 feet. Numerous overflow features occur on each end of this spring horizon, with the perennial discharge points in the middle. The springs each have short runs that join and then flow down to the Nolin River near Spurrier. Tracer data show that Goodman Springs drains an area of 14.7 mi^2. The base flow for this spring has been measured at 4.6 ft^3/s (Blair et al., 2012).



Figure 3.7.8 Goodman Springs; from Blair et al., 2012.

Head of Rough River Spring is located in Hardin County in the northwestern portion of the Howe Valley 7.5-minute Quadrangle and appears on the USGS topographic and geologic maps. The spring discharges from the Ste. Genevieve Limestone through talus located near the head of a pocket valley. An overflow spring discharges from a low cave approximately 50 feet to the north of the main spring at the head of the same pocket valley. As indicated by its name, this spring forms the head of the Rough River. Base flow at this spring has been measured at 4.0 ft^3/s. Tracer data show that this spring has a groundwater basin area of 17.7 mi^2 (Blair et al., 2012).



Figure 3.7.9 *Left*: Head of Rough River Perennial Spring. *Right*: Head of Rough River Overflow Spring located about 50 feet north of perennial spring. From Blair et al., 2012.

Mahurin Spring is located in Grayson County in the south-central portion of the Falls of Rough 7.5 minute Quadrangle, but is not mapped on the USGS topographic or geologic maps. Mahurin Spring issues from an opening approximately 25 feet wide by a few feet high located beneath a limestone bluff. Blair et al. (2012) note that although the geologic formation is listed as the Ste. Genevieve Limestone, this determination is approximate as the setting is complicated by the Rough Creek Fault System and numerous geologic formations are present. The spring run flows 300 feet to its confluence with Spring Fork. Base flow at Mahurin Spring is 2.1 ft^3/s, but this figure is based on a limited number of measurements. Tracer data show that this spring drains an area of 25.3 mi^2 (Blair et al., 2012).



Figure 3.7.10 Mahurin Spring; from Blair et al., 2012.

Mill Spring is located in Grayson County in the south-central portion of the Millerstown 7.5-minute Quadrangle and is mapped on the USGS topographic and geologic maps. This spring discharges from a large conduit in the Reelsville Limestone at the base of a bluff located at the head of a small pocket valley. The spring flows into the Nolin River where it has been impounded by the Nolin Reservoir. A limited number of measurements place this spring's base flow at about 3.0 ft^3/s. Tracer data show that this spring has a groundwater basin area of approximately 7.1 mi^2 (Blair et al., 2012). Mill Spring is called "White Mills Spring" by Van Couvering, 1962 (see Table 3.7.2).



Figure 3.7.11 Mill Spring; from Blair et al., 2012.

Nolynn Spring is located in Larue County in the east-central portion of the Tonieville 7.5-minute Quadrangle, but is not mapped on the USGS topographic or geologic maps. The main discharge from Nolynn Spring issues from a conduit formed in the St. Louis Limestone, but there is also a small bluehole discharge approximately 75 feet down the spring run. This spring discharges almost directly into the North Fork of the Nolin River. Tracer data show that just over half of the spring's base flow is derived from a subterranean cutoff of the North Fork of the Nolin River about 3 miles upstream of the spring. This spring has a groundwater basin area of 56.4 mi^2 and its base flow is 4.6 ft^3/s. Nolynn Spring is the former water supply for Hodgenville, but its use was reportedly abandoned due to contamination from a sewage treatment plant upstream of the sink point in the North Fork.



Figure 3.7.12 Nolynn Spring – note unused pump station and pipe; from Blair et al., 2012.

Mammoth Cave National Park Springs

Mammoth Cave National Park and the surrounding area are dotted with sinkholes, which is typical for karst topography. As the sinkholes south of the park drain, the surface water flows underground through caves within the Mammoth Cave plateau eventually emerging through springs along the Green River which flows from east to west through the center of the park.

River Styx Spring and **Echo River Spring** are two springs accessible to park visitors via marked trails. The two springs are often just a trickle of water and may even act as sinks for the Green River if the river rises sufficiently; this reverses the flow. The locations of many springs along Green River, and particularly for River Styx Spring, are then unrecognizable unless pointed out by a park ranger or a knowledgeable visitor.

The Mammoth Cave area is one of the most researched karst systems in the United States and boasts the largest number of dye tracing tests carried out in the country, in order to reveal the many secrets of the underlying karst aquifer. This is not surprising because of the simple fact that Mammoth Cave is the longest cave in the world, with 426 miles of mapped passages as of April 2026. A national park was established in 1941 because of the cave. Although the park was authorized in 1926 , it was another 15 years before becoming official.



Figure 3.7.13 Echo River Spring in Mammoth Cave National Park. Photo courtesy of Nenad Marić.



Figure 3.7.14 River Styx Spring in Mammoth Cave National Park. *Left*: during average flow conditions; photo courtesy of Nenad Marić. *Right*: when backed up by muddy water from Green River. Water falls from the rock ledges above the cave orifice of the spring. Spring drains parts of the hydrologically active passages of the Mammoth Cave system and saturated portion of the karst aquifer. Photo courtesy of NPS.

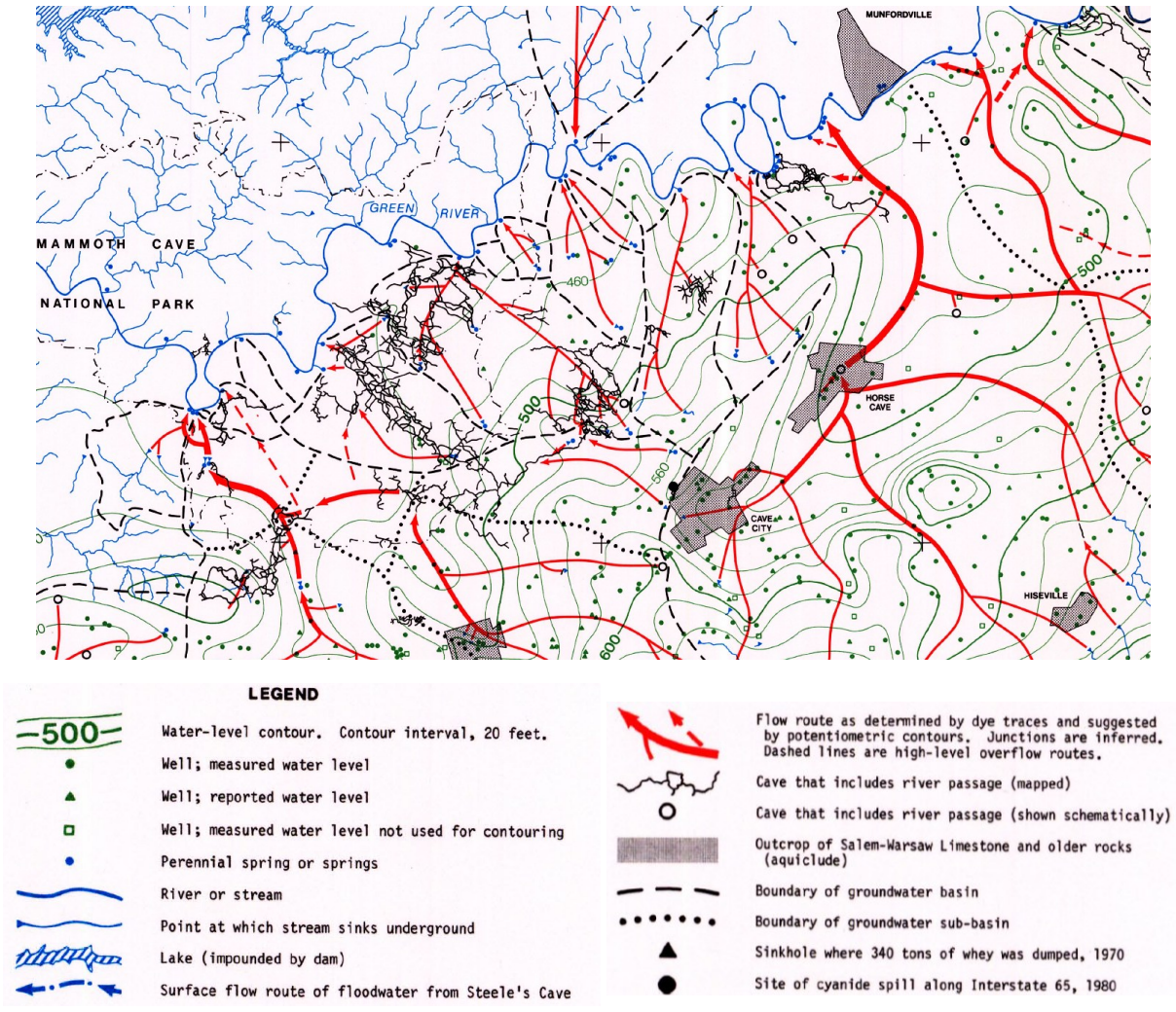


Figure 3.7.15 Part of map of "*Groundwater Basins in Mammoth Cave Region, Kentucky Showing Major Caves, Flow Routes, and Potentiometric Surface*" by hydrogeologists James F. Quinlan and Joseph A. Ray of National Park Service, published in 1981 (revised in 1989) as Occasional Publication No. 2, Friends of Karst, Mammoth Cave, Kentucky. This map remains the gold standard for hydrogeologic mapping in karst terrains.

Turnhole Spring

Turnhole Spring in Mammoth Cave National Park is the third largest spring in Kentucky. It is an outlet for an underground river system that drains a large area of sinkholes south of the park, including the nearby Cedar Sink karst window, totaling 133 square miles. Located at a sharp U-shaped bend in the Green River, this historic, high-discharge spring (ranging from 100 to 6,000 gallons per second according to NPS; KY springs database lists 15 cfs average flow) can be viewed, when there is no forest canopy, from an outlook accessible via the Turnhole Bend Nature Trail, a short loop that also features large, impressive sinkholes. Because the spring emerges below the waterline of the river, it is visible as a wide, calm "bend" in the water rather than a typical flowing spring. The name originates from the 19th century, when it was used by riverboats to turn around safely (NPS).

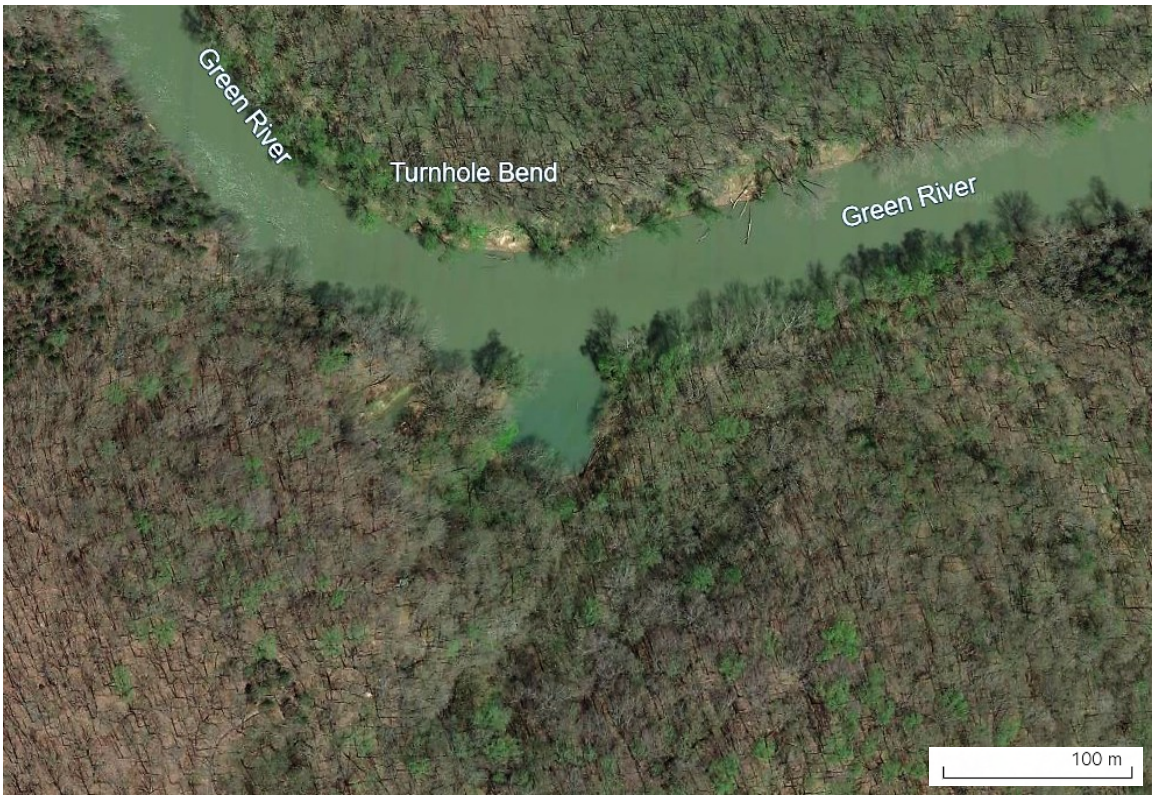


Figure 3.7.16 Google Earth Image of Turnhole Spring (in the center) acquired April 17, 2014.

Boiling Springs, and Schenley Spring (Head of Doe Run Spring)

Boiling Springs in Breckinridge County, and Schenley Spring in Meade County are the largest springs in the northern part of the Pennyroyal Plateau which is drained by the Ohio River. The main surface drainage in this high-relief area is Sinking Creek, one of the largest losing streams in Kentucky. This system heads at Blue Fork and Stoney Fork springs, in eastern Breckinridge County, and gains substantial flow from the Flat Rock Spring distributary and Fiddle Spring just NW of Rosetta. The main losing reach of Sinking Creek is about 3 mi south of Irvington. A meandering 12 mi-long dry channel trends NW from the losing reach to Boiling Springs, where Sinking Creek resurges (Ray et al., 2005). From its resurgence, Sinking Creek flows northwest to the Ohio River.

Schenley Spring, more officially referred to as Head of Doe Run, creates Doe Run Creek that flows approximately four miles before emptying into the Ohio River.

Boiling Springs in north-central Breckinridge County discharges from the Ste. Genevieve Limestone. Boiling Springs is a large 60-70 ft-wide alluviated bluehole near the mouth of a local dry ravine at about 408 ft elevation. The spring develops a 600 ft-long spring run to Sinking Creek, where ruins of an old water mill exist. Above the confluence of Boiling Springs, Sinking Creek, which is primarily an overflow channel, discharges about 0.2 ft^3/s) of local flow during summer low flow conditions. Over eight years Boiling Springs has been gaged six times during low flow, ranging from a high of 12.9 ft^3/s to a low of 6.3 ft^3/s during the 1999 drought. The typical low flow discharge averages 9.8 ft^3/s. Flood flow has been estimated at 2,000 ft^3/s (George, 1976), 200 times greater than low flow. Numerous overflow features have developed around the bluehole's perimeter, which indicate a large fluctuation in discharge (Ray et al, 2005).

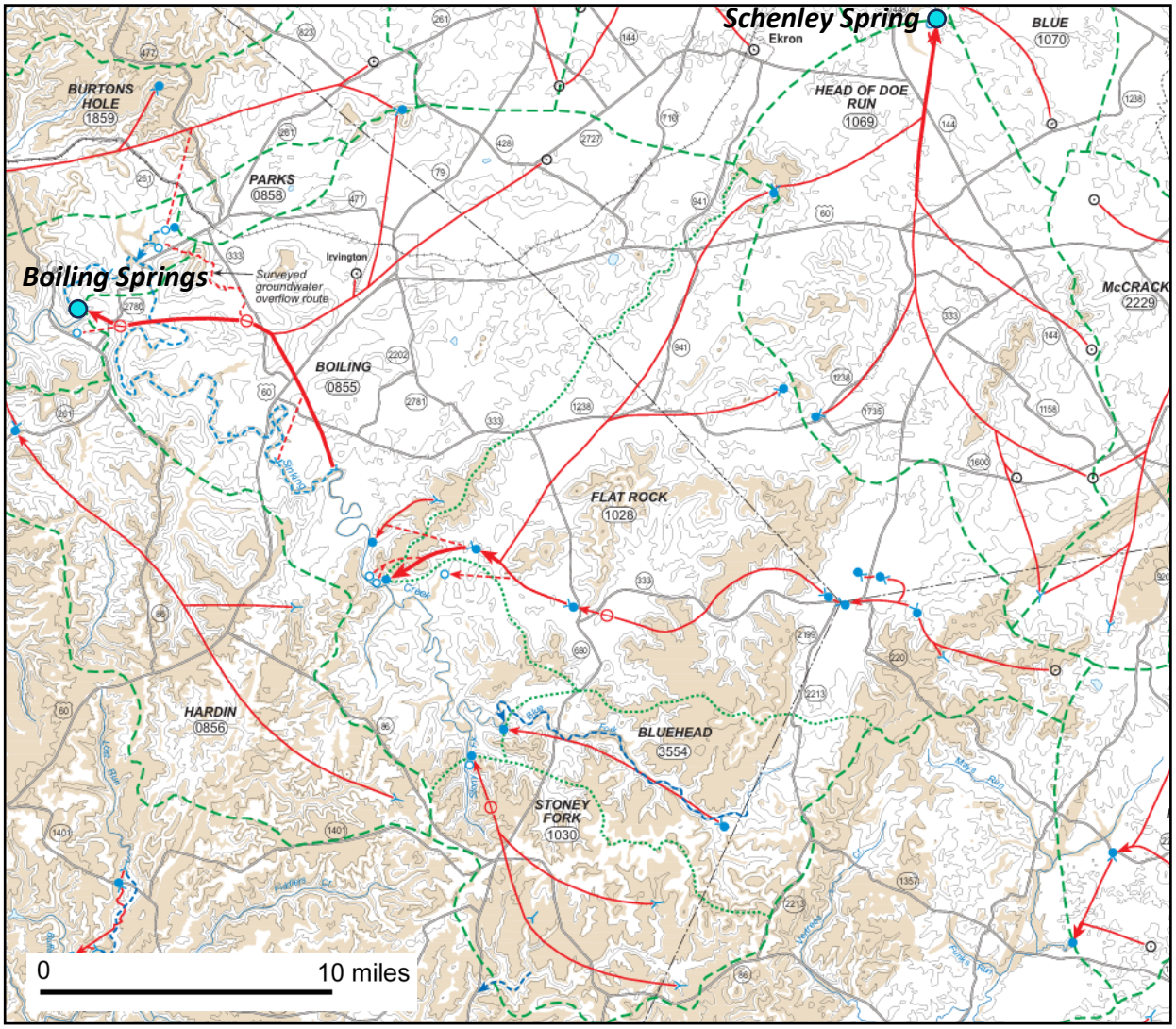


Figure 3.7.17 Boiling Springs. From Ray et al., 2005.

Head of Doe Run Spring (**Schenley Spring**) discharges from the St. Louis Limestone at an elevation of 575 ft, and was gaged 24 times from 1952 through 1960, with one measurement aborted due to high water in 1956. The discharges ranged from 4.2 to 35 ft^3/s, an 8-fold increase. Temperature ranged from 54 to 59 degrees Fahrenheit (Ray et al., 2005). The spring, on private land and with restricted access, emerges as a pool of clear, cold water directly from the rock face, which then quickly forms Doe Run Creek that flows approximately four miles before emptying into the Ohio River. Historically, the high-volume output from Schenley Spring powered a massive stone mill. The mill was later converted to the Doe Run Inn, which closed for auction in 2016.



Figure 3.7.18 Historic Steven's Mill, originally built between 1788 and 1790 by Jonathon Essery, later renamed to Doe Run Mill. https://weirdmeadecounty6.wordpress.com/the-ghosts-of-doe-run-inn/



LEGEND

- Area of potential karst groundwater basin development
- Area of limited karst groundwater basin development
- Inferred perennial groundwater flow route
- Subsurface overflow (high-flow) route
- Surface overflow (high-flow) route
- Groundwater basin catchment boundary
- Groundwater basin catchment sub-boundary
- Stream sink or swallet
- Underflow spring (perennial)
- Overflow spring (high flow)
- Karst window or sinking spring
- Cave stream
- Other tracer-injection point
- (1063) Kentucky Division of Water AKGWA spring identification number

Figure 3.7.19 Drainage areas of Boiling Springs and Schenley Spring as depicted on map entitled *Part of Mapped Karst Groundwater Basins in the Tell City and Part of the Jasper 30x60 Minute Quadrangles* by Ray et al., 2009.

Mill Stream Spring in east-central Trigg County is in the western part of the Pennyroyal Plateau. It is a rising spring that flows from the base of a 25 ft-high limestone bluff, through a 600 ft-long pocket valley. The spring discharges from the base of the Ste. Genevieve Limestone at about 390 ft elevation. Ruins of an old water mill are located about 200 ft from the springhead. Mill Stream Spring is the resurgence of Sinking Fork, which follows a 4.75 mi, east-west diversion beneath the plateau and rejoins the entrenched channel of Sinking Fork. Two minor sinking streams and numerous sinkholes contribute additional local recharge to the cutoff route, which passes through Pipeline Cave and Boatwright Hole (karst window), en route to Mill Stream Spring. The spring was gaged during low flow at 3.2 ft^3/s and 2.5 ft^3/s on 9-11-93 and 8-24-99, respectively. Earlier USGS measurements range from 1.5 ft^3/s (1956) to 178 ft^3/s (Van Couvering, 1962), a 118-fold increase (1953-02-26 to 1964-11-16). Water temperatures ranged from 46-65 degrees F, compared to average groundwater temperatures of 54-59 degrees F, showing the influence of losing stream flow rapidly contributing to the spring (Ray et al., 2005).



Figure 3.7.20 Mill Stream Spring; from Ray et al., 2005.

Big Springs in Princeton

Downtown Princeton in Caldwell County is home to a small park with Big Springs which issue from the Mississippian Ste. Genevieve Limestone and drain a part of the Western Pennyroyal Karst System. There are no reported measurements of the spring's discharge rate; however, it is estimated that the average discharge rate exceeds 2 cfs based on its perennial nature (it does not dry out even during severe droughts) and other characteristics.

Adjacent to the city park is a Trail of Tears Commemorative Park featuring a large, engraved granite monument that reads "A Mother's Burden" both in English and in Cherokee. The stones for the monument were sourced from a quarry along the original trail route and dedicated to the park. The monument is shaped like a tear drop to depict forced removal of the Cherokee Nation from their ancestral lands.

"During the forced removal of 1838-1839, 11 of the 13 detachments of Cherokee followed the northern route of the Trail of Tears. More than 10,000 men, women, and children endured the long trek and difficult conditions traveling on foot or in horse-drawn carts. Each detachment would stretch for miles along the route. Big Springs, a natural spring that emerges from the limestone, served as a water source and stopping point for the weary travelers.

Today, people visit Big Springs for day trips or weekend getaways. The serene and peaceful environment, combined with the natural setting, provides an enjoyable escape from the city. It is a picturesque destination where visitors can connect with nature and learn about local history. The site around Big Springs features picnic spots,

walking paths, and seating areas where people can relax and enjoy the beautiful surroundings. Please note that the cave is not accessible, and visitors are cautioned not to drink from the spring." (https://home.nps.gov/places/big-spring-kentucky.htm)



Figure 3.7.30 Big Springs in downtown Princeton. Photographs courtesy of Four Rivers Explorer. Detailed description of the spring and Princeton's history, accompanied by more photographs, is available at https://www.fourriversexplorer.com/big-springs-cave-princeton/

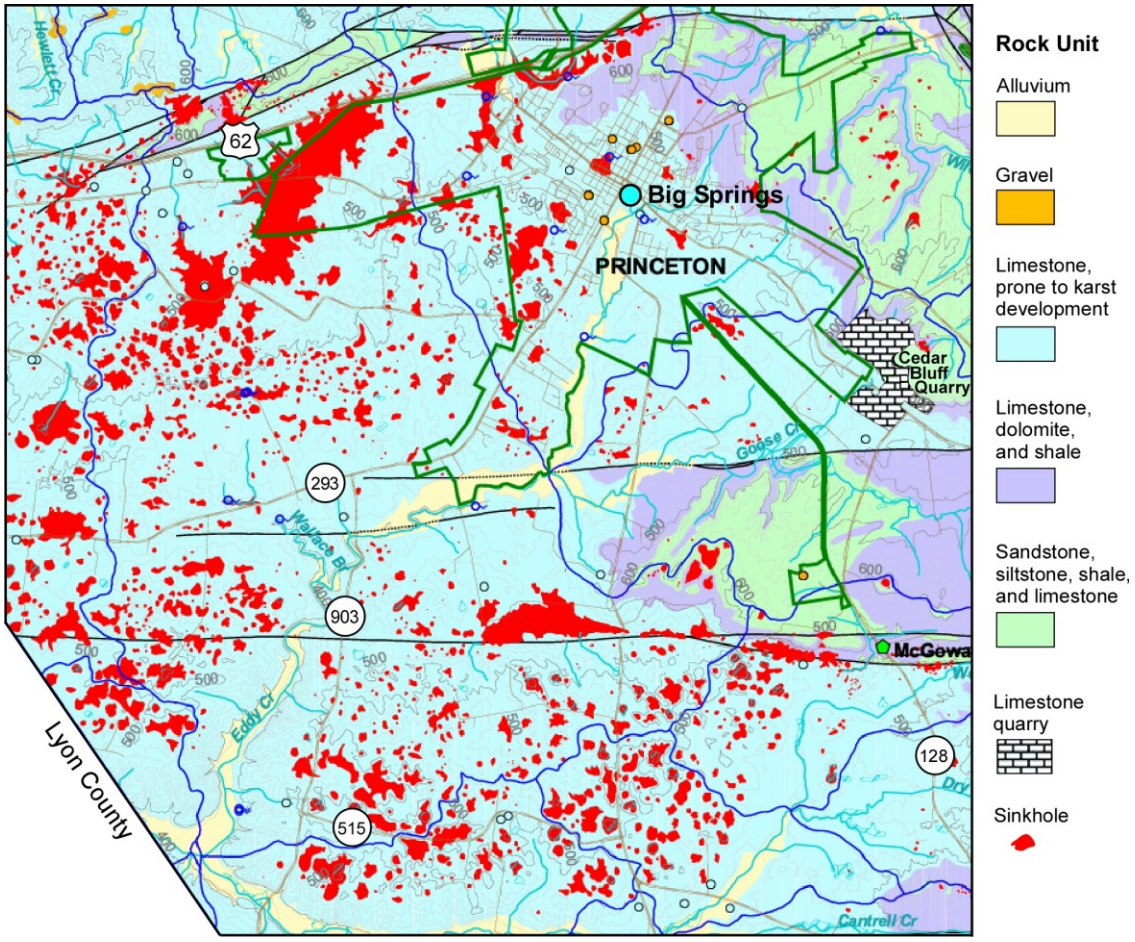


Figure 3.7.31 Part of generalized geologic map for land-use planning, Caldwell County. Modified from Beck et al., 2005.

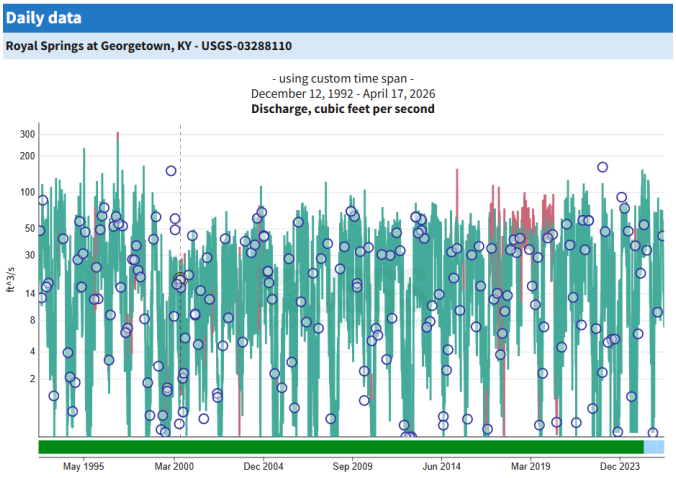
Royal Spring

Royal Spring in Scott County is the largest spring in the Inner Bluegrass region and drains an area of over 25 square miles. It emerges from the Ordovician Lexington Limestone, with an average discharge rate of 25.7 cubic feet per second (cfs; USGS station 03288110 Royal Springs at Georgetown, KY). The spring's discharge rate is highly variable and sensitive to rainfall: from less than 0.1 cfs to a maximum of 268 cfs recorded on March 2, 1997. The city of Georgetown and Scott County residents use Royal Spring as a source of public water supply. During droughts, most of the flow is captured for water supply, and the spring dried up completely a dozen times or so, for one to several days at the time, between 1992 and 2026.

The groundwater basin for the spring extends into northern Fayette County, and is susceptible to contamination from development, agriculture, and transportation on I-75. The city lost its water supply from the spring during the winter of 1988-89 when gasoline was detected. The gasoline leaked into the ground from a storage tank somewhere in the watershed of the spring. Georgetown water customers had to be issued bottled water for several weeks until a new water-treatment system could be installed (Currens, 2002).



Figure 3.7.32 Royal Spring in Georgetown, Scott County. Photo by Bart Davidson, Kentucky Geological Survey



Urban legend has it that Royal Spring is the birthplace of bourbon, a liquid with a transparent color, and taste agreeable to an unknown but significant number of citizens in the United States and around the world. This legend is reinforced by a historic landmark near the spring. However, there are also differing opinions (e.g., see discussion by Tom Wilmes at https://gardenandgun.com/articles/bourbon-myths-debunked/)

Figure 3.7.33 Mean daily discharge rate at Royal Spring between Nov 1992 and Apr 2026. Average is 25.7 cfs.

"The main source of water for our area has been the Big Spring since John McClelland and his party of frontiersmen and women built a fortified settlement in 1775. In 1889, Georgetown Water Works Company was incorporated as the first authority to regulate, treat and distribute this spring water for the community. In 1945, The City of Georgetown purchased that company and established the 'Municipal Water Works Plant'. The Big Spring is now known as Royal Spring." (https://www.gmwss.com/about.htm).

McConell Springs

McConnel Springs, a National Registered Historic Site, is located off Old Frankfort Pike inside New Circle Road near downtown Lexington. The springs are in the park of the same name managed by Friends of McConell Springs, a non-profit organization, in partnership with the Lexington-Fayette Urban County Government Division of Parks and Recreation. McConnell Springs has an education center and two miles of trails, with a half-mile paved loop which makes the park accessible to most visitors.

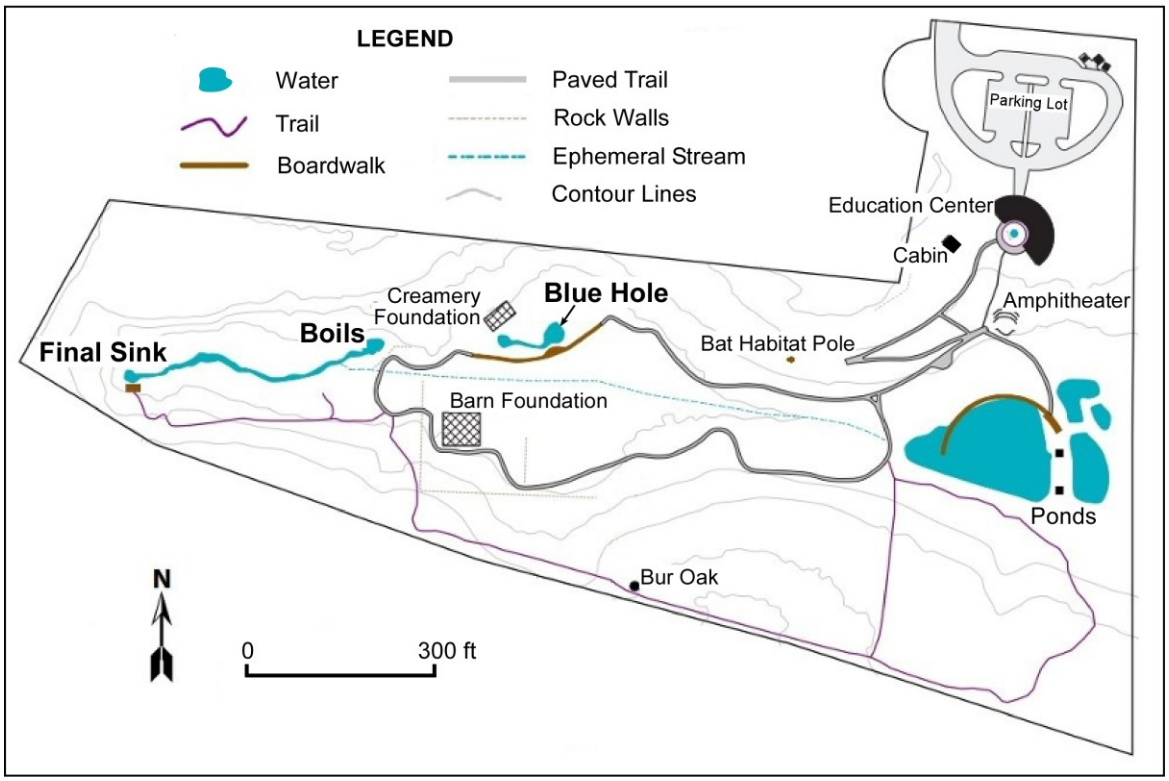


Figure 3.3.34 Trail map of McConnel Springs park. Courtesy of https://www.lexingtonky.gov/playing/parks-natural-areas/natural-areas/mcconnell-springs-park

As explained on the webpage of McConnell Springs Park (https://mcconnellsprings.org/), in June 1775, a pioneer from Pennsylvania named William McConnell, his brother Francis McConnell, and their fellow frontiersmen were exploring the wilderness of the Virginia territory known as Kentucky. Like many other Scots-Irish settlers of the time, they were interested in acquiring land and improving their family circumstances. As they surveyed and mapped the land around the forks of the Elkhorn Creek, they built crude improvements that allowed them to stake claims to the land under the laws of Virginia at that time. William McConnell's claim included the land around a "sinking spring" where the party had set up camp. It was at this encampment that the explorers received word from nearby Fort Boonesborough that the first battles of the American Revolution had been fought April 19, 1775 in Lexington & Concord, Massachusetts. In honor of this event, the group named their future settlement "Lexington". The ensuing years were marked by raids and invasions by the British & Indians, but the influx of settlers from the East continued. In 1779 a permanent blockhouse was built, and in 1780 Lexington was named seat of Fayette County, Virginia, and in 1782 the town was chartered. Kentucky then became the 15th state to join the union in 1792.





Figure 3.7.35 *Left*: The Blue Hole is the first of two major springs at McConnell Springs. Its otherwise blue color (to which it owns its name) during times without significant precipitation, quickly turns to the shade shown in this photo after notable rainfall. The spring waters originate from a wide area of south-western Lexington, flowing underground through the Ordovician Lexington Limestone bedrock. Photograph courtesy of McConnell Springs Park. *Right*: "The Boils", second spring of the McConnell Springs system. During heavy rains a column of water rises from the spring to a height of up to 24 inches. The Boils and the Blue Hole are both artesian springs. Photo courtesy of Alan Fryar.



Figure 3.7.36 The stream at McConnell Springs Park flowing into the Final Sink, to reappear about 1/3rd of a mile from here at Preston's Spring Park (1937 Dunkirk Dr.). Photo courtesy of McConnell Springs Park, November 21, 2019

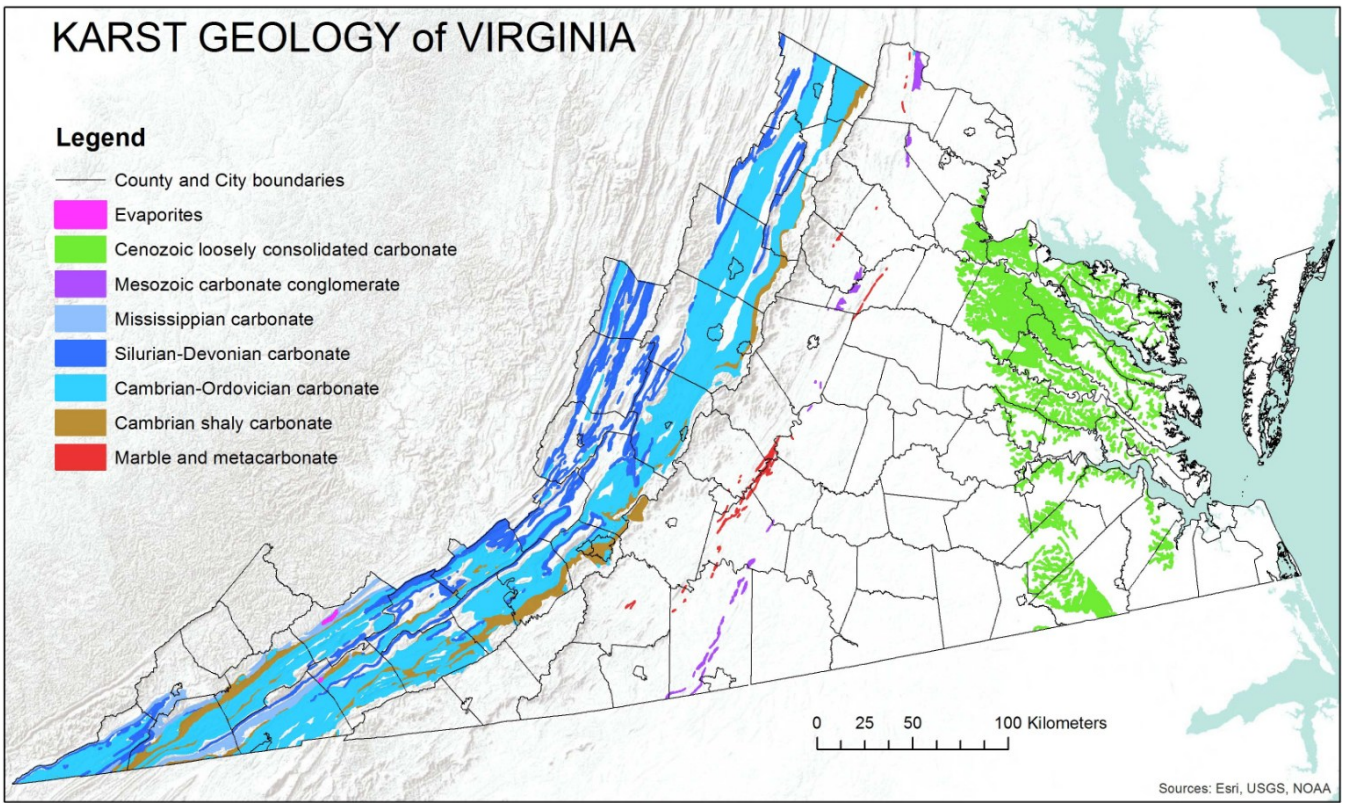
Reading an outstanding publication by Nancy O'Malley entitled *McConnell Springs in Historical Perspective* is a must for anyone interested in the fascinating archaeology and the history of McConell Springs, from the Historic Contact Period (A.D. 1540-1795) to the present. This booklet, published in 2020, is available for download at https://mcconnellsprings.org/wp-content/uploads/2020/08/McConnellSprings_in_Historical_Perspective.pdf.

The many people who support the effort to save McConnell Springs from industrial development consider the place to be important. But why should this place be preserved? Part of the value of McConnell Springs is derived from the natural environment: the springs, the karst features, and the remnant native vegetation. The rest of the significance of this place is derived from the human activities that left discernible traces on the landscape (in the form of culturally altered soil deposits, structural foundations, stone fences, dam abutments, vegetational patterns and the like).

Nancy O'Malley

3.8 Virginia

Virginia features extensive karst topography and productive karst aquifers that span across at least 29 counties, primarily concentrated along the Interstate 81 corridor and within the Valley and Ridge physiographic province in the western part of the state where there are more than 4,400 documented caves. Grand Caverns in Grottoes, Shenandoah Valley is a National Natural Landmark and the oldest continually operating show cave in the United States, while Luray Caverns in Page County is the most visited and largest show cave in the Eastern part of the United States. The first thermal spa in the country, established in 1761 and continuously operating ever since, is in Warm Springs, Bath County. It relies on one of the largest karst springs in Virginia which discharges at a constant rate of 1,700,000 gallons per day (3.2 cfs), and a temperature of 98 to 99 degrees Fahrenheit. Just 32 years after the Revolutionary War, in 1808, Winchester in Shenandoah Valley was the first town in the country to lay pipelines for its public water system using a karst spring as the source. This brief overview demonstrates why Virginia, for many decades, has been considered one of the premier grounds for karst research and karst water resources development in the United States.



3.8.1 Karst geology of Virginia map Available at https://www.dcr.virginia.gov/natural-heritage/karsthome

In the Valley and Ridge Province of Virginia, karst aquifers are a primary source of water for individual and public supply in many areas, especially in the Shenandoah Valley. The Great Valley aquifer, largely coinciding with the Shenandoah Valley, is the main karst aquifer in Virginia, formed in thick Paleozoic limestone and dolomite sequences over 10,000 feet thick. In the Shenandoah Valley, larger springs—often artesian—account for more than 85% of stream flow, making them a critical link between groundwater and surface water. Many towns and cities in the Valley and Ridge rely on wells tapping into these karst aquifers for public water supply. The fractured and

karstified carbonates under the valleys recharge quickly from runoff on the ridges and produce wells with yields up to 150 gallons per minute (USGS, 2021).

Pockets of karst exist east of the Piedmont and Blue Ridge where marble or localized carbonate rocks occur. For example, Loudoun County features roughly 18,000 acres of karst terrain near Leesburg.

Established by the Virginia Cave Board, The Virginia Cave and Karst Trail features over 20 educational stops, including famous commercial (show) caves like Luray Caverns, as well as protected wetlands fed by karst springs (https://www.dcr.virginia.gov/natural-heritage/vacavetrail).



Figure 3.8.2 Caves in far southwestern Virginia. Photographs by Ryan Maurer, courtesy of Virginia Department of Conservation and Recreation. Pop... - Virginia Department of Conservation and Recreation | Facebook



Figure 3.8.3 *Left*: The 215-foot high Natural Bridge in the Natural Bridge State Park, Rockbridge County is a remnant of a collapsed cave in the Lower Ordovician Beekmantown Formation Limestone. Photo by Steve Hawks. *Right*: Natural Tunnel in Natural Tunnel State Park, Scott County is carved in Maynardville Limestone of the Knox Group (Upper Cambrian-Lower Ordovician). It is over 850 feet long and "10 stories high". William Jennings Bryan called it the "Eight Wonder of the World". Photographs courtesy of Virginia State Parks.



Figure 3.8.4 Luray Caverns is the largest cavern in the eastern United States, yet walking through feels more akin to an otherworldly experience. Enormous chambers are filled with towering stone columns, shimmering draperies and crystal-clear pools. "The Great Stalacpipe Organ is the world's largest musical instrument. It literally makes stalactites sing by gently tapping them throughout three acres of the caverns. It's a musical masterpiece that can't be found anywhere else in the world … or under it." The National Park Service and the Department of Interior designated Luray Caverns as a Registered Natural Landmark. Photo courtesy of Luray Caverns. https://luraycaverns.com/

In 2023, Virginia Department of Environmental Protection (VDEP) published the groundbreaking *Springs of Virginia* (authored by Joel Maynard, Office of Water Supply, Groundwater Characterization Program). All historical and modern spring data available to or collected by the author were compiled into a single database that was used to document the ranges of physical and chemical spring characteristics throughout Virginia, and for the first time investigate geologic factors that may influence their occurrence in the region.

As pointed out by Maynard, the hydrogeologic unit (HGU) with the greatest number of springs catalogued in the database was the Cambro-Ordovician Carbonate (C-O Carbonates) HGU with its Conococheague Formation component being the formation-level unit with the most springs. However, when considered in the context of outcrop area, the karstified limestones of Ordovician Edinburg-Lincolnshire-New Market (O-ELN) HGU emerged as having the greatest number of springs per square mile of calculated outcrop area.

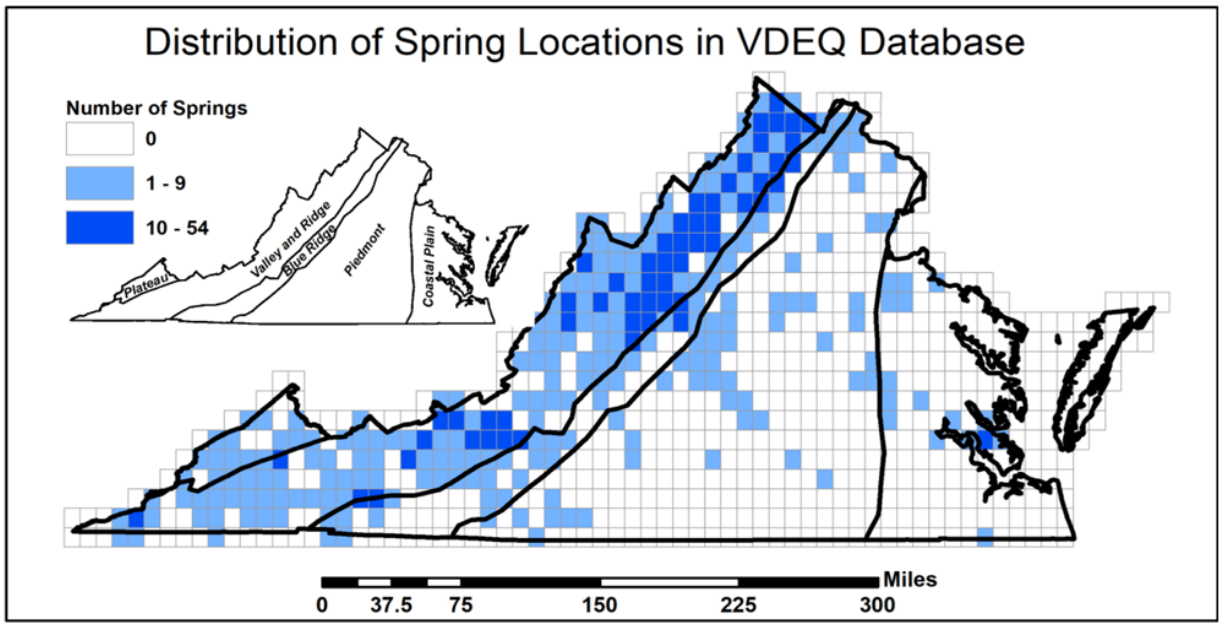


Figure 3.8.5 Map showing distribution of documented springs in the Virginia Statewide Spring Database by USGS 7.5 minute topographic quadrangle. Approximately 75% of spring locations documented in the database occur in the Valley and Ridge physiographic province, a region characterized by Paleozoic carbonate and clastic rocks that were folded and thrust faulted during the Alleghanian Orogeny. The prevalence of springs in the province reflects the occurrence of carbonate bedrock units that tend to supply greater amounts of water than in other parts of the state and are therefore more likely to have been inventoried or studied throughout the years. From Maynard, 2023. The springs' database is available at VDEQ_Spring_SITES | Virginia Environmental Data Hub.

Springs that occurred in the O-ELN HGU stood apart from other sedimentary rock HGUs in several physical and chemical characteristics. On average, springs in this unit were found to occur at lower elevations and discharge greater volumes of water than other sedimentary rock HGU's. O-ELN springs were also found to discharge groundwater that had a higher mean temperature, specific conductance, dissolved solids, hardness, calcium, magnesium, bicarbonate, sulfate, chloride, iron and nitrate than other sedimentary rock HGUs. These factors suggest that groundwater discharging from O-ELN rocks tends to be more chemically mature and influenced by longer, deeper flowpaths. Rocks of this HGU tend to occupy topographically low valley floor positions, often at slightly higher elevations than less transmissive shale units of the Martinsburg Formation (part of the O-S Silici HGU in this study). This contrast probably acts as a barrier to groundwater flow and forces deep groundwater flowpaths from O-ELN and other upland HGUs to the surface in or near O-ELN rock units (Maynard, 2023).

Rock Type Group	Hydrogeologic Unit	Area (Miles²)	Age	Lithologic Units	Primary Rock-type	Number of Springs
Limestone	O - ELN	376	Ordovician	Edinburg Formation, Lincholnshire and New Market Limestones	limestone	105
			Ordovician	Hardy Creek, Ben Hur, Woodway, Hurricane Bridge, Martin Creek, Rob Camp, Poteet, and Dot Limestone	limestone	24
Dolomite	O - Beekmantown	715	Ordovician	Beekmantown Group	dolostone (dolomite)	174
Limestone	C - O - Carbonates	1,351	Cambrian-Ordovician	Knox Group	dolostone (dolomite)	64
			Cambrian-Ordovician	Conococheague Formation	limestone	178
			Cambrian-Ordovician	Chepultepec and Copper Ridge Formations	dolostone (dolomite)	3
			Cambrian-Ordovician	Lower Ordovician and Upper Cambrian Formations - undivided	limestone	17
Dolomite	C - Dolomites	1,119	Cambrian	Elbrook Formation	dolostone (dolomite)	149
			Cambrian	Shady Dolomite	dolostone (dolomite)	27
			Cambrian	Waynesboro and Tomstown Formations	dolostone (dolomite)	4
			Cambrian	Waynesboro Formation + (Ordovician) Mascot / Kingsport Dolomite	dolostone (dolomite)	23

Figure 3.8.6 Rock type groupings, formations, ages, and rock-type compositions for various carbonate hydrogeologic units used for analysis in the VDEP study. Information and geographic extent were obtained from the USGS 1:500K Virginia Geologic Map (Virginia Division of Mineral Resources, 2003). From Maynard, 2023.



Figure 3.8.7 Outcrop of Cambrian-Ordovician Conococheague Limestone on the banks of Cedar Creek near Marlboro, Frederick County. It was examined closely by a local amateur hydrogeologist at the time this zoom photo was taken.

Woolwine Spring, Pulaski County

Woolwine Spring, located 4 miles east of Newbern, near the New River in Pulaski County, was thought to be the largest in Virginia at the time, before it was submerged by the construction of Claytor Lake Reservoir in 1938 (Helfrich et al., 2009). It discharges from the Beekmantown to Elbrook carbonate series and, when surveyed in July of 1928, had a discharge rate of 10,300 gpm (Collins et al., 1930). The 1930 publication by Collins et al. lists 20 more springs in the southern part of the Great Valley that had the recorded discharge rate >3,000 gpm, most of which are issuing from the Beekmantown carbonates.

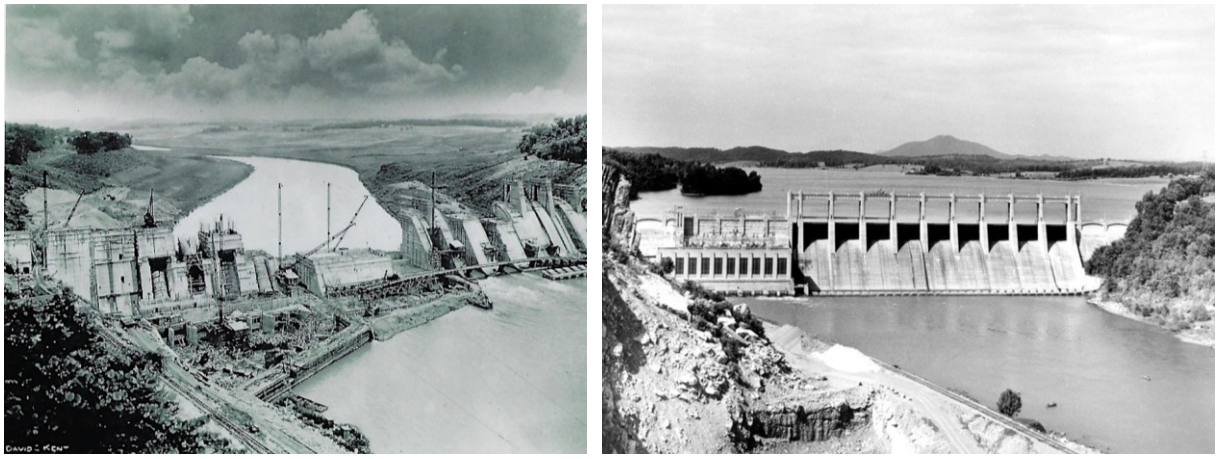


Figure 3.8.8 Claytor Lake was created by damming the New River at Radford, Pulaski County. The dam was built between 1937-1939. The lake submerged Woolwine Spring which was thought to be the largest in Virginia at the time. Photographs courtesy of Virginia State Parks, and Claytor Power (https://www.claytorhydro.com/about/).

Coursey Spring, Bath County

Discharging at an average rate of 10,000 to 11,000 gallons per minute (gpm; roughly 22 to 25 cfs), Coursey Spring, located just south of Williamsville, is officially the largest accessible cold spring on dry land in Virginia (the submerged Woolwine Spring in Pulaski County had a similar, one-time reported discharge rate of 10,300 gpm as noted earlier). The average minimum rate during low flow (drought) conditions is about 3,500 gpm. The water of the spring has a nearly constant temperature of 49°F to 54°F year-round. Coursey Spring serves as the water source for the Coursey Springs State Fish Hatchery, which produces 400,000 catchable-size fish each year. The spring discharges into a 1.6-acre basin that is now covered completely to shield the hatchery's clean, incoming groundwater from outside elements such as debris, natural contaminants, and wild animal pathogens. It also helps maintain the consistent water temperatures required to raise healthy brook, rainbow, and brown trout.

Coursey Spring was historically called Meadow Lake Spring, which, in 1900s, hosted the Meadow Lake Sawmill that operated a vertical reciprocating saw. The original Coursey Springs Fish Hatchery made use of the sawmill's cut-stone head race for one of the hatchery's first fish rearing ponds (Biggs and Hoy, 2017).

Following are excerpts from an essay "In Pursuit of Losing Streams, Caves and Springs" by Phil Lukas (https://cowpastureriver.org/wp-content/uploads/2019/08/Essay-No.-6-In-Pursuit-of-Losing-Streams-Caves-and-Springs.pdf).

"*Coursey Springs – Perhaps the strangest conundrum of underground streams routes in Virginia is near the town of Williamsville where the underground Cowpasture River flows beneath the Bullpasture River.*

About four miles northeast of Williamsville, the Cowpasture River becomes a losing stream during dry periods. This underground Cowpasture River drainage has been dye-traced for five miles to the south where it reemerges as Coursey Springs. The long distance the surface water travels underground has reduced its temperature to near the nominal temperature of the region (about 50 degrees). The geologic structure here is similar to Windy Cove gap. The Cowpasture River becomes a losing stream when the river flows against the flank of the Bullpasture Mountain where there are (Silurian and Devonian) limestone exposures. The river eventually loses its entire flow into the limestone channels beneath the surface riverbed in this area. Four miles downstream, the Bullpasture River flows from the west through the Bullpasture Gorge and just east of Williamsville, flows for a half mile across thick beds of (Devonian Millboro-Marcellus) shale to its confluence with the Cowpasture River. Deep below and within limestone beds the underground Cowpasture River crosses perpendicularly beneath the Bullpasture River! For the underground Cowpasture River to rise at Coursey Springs, it must pass up from the limestone layers through a strata of sandstone and perhaps even through some shale. Because there is much folding and faulting in the geology of what we call the Valley and Ridge Province, it is likely that a sharp fold or a fault brings the limestone close enough to the surface to allow the Cowpasture River water and other groundwater streams to resurge at Coursey Springs." (Lukas, 2015.)



Figure 3.8.9 Google Earth image of Coursey Spring and state hatchery after the spring basin was covered in 2010, and raceways replaced by 40 indoor, modern oxygenation stainless steel circular tanks which boosted production capacity by over 40%.



Figure 3.8.10 *Left*: Stainless steel circular oxygenation tanks that replaced the traditional open raceways in 2010. Photo courtesy of Coursey Springs State Fish Hatchery. *Right*: The spring basin is covered to shield the hatchery's clean, incoming groundwater from outside elements. Photo courtesy of Sarah White, 2024; Cowpasture River Karst Trail. Located near McDowell, Virginia, the Cowpasture River Karst Trail is a 35-mile-long trail that follows the Cowpasture River. Including natural sinkholes, springs, and monuments, this karst trail in Bath and Highland counties offers a wide variety of amazing topography and water features within Virginia's cave and karst system. It is rich in natural karst elements and original history, making this area a unique and enlightening part of experiencing Virginia's breathtaking beauty. Cowpasture River Karst Trail.



Figure 3.8.11 Nestled in a remote valley in Bath County, Spring Run flows peacefully out of the Coursey Springs fish hatchery to merge with the put-and-take waters of the Cowpasture River about 3/4 -mile downstream and offers anglers a prime catch-and-release alternative in the area. Spring Run has runs, riffles, and long, slow pools and glides where rainbows, browns, and brookies of all sizes can be easily seen cruising and feeding –in other words, the sight fishing is incredible! Courtesy of Mossy Creek Fly Fishing.
https://mossycreekflyfishing.com/pages/spring-run

Aqua Spring, Highland County

Aqua Spring (sometimes referred to as Lockridge Spring) is located within the Bullpasture River Gorge, in the Cowpasture River drainage area of western Virginia. The Gorge is part of the Highland Wildlife Management Area (WMA) in Highland County, a county with the highest average elevation of any county east of the Mississippi River. Aqua spring is the largest of the springs along the Bullpasture River, associated with four distinct karst basins which, from the farthest upstream to the farthest downstream, are: Emory Spring, Aqua Spring, Cathedral Spring and Blue Spring. The carbonate aquifer of Burnsville Cove, the primary recharge area for the four springs, is developed in folded and fractured Tonoloway and Keyser limestones (Upper Silurian to Lower Devonian), with two sandstone tongues of the Clifton Forge formation acting as confining layers. Surface drainage from the clastic rock slopes of Jack and Tower Hill Mountains generally sinks upon encountering the carbonate rocks. Subterranean drainage in general follows structural and stratigraphic controls from its source to springs along the Bullpasture River (Davis et al., 1982). During a multi-year study, a total of 22 individual sink-to-spring dye tracings and 7 internal traces to the Butler Cave –Sinking Creek System were conducted to define the drainage divides between each of these basins.



Figure 3.8.12 Aqua Spring (sometimes called Lockridge Spring) is the largest spring in the Bullpasture River Gorge. Photo courtesy of Phill Lucas. See also Fig. 1.60 in Chapter 1.

These traces and other hydrologic evidence indicate that residence times for conduit flow in Aqua Spring and Cathedral Spring basins are relatively short (usually less than 2 weeks) while Emory Spring and possibly Blue Spring have somewhat longer residence times due to likely larger phreatic conduit volumes (Davis et al., 1982; Schwartz and Doctor, 2009.)

Aqua Spring flows from an underwater opening 2 ft high and 9 ft wide at the base of a 30-foot cliff of Keyser Limestone, which dips 22° southeast. Diving in the spring led to the discovery of Aqua Cave. The underground stream that feeds the spring can be followed 0.4 mi through a vadose passage, which averages 30 feet wide and 12 ft high, to a sump. Here, the upper Clifton Forge sandstone dips downward toward the axis of one of the many minor folds which complicates the structure and the passage is constrained to follow the sandstone downward. The siphon has been penetrated 394 ft to a depth of 82 ft by Hank Hoover. At this point the passage is 5 ft high and 12 ft wide and still leading downward. A map by Hoover and Kutz (1962) shows the terminal siphon to be 40 feet above the spring. The water from the spring drops another 70 ft in reaching the river. After any storm, Aqua Spring rapidly becomes muddy. Flow has been measured as high as 170 cfs. Higher flow rates have been observed but not measured (see Fig. 1.60 in Chapter 1). Two discharge rates recorded during low flow conditions were 4.9 cfs and 5.8 cfs in August 1973 and October 1972 respectively (Davis et al., 1982).

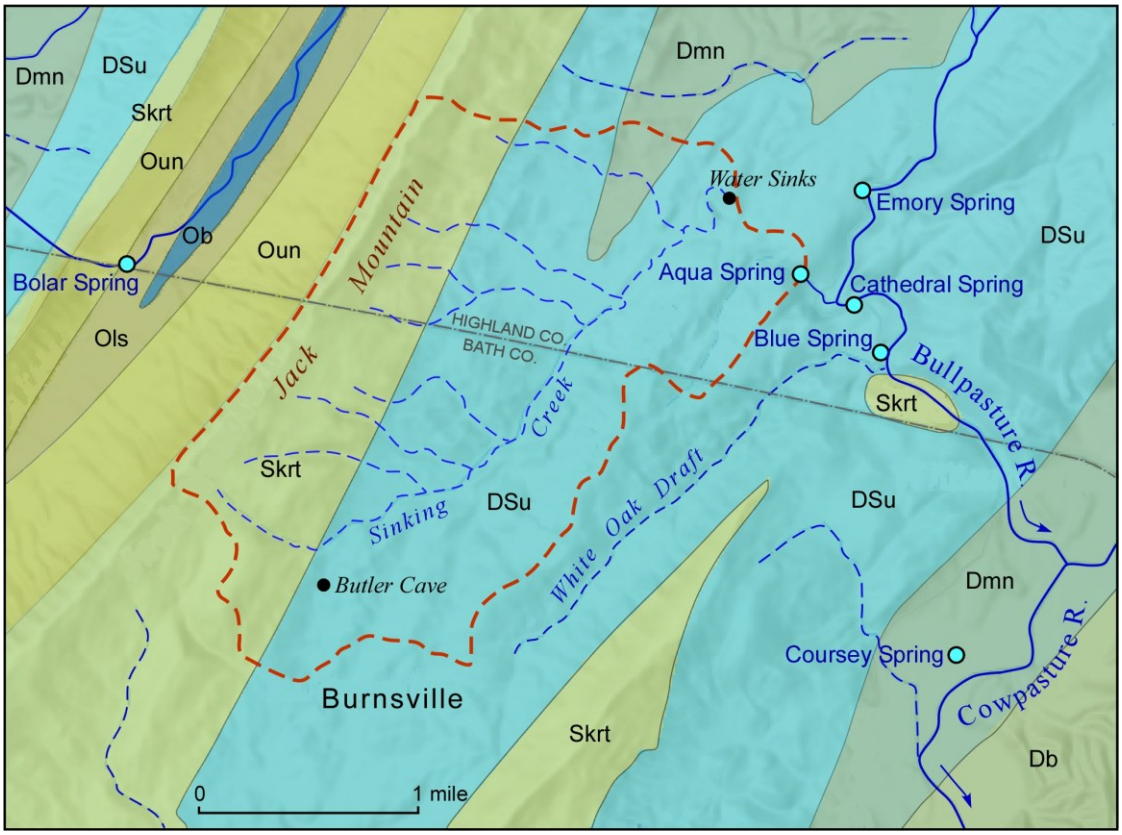


Figure 3.8.13 Drainage area of Aqua Spring, shown with dashed red line (from Davis et al., 1982). Geologic map from Virginia Department of Energy, available online at DGMR. Geologic units, from youngest to oldest: Db: Devonian Brallier Formation; primarily shale. Dmn: Devonian Millboro Shale and Needmore Formation; primarily shale, punctuated by several distinct carbonate intervals. DSu: Upper Silurian–Lower Devonian: Ridgeley Sandstone, Helderberg and Cayuga Groups; primarily Helderberg, Keyser, and Tonoloway Limestone. Skrt: Silurian Keefer Sandstone, Rose Hill and Tuscarora Formations; primarily arenite. Oun: Ordovician Juniata, Oswego, Martinsburg (Reedsville and Dolly Ridge) and Eggleston Formation; primarily shale., Ols: Ordovician Mocassin Formation and Bays Formation; primarily limestone and shale. Ob: Ordovician Beekmantown Group; primarily dolostone.

The Burnsville Cove in Bath County, Virginia, hosts an extensive karst system (>62 mi of mapped passages) developed under a complex synclinal valley in the Silurian-Devonian Keyser Limestone of the Helderberg Group. Observable patterns of cave development are the result of hydrogeologic controls on paleo-conduit formation, landscape evolution, and several episodes of conduit modification as the subterranean drainage system adjusted to changes in surface drainage and morphology. Currently, most of the mapped caves contain vadose free-surface streams that drain north-northeast toward the Bullpasture River, which flows south into the Cowpasture River. However, many passages are dominated by solutional and sedimentary features indicative of former phreatic conditions and substantially different paleo-drainage characteristics. Widespread evidence of deep phreatic development under low-velocity conditions exists throughout the Burnsville Cove in cave passages between 0 and >750 ft above modern spring elevations. Mineralogical and geological evidence of hydrothermal fluid migration and volcanism in the area has recently been recognized and may have contributed to the formation of proto-conduits which influenced early stages of karstification (Schwartz and Doctor, 2009).

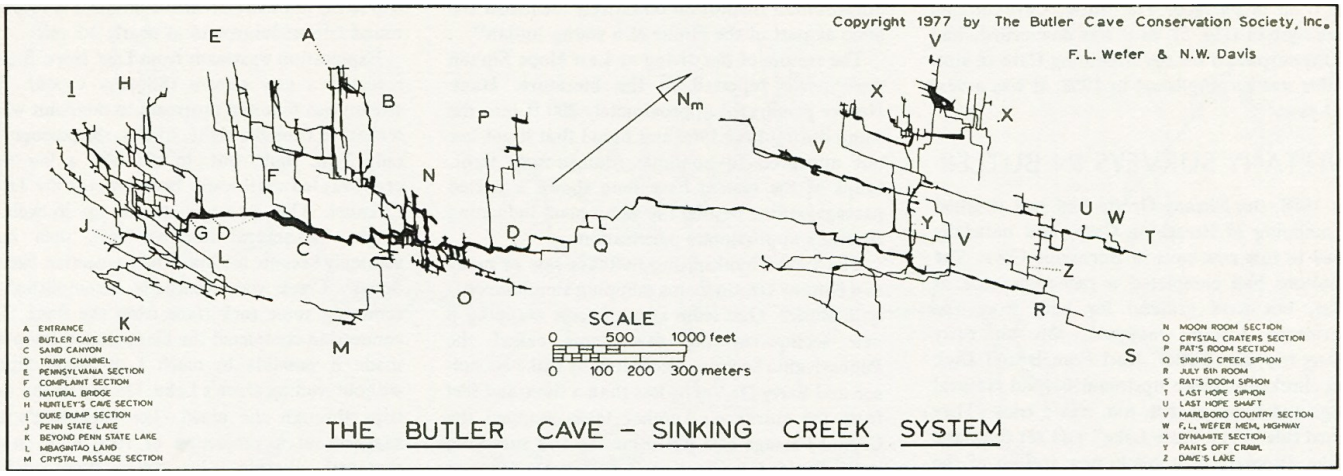


Figure 3.8.14 Map of The Butler Cave – Sinking Creek System from 1977, showing approximately 15 miles of passages. Copyright by The Butler Cave Conservation Society. From Davis et al., 1982. As of spring 2026, the system is approximately 17 to 18 miles long (The Butler Cave Conservation Society (BCCS). Butler Cave had been designated by the National Park Service as a National Natural Landmark, and the Burnsville Cove Conservation Site has been designated as one of the seven "Significant Karst Areas" in Virginia by the Natural Heritage Program of the Virginia Department of Conservation and Recreation.



Figure 3.8.15 Silurian-Devonian Keyser Limestone of the Helderberg Group exposed at Water Sinks, the terminal sink of Sinking Creek in Highland County.

Crystal Spring, Roanoke

Crystal Spring is Roanoke's oldest drinking water source. It is the primary reason the City of Roanoke grew exactly where it did. Long before European settlement, Native Americans used the site. In 1740, a Welsh immigrant named Mark Evans secured a land grant for the property. For over a century, the site was known as "Big Spring" or "The Fountain," powering a local grist mill. In the 1880s, the Atlantic, Mississippi and Ohio Railroad (later the Norfolk and Western) selected the tiny town of Big Lick as its major hub. The town was renamed Roanoke in 1882. The massive, reliable freshwater output of Crystal Spring allowed the rapidly growing railroad boomtown to survive and expand. In 1889, the land holdings surrounding the spring were transferred to the Roanoke Water Company, which laid the primary distribution mains connecting the spring to downtown businesses and homes (https://roanokehistory.org/crystal-spring-pump-station/).

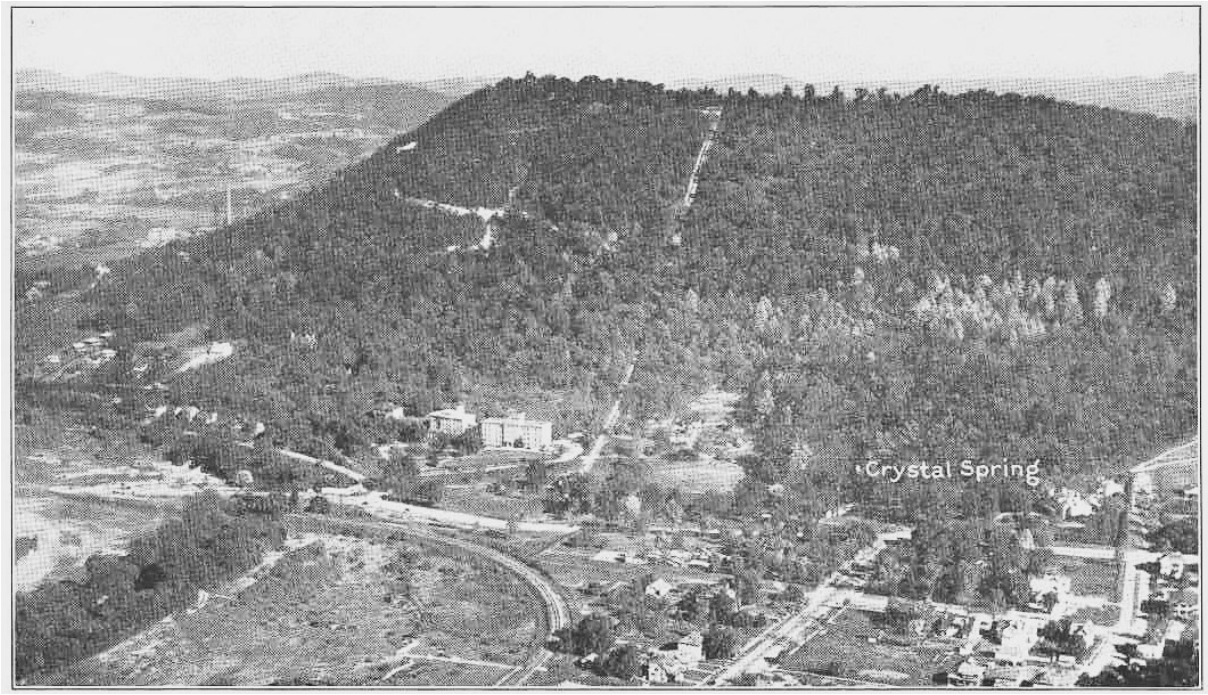


Figure 3.8.16 West slope of Mill Mountain showing location of Crystal Spring. Aeroplane photographs by Underwood and Underwood. Photograph courtesy of Roanoke Chamber of Commerce. Plate 28 from Woodward, 1932.

Crystal Spring discharges from the Cambrian Shady Dolomite beneath the Blue Ridge thrust sheet on top of Mill Mountain which is comprised of quartzite and shale conglomerates of the Cambrian Chilhowie Group. As reported by Woodward in 1932, *It is the largest spring in the vicinity of Roanoke and is an important contributor to the city water supply. The flow of the spring is about 7 cfs or 4,500,000 gallons of water daily. The flow in past years is reported to have reached 6,000,000 gallons daily. All of the water from this spring is utilized by the Roanoke Water Works Company for water supply purposes in Roanoke, being pumped to a reservoir on top of Mill Mountain and thence distributed by gravity flow*.

It is obvious that the underground circulation through the limestones of this area must be very free and easily open to contamination from the surface. Many of the sinks are filled with waste of all kinds and in some places sewage is diverted into them. Great care should be exercised in using water for domestic purposes from the springs of a limestone region. R. J. Holden, of Virginia Polytechnic Institute, Blacksburg, has been conducting a series of

experiments to ascertain the channels of underground circulation in Montgomery and Pulaski counties, by putting fluorescein into the larger intakes of ground water, and then testing the various' springs and wells in the neighborhood for its presence. It is thus possible to determine the larger channels of circulation. (Woodward, 1932).

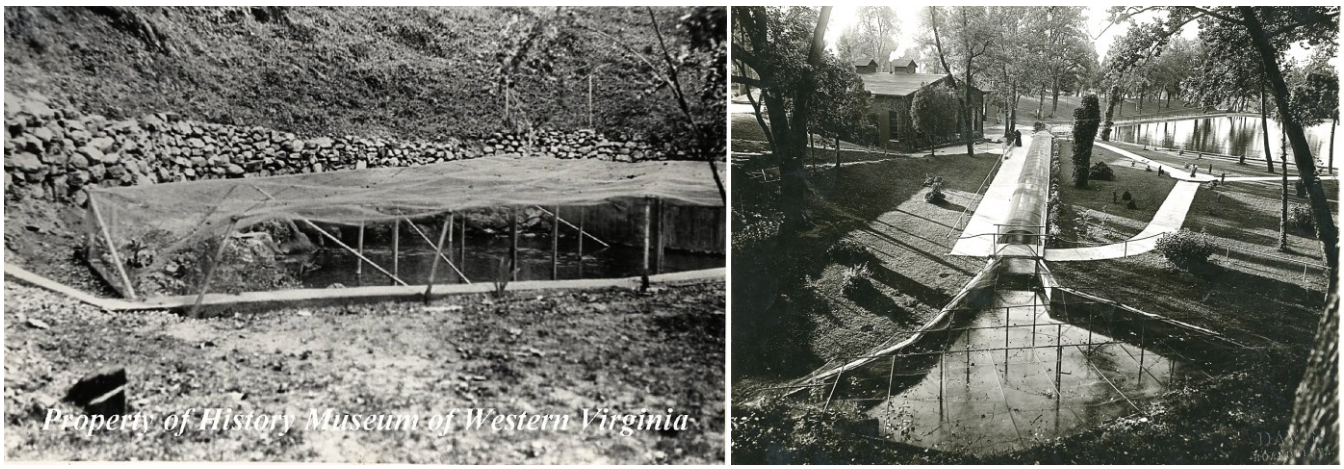


Figure 3.8.17 *Left*: Crystal Spring before pumping station was built in 1905. *Right*: Crystal Spring sluiceway, pump house, and reservoir, circa 1915. Photo by George C. Davis. Courtesy of History Museum of Western Virginia.

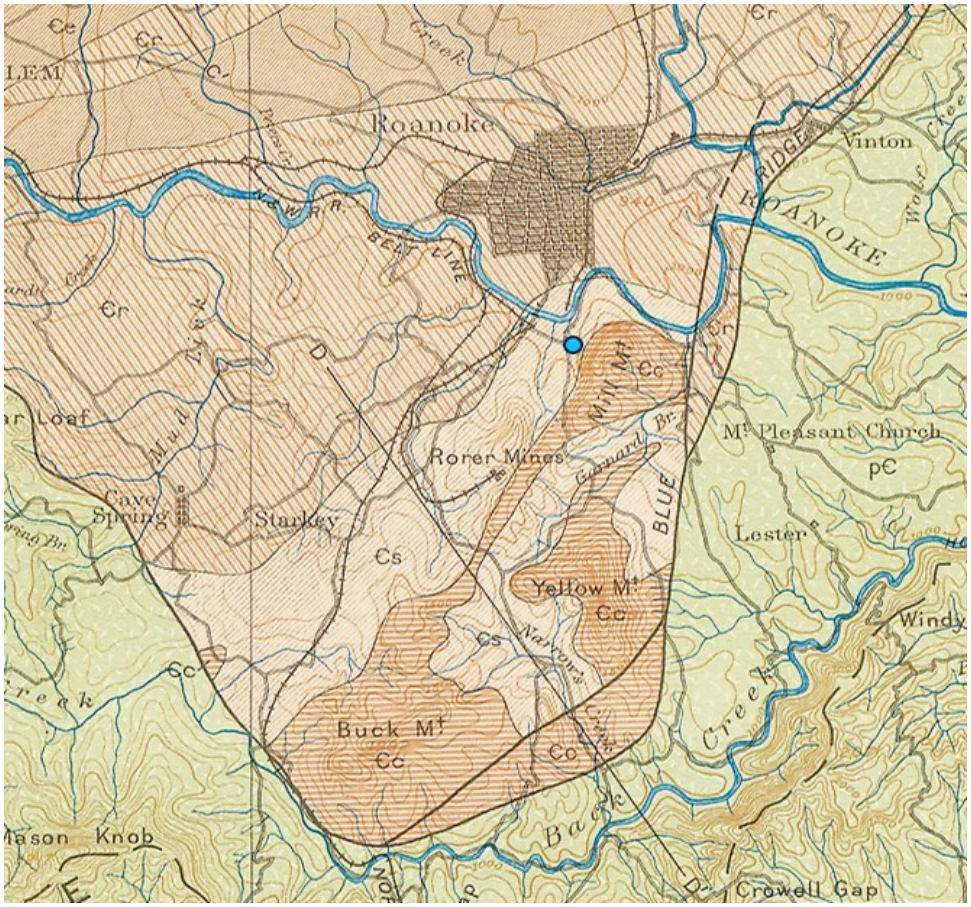


Figure 3.8.18 Geologic map of the vicinity of Crystal Spring (denoted with blue dot) in Roanoke. Є*e*: Elbrook Formation of Middle and Late Cambrian age; thinly bedded limestone and dolomite with interbedded calcareous shales. Є*r*: Rome Formation of Early and Middle Cambrian age; shale with interbedded limestones and some calcareous sandstone. Є*s*: Massive Shady dolomite and calcareous shale of early Cambrian age. Є*c*: Chilhowie Group of early Cambrian age; massive quartzite, shale conglomerate, quartzite, arkose, and hematite beds. p*Є*: Undifferentiated metamorphic and igneous rocks of pre-Cambrian age, including schists, gneisses, granites, and gabbros. From Woodward, 1932.



Left: In the 1960s, the open pond reservoir was covered with tennis courts. *Right:* Treated water was stored under the tennis courts which were supported by concrete pylons.



Left: The Crystal Spring Snow Steam Pump operated 24 hours a day from 1906 to 1957. *Right*: In 2013, high efficiency electric pumps replaced equipment from 1957. Photos courtesy of Western Virginia Water Authority.



Left: Crystal Spring's captured discharge with average flow of 4 MGD. *Right*: Since 2002, water from the spring has been filtered at the Crystal Spring Ultrafiltration Facility.

Figure 3.8.19 Evolution of Crystal Spring waterworks for water supply of Roanoke. Courtesy of Western Virginia Water Authority.

Maiden Spring, Tazewell County

Maiden Spring is located 6 mi east of Paint Lick and 3.4 mi southwest of Liberty Hill in Tazewell County. According to Collins et al. (1930), it discharges from a cave at the base of a cliff in the Ordovician Beekmantown Limestone. In August 1928, it had a reported flow rate of 4,050 gpm or 9 cfs (Collins et al., 1930). More recent discharge measurements are not available.

As described by George Washington Lafayette Bickley in 1852, "*The Maiden Spring fork, which rises in Thompson's valley, flows a short distance, sinks several miles, and rises again near what is known as Maiden Spring, owned by Col. Rees T. Bowen, and one of the loveliest places in Tazewell. This spring is named also, from an incident which happened to Rees Bowen, the earliest settler near it, and grandfather of its present owner.*

When Mr. Bowen first saw the spring, he discovered a fine young female deer, feeding on the moss within the orifice from which gushes the spring. He shot it, and when he went to get his deer, saw a pair of elk horns standing on their points, and leaning against the rocks. Mr. Bowen, was a very large and tall man, yet he had no difficulty in walking upright under the horns. He chose this place for his home, and the spring and river, have since been known as Maiden Spring and Fork." (Bickley, 1852, p.77)

Rees Bowen, an early settler in the Clinch River valley, initiated construction of a stockade known as Maiden Springs Fort in 1773 on his property near the spring. This structure served as the second stockade in the region, providing defensive refuge for local families against raids by Native American tribes, particularly Shawnee and Cherokee groups contesting European expansion into southwestern Virginia. Maiden Spring functioned as a self-sufficient antebellum farm under Bowen family management, emphasizing mixed agriculture and livestock rearing typical of southwest Virginia estates in the 19th century. The property retained its original field layout, supported by a mid-19th-century barn and clustered outbuildings dating from that era through the early 1900s, which facilitated crop cultivation and animal husbandry. In 1994, Maiden Spring homestead was officially listed on the National Register of Historic Places. The property is privately owned and public access is restricted. (https://www.dhr.virginia.gov/historic-registers/)



Figure 3.8.20 Maiden Spring as seen from a local road. The spring is on private property, and access is restricted Photo courtesy of Phill Lucas.

The Maiden Spring specific ecosystem is a hotbed for hyper-localized, globally rare endemic species. For example, it houses the Maiden Spring Cave Beetle (*Pseudanophthalmus virginicus*), an endangered insect known globally from only this single cave environment.

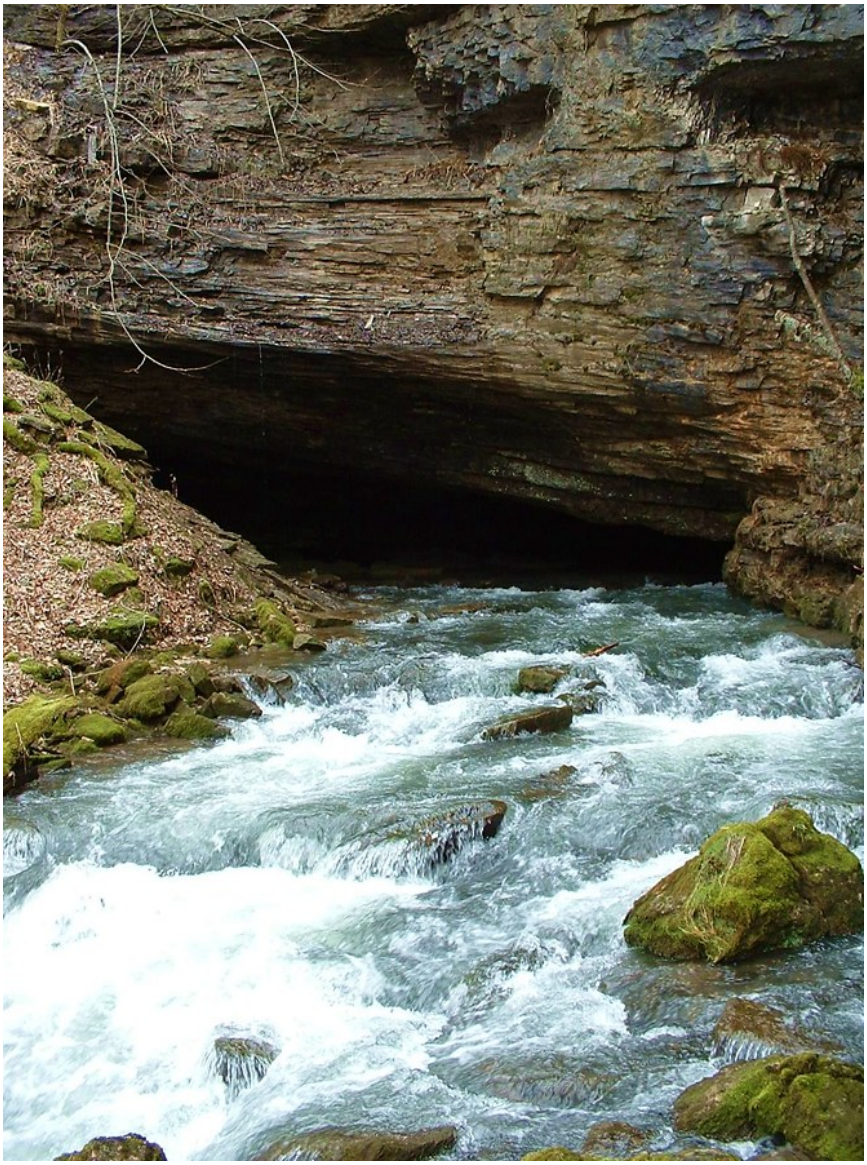


Figure 3.8.21 Maiden Spring. Photo courtesy of Phill Lucas.



Figure 3.8.22 Maiden Spring Cave Beetle (*Pseudanophthalmus virginicus*), an endangered insect known globally from only the Maiden Spring cave environment. Photo courtesy of Virginia Natural Heritage Program, Virginia Department of Conservation and Recreation.

Gardner Spring, Augusta County

Gardner Spring is a major karst spring in Augusta County and serves as a primary water source for the City of Staunton, supplying approximately half of the city's drinking water. It also supports baseflow in the Middle River. The spring issues from limestone conduits of the Ordovician Edinburg, Lincolnshire, and Newmarket formations at the base of the hillside that are protected by a concrete spring vault. Dye traces were performed in the spring's watershed to evaluate potential impacts of the proposed Atlantic Coast Pipeline in 2018. Fluorescein dye was detected at the spring 12 days after 2 pounds of dye was flushed into a karst feature approximately 4 miles southwest of the spring in Ordovician Beekmantown rock units.

The Gardner Spring raw water pump station, which was recently upgraded to a modern, flood-resilient facility, is capable of delivering a flow of 7.2 MGD to the treatment plant.



Figure 3.8.23 Gardner Spring is a major municipal water supply in Augusta County and supports baseflow in the Middle River. Photo courtesy of Joel Maynard.

Blue Hole (Blue Sapphire) Spring, Augusta County



Figure 3.8.24 William Orndorff, manager for Virginia Department of Conservation and Recreation's Karst Program, collects field parameters at Blue Sapphire (Blue Hole) Spring in Augusta County. The spring emerges from Conococheague carbonate rocks (Cambrian and Ordovician) and is known for its deep blue karst pool. It was dived to a depth of 52 ft in a continuing conduit before a disgruntled trout made the diver turn around (Simmons, 2003). Photo courtesy of Joel Maynard.

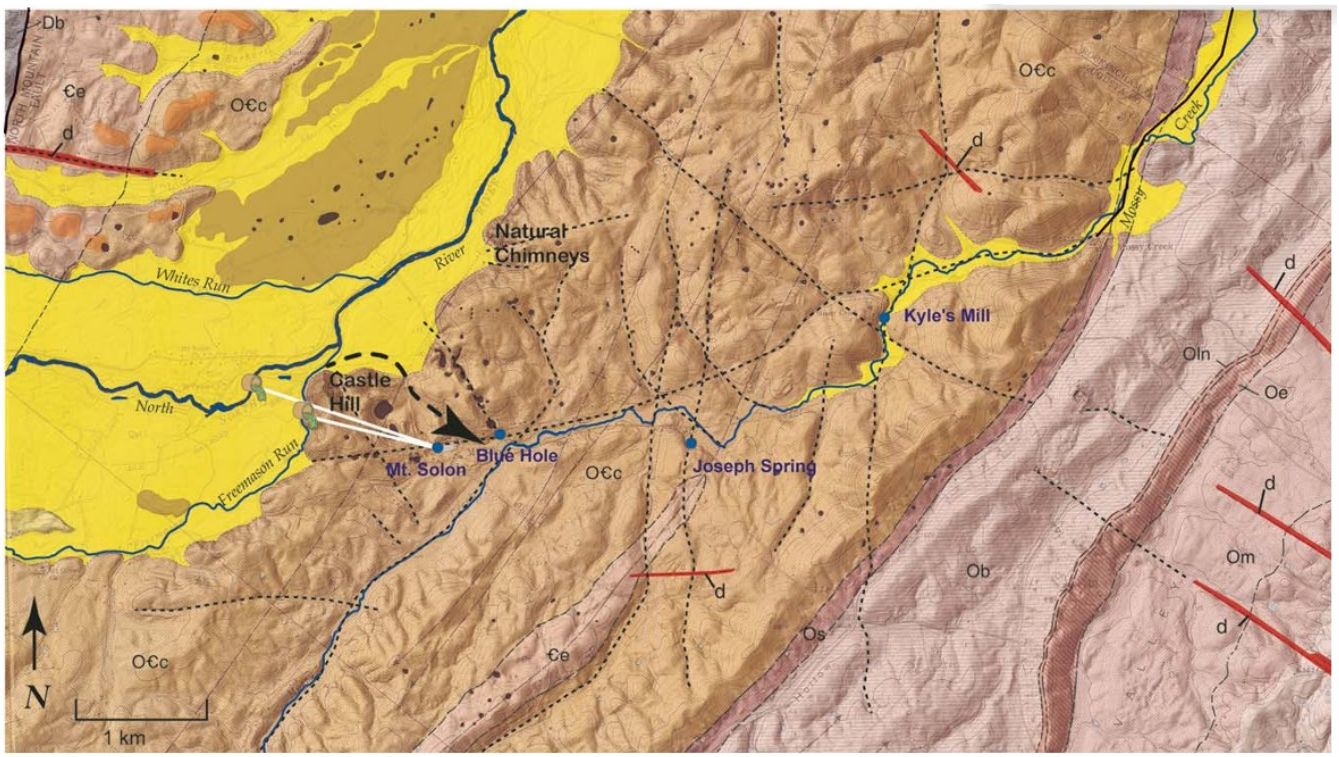


Figure 3.8.25 Geologic map of the Mt. Solon and Blue Hole Spring area. From Doctor et al., 2014; modified after Rader, 1969. Short-dashed lines show inferred faults or lineaments, and black polygons show closed depressions from interpretation of the LIDAR DEM. Spring locations generally line up on these lineaments. The white lines show positive dye traces to Mt. Solon Spring; the black dashed arrow shows the known overflow path of North River into the channel of Mossy Creek at very high flows. Note that several lineaments contain or are parallel with mapped igneous dikes. Db—Brallier Formation; Ce—Elbrook Formation; d—igneous dike; O€c—Conococheague Formation; Ob—Beekmantown Group; Oe—Edinburg Formation; Oln—Lincolnshire and New Market Limestones; Om—Martinsburg Formation; Os—Stonehenge Formation. ©2014 Copyright Geological Society of America.

Surgener Cave Spring, Lee County

Surgener Cave Spring is located in The Cedars Natural Area Preserve in Lee County, the absolute westernmost part of Virginia, wedged between the borders of Kentucky to the north and Tennessee to the south. In 1985, the Virginia Cave Board designated the Central Lee County Karst region, including the local area known as The Cedars, as a Significant Karst Area for its unique geological, hydrological, and biological values. The geochemistry, juxtaposition, hydrology, and climate of The Cedars are elemental to the limited habitats of 33 rare plant and animal species, including the Lee County cave isopod. This isopod is endemic to southwestern Virginia, where it has been documented from only two cave systems and two springs in Lee County (Roble et al., 1997).

The Lee County cave isopod was federally listed as endangered in November of 1992 (U.S. Fish and Wildlife Service, 1992.) The species was listed when the population in Thompson Cedar Cave was extirpated by the effects of sawmill waste being dumped in the entrance sinkhole and surrounding area. After the sawmill operations were discontinued, mitigation efforts were successful in allowing the population to reestablish. The cave environment is still degraded by the influx of leachate from old sawmill waste (Lewis et al., 2023).

Today, The Cedars Natural Area Preserve supports an exceptional natural community of rocky, dry, limestone glades and woodlands covering 30 to 40 square miles in Lee County near the Powell River. Surgener Cave lies on

the Preserve and is managed by the Virginia Department of Conservation and Recreation Division of Natural Heritage (https://www.dcr.virginia.gov/natural-heritage/natural-area-preserves/thecedars).



The Preserve's topography is characterized by extensive bare limestone ledges solutionally etched and sculpted (karren), numerous sinkholes, blind valleys, sinking streams, subterranean drainages, and caves (Holsinger and Culver 1990).

Figure 3.8.26 Surgener Cave Spring, home to federally endangered, endemic isopod *Lirceus usdagalun*. Photo courtesy of Ryan Mauer.



Figure 3.8.27 The impressive size of the Surgener Cave reveals how much water can flow through the system during high water levels. The cave is home to more cave-adapted species than any other cave in Virginia. The short stream formed by the spring flows into the Powell River, home to several rare freshwater mussels. Text and photo courtesy of Katarina Kosič Ficco.

The Cedars is a mature karst terrain developed on soluble limestone of middle Ordovician age. Approximately 300 million years ago during mountain-building activity, these rocks were structurally deformed and thrust for miles along the Pine Mountain Overthrust Fault. As a result, the structural profile is that of a slightly synclinal (down-warped) basin imprinted by distinct bedrock fractures and joints. Bedrock is nearly horizontal along the trough of The Cedars syncline and strikes 60° to 70° northeast. The fracture porosity superimposed on the soluble bedrock apparently facilitated the development and integration of subterranean conduits in the Hurricane Bridge and underlying Martins Creek carbonate units (Miller and Brosge, 1954).

Accessible caves in The Cedars provide a glimpse of the solution-enlarged, underdrain system that captures and conveys water from sink points near U.S. Route 58 to the Powell River. Thompson Cedar Cave, Molly Wagle Cave, Wynn Cave, Gibson-Frazier Cave, Surgener-Gallohan Cave, and others have formed close to the surface and can be directly affected by surface activities producing sediment, increased runoff, and chemical/bacterial pollutants. Undiscovered cave passages most likely underlie several portions of The Cedars (Roble et al., 1997).



Figure 3.8.28 The Lee County cave isopod, *Lirceus usdagalun*, was federally listed as endangered in November of 1992. It is a small freshwater crustacean discovered by John Holsinger and William Mauck in 1961. Unlike other members of the genus *Lirceus*, it is an obligate cave dweller and lacks eyes and pigmentation. Reaching 7 mm in length, the body is more than twice as long as it is wide. The head is one-third as long as it is wide and has deep, narrow lateral incisions. In addition to water quality degradation, threats to the isopod include the use of sinkholes as disposal sites for household, industrial and agricultural wastes, nonpoint-source pollution, failing septic tanks, toxic spills, and improper development on or near key karst areas. Photo by William Orndorff, Courtesy of Virginia Department of Conservation and Recreation, Natural Heritage Program.

Springs of the Northern Shenandoah Valley

Rocks of the carbonate aquifer system underlying northern Shenandoah Valley range from Middle Cambrian to Late Ordovician in age and consist of carbonate and clastic lithologies. Rocks from the Middle and Upper Cambrian Elbrook Formation through the Middle Ordovician Edinburg Formation are predominately limestone and dolostone, whereas rocks of the Middle and Upper Ordovician Martinsburg Formation contain siltstone, sandstone, shale, and minor amounts of limestone.

In a publication entitled *Ground-water resources of northern Virginia* (published by Virginia Geological Survey in 1938 as *Bulletin 50*), Richard Carlysle Cady provides explanations of the northern Shenandoah Valley karst aquifers that stood the test of time and were confirmed by various subsequent investigations including by USGS. Below are several key excerpts from this outstanding publication.

In the Shenandoah Valley the rocks are limestone and shale of Upper Cambrian and Ordovician age. They are folded into a complex asymmetric syncline that trends northeast by north, with the Martinsburg shale at the axis; the dip of the rocks is steep on the east limb of the fold-indeed, farther east in Clarke County the beds are overturned-but on the west limb the dip is slight. Many smaller folds are superimposed upon the larger fold. The whole syncline is part of an overthrust sheet that moved from the southeast along a fault plane and overrode the younger sediments to the northwest, so that along the overthrust zone at Little North Mountain the Elbrook limestone, of Middle and Upper Cambrian age, has come to lie adjacent to Silurian and Devonian sediments.

The deepest well reported in the area is one owned by the Winchester Woolen Mill (No. 161) in the southeastern part of the city. It was drilled to a depth of 1,432 feet through dolomite and limestone. Water-bearing openings in the rock were passed through at about 100 feet, 300 feet, 700 feet, and between 1,100 and 1,200 feet. No more were encountered below 1,200 feet. The water stood at 16 feet below the surface and is drawn down 104 feet when it is pumped at 150 gallons a minute.

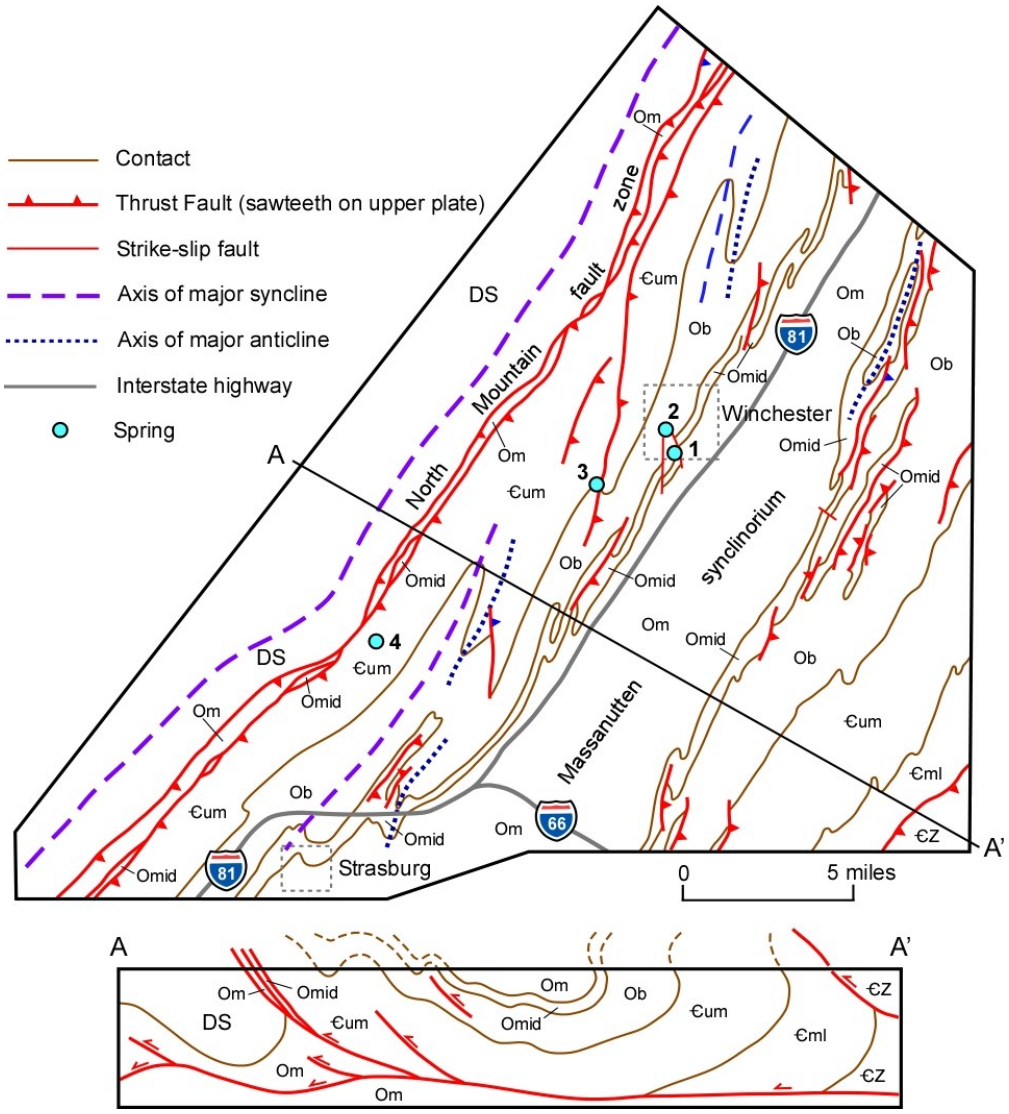


Figure 3.8.29 Generalized geologic map, and cross section of the Shenandoah Valley of northern Virginia and location of major karst springs. DS-Devonian and Silurian rocks; Om-Upper and Middle Ordovician rocks of the Martinsburg Formation; Omid-Middle Ordovician carbonate rocks; Ob-Middle and Lower Ordovician rocks of the Beekmantown Group; Ꞓum Upper and Middle Cambrian carbonate rocks of the Conococheague and Elbrook Formations; Ꞓml-Middle and Lower Cambrian rocks of the Waynesboro and Tomstown Formations; ꞒZ-Cambrian and Neoproterozoic rocks of the Blue Ridge Province. 1: Rouss Spring; 2: Shawnee Spring 3: Vaucluse Spring; 4: Marlboro Spring. Modified from Orndorff and Harlow, 2002.

The driller reported that the water was flowing through the deepest channels with sufficient force to wash out the drill cuttings. A well of such great depth is very expensive, and it is not certain that water-bearing cavities will be encountered at great depths in all places, in spite of the fact that some of the drillers in the area are confident that water can be obtained at low levels.

It is believed that the structure of the rocks in the eastern part of Frederick County exerts a definite influence upon the movement of the ground water in the areas of limestone and Martinsburg shale. The rocks constitute a syncline, with the shale in the axial region and limestone on the western limb passing under the shale and emerging at the surface at the east in Clarke County.

The land surface slopes eastward from Little North Mountain to Opequon Creek, so that the surface of the limestone just west of the shale belt is 200 to 300 feet higher than it is just east of the shale. The shale belt is 5 to 6 miles wide near Winchester. The ground water is thought to flow eastward through the limestone on the western limb of the fold, passing rather rapidly through the cavernous zone which extends 400 feet or more below the surface, then coming near the shale, which, in spite of its rather high content of lime, is less permeable than the soluble limestone. The water from the limestone, carrying its dissolved lime, enters the shale, but as it moves slowly through the small channelways in the shale its hardness increases, as shown by analyses. But analyses of water taken in counties farther south in the valley indicate that the hardness of the shale water decreases eastward suggesting less of the original water from the limestone and more of surface water percolating downward.

That the shale obstructs the eastward movement of the ground water from the limestone and may act as a dam is further suggested by the occurrence of some of the largest springs of the county in the limestone near the contact with the shale. Such springs are the two at Winchester that furnish the present public supply and the large spring at Vaucluse. Whatever water that does not emerge at the surface or penetrate the shale may pass below the shale through the upper beds of limestone under the head resulting from the difference in altitude between the western and the eastern limbs of the syncline. The assumption of such an artesian circulation of the water in the limestone would make it easier to understand the strong flows of water encountered in cavities at depths of 1,100 and 1,200 feet in the well of the Winchester Woolen Mills. Moreover, on the basis of several analyses of ground-water in the limestone the water in the eastern limb of the syncline, in Clarke County, is harder than the limestone waters in the western limb of the fold. It is also interesting to note in this connection that most of the strongest wells in the shale belt were said to occur near the western boundary, where water might be entering the shale from the limestone under some artesian head, if the hypothesis of artesian circulation is correct.

Many smaller springs are used locally for domestic supplies. However, the spring water especially during wet weather is likely to be contaminated by water that passes from the surface into sinkholes and along the large solution channels, and it may be objectionably laden with mud. Moreover, many of the springs weaken seriously or go dry during dry seasons.

A spring known as Tidal Spring, on the farm of J. F. Orndorff, near Marlboro, is reported to ebb and flow. At the time it was visited by the writer it was discharging at an approximately uniform rate, but Mr. Orndoff confirmed the report that at some times it has a periodic action.

As discussed by Orndorff and Harlow (2002), many large springs in the northern Shenandoah Valley (also referred to as carbonate valley) are associated with faults, indicating that faults are important directional controls on the flow of groundwater. This includes Rouss, Shawnee, Vaucluse and Marlboro Springs in Frederick County, which are, together with Carter Hall Spring in Clarke County, the largest in northern Virginia.

Winchester springs: Rouss Spring, Shawnee Spring, and Old Town Spring

A number of large springs issue from the carbonate rock formations in the Northern Shenandoah Valley. In the past, many of these springs served as public water supplies. Until 1950s, the City of Winchester obtained its water supply from a variety of springs that have included Old Town Spring, Rouss Spring, and Shawnee Spring. As noted by Cady (1938, p. 67), the occurrence of these springs near the contact between carbonate formations of the west limb of the Massanutten synclinorium and the shales of the Martinsburg Formation suggests, "*the shale obstructs the eastern movement of the ground water from the limestone and may act as a dam*." Additionally, they occur near lithologic contacts and faults between carbonate rock formations (see Fig. 3.8.30).

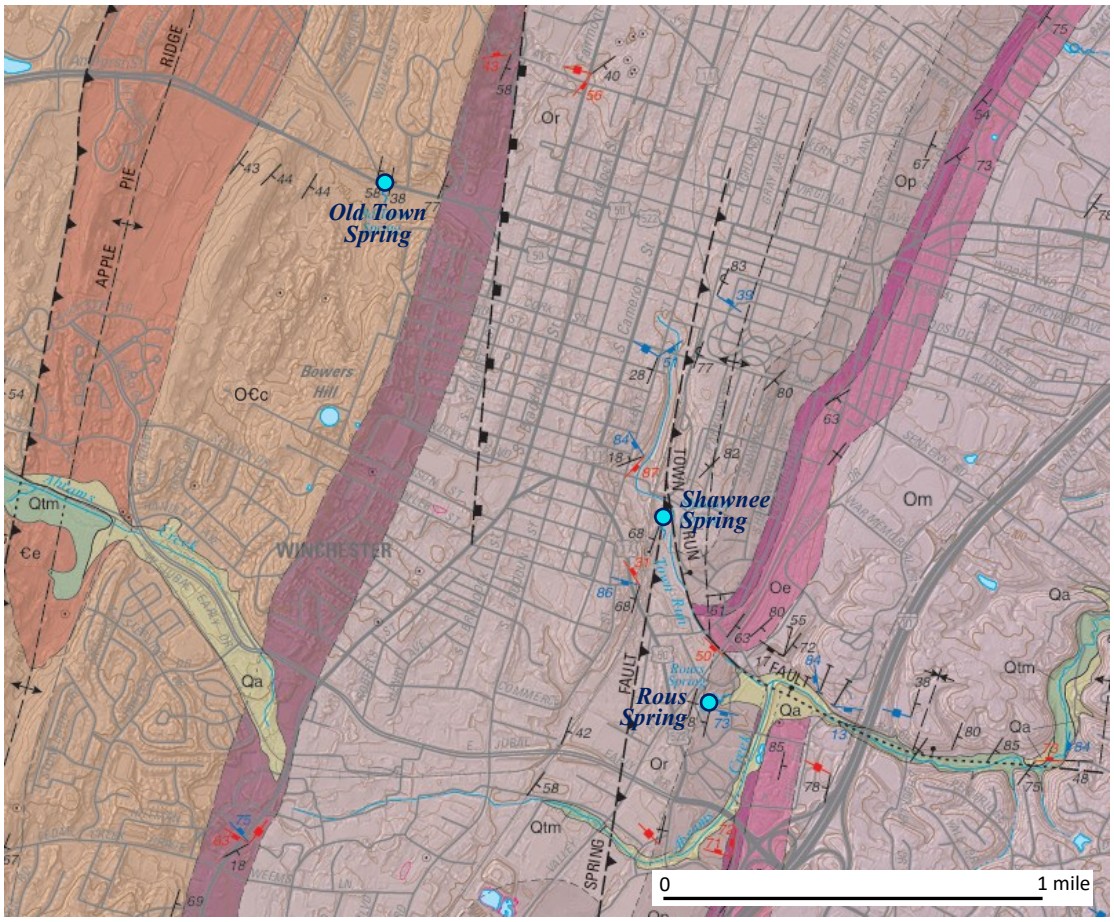


Figure 3.8.30 Part of geologic map of Winchester quadrangle. Q denotes Quaternary sediments. Modified from Weary et al., 2022.

Rouss Spring

In 1890, philanthropist Charles Broadway Rouss gave the city of Winchester $30,000 to buy a large spring outside town. The city bought the spring and the neighboring Hollingsworth Mill in 1890. The mill became a pumping station, and the spring was used as the city's main water supply until 1956, when Winchester began drawing water from the North Fork of the Shenandoah River.

Throughout history, the spring has had several names. To honor Mr. Rouss, the name was changed from Hollingsworth Spring to Rouss Spring. The spring now feeds into Wilkins Lake in Jim Barnett Park which is owned by the city and provides recreational activities for citizens and visitors alike, including fishermen who frequent the lake because of the excellent catch thanks to the always clear water of the spring.

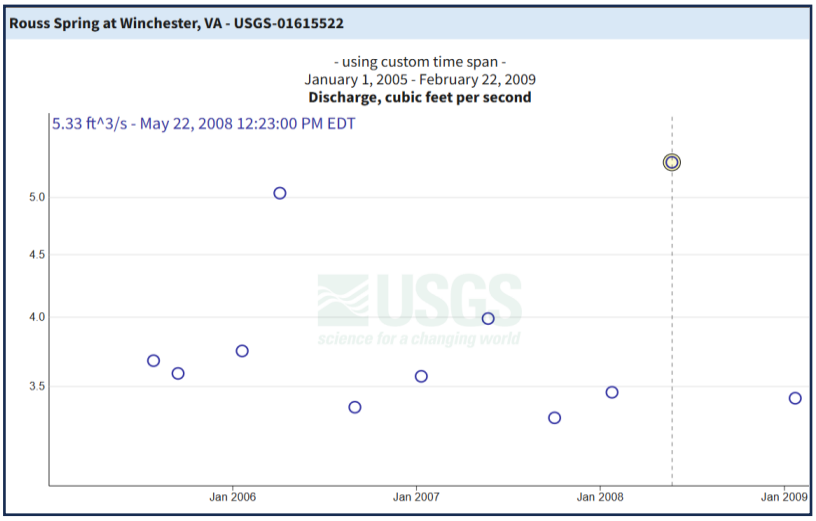


Figure 3.8.31 Available USGS field measurements of discharge rate at Rouss Springs. The average is 3.86 cfs, maximum is 5.33 cfs, minimum is 3.29 cfs.



Figure 3.8.32 Aerial view of Rouss Spring basins. The main spring is in the oval holding pond, which was later supplemented with the larger holding one. Both ponds are made of concrete retaining walls and have open bottom, allowing for free groundwater discharge. Photo courtesy of Winchester-Frederick County Visitor Center.



Figure 3.8.33 Outcrop of Ordovician Rockdale Run Formation carbonates at Rouss Spring, displaying bedding dissolution. Deeper parts of the karst aquifer are in the Middle Ordovician Pinesbrook Station Dolomite.



Figure 3.8.34 *Left*: The large holding pond of the former City Water Works at Rouss Spring. Visible is old plumbing from when the spring was used as the main source of water supply for Winchester. Small spring vents are marked by the lack of vegetation and blue color. *Right*: Normal overflow from the large holding pond shown on the left photo.

Shawnee Spring

Winchester and Frederick County were once Shawnee Indian camping grounds to which Pennsylvania Quakers came to settle in 1732. The main reason for establishing the settlement was a large, reliable spring which they named Shawnee Springs. The Springs were considered sacred by the local Native American people, who attributed healing powers to the water. The new town was first named Frederick Town after Frederick, father of George III of England. In 1752 the name was changed to Winchester in honor of the ancient English capital.



Figure 3.8.35 Historic postcard of Shawnee Springs in Winchester.

Discharge was measured approximately 13 times at Shawnee Springs between August 2001 and December 2002. The mean discharge was 1.1 cfs with a minimum of 0.8 cfs and a maximum of 1.4 cfs (Orndorff and Harlow, 2002).

The Shawnee Springs Preserve is a 14-acre protected city park located between downtown Winchester and Jim Barnett Park. It serves as a historical and ecological refuge. The Preserve protects local wetlands, upland forests, and the city's original municipal spring water source including remnants of the old concrete waterworks basins. It also contains part of the Sheridan's Field Hospital site. Following the massive casualties at the Third Battle of Winchester, Union forces established the largest field hospital of the Civil War on this site. It consisted of roughly 500 tents and treated over 4,000 wounded soldiers using an innovative underground heating system.

Old Town Spring

In 1808, just 32 years after the signing of the Declaration of Independence, Winchester was the first town in the United States to lay pipelines for its public water system. The fascinating story of the first pipeline, as well as the development of the Winchester Water Works through time, is told by R.H. Lemon (*Pipe Salesman*) in an article entitled *A Modern Water Supply for Historic Winchester* published in magazine *The Iron Worker* in 1955 (Vol. XIX, No. 3). Here are several excerpts:

To supply the necessary pipe, since none was being manufactured in this country at that time, Dr. Brown introduced a horse-driven device for boring logs. The logs used were approximately ten inches in diameter. A two-inch hole was bored through those used for the main line, while a one-inch hole was bored through those used for service connections. The ends of these wooden pipes were joined by short iron sleeves on the inside and iron bands around the outside. This initial water system operated by gravity flow and extended from Town Spring on Amherst Street down to Loudoun Street. The citizens along this line opened ditches in front of their property and the corporation furnished the log pipe and laid them.

In 1826 the first cast iron pipe was used. This was a six-inch line from Town Spring to Cameron Street.

In 1891 a second source of supply, Rouss Spring, was brought into service by the installation of a steam-driven pump and a ten-inch cast iron force main through the south end of town. This main led to a 300,000 gallon reservoir which acted as a stand pipe and water was distributed to different sections of town by branches from the ten-inch main

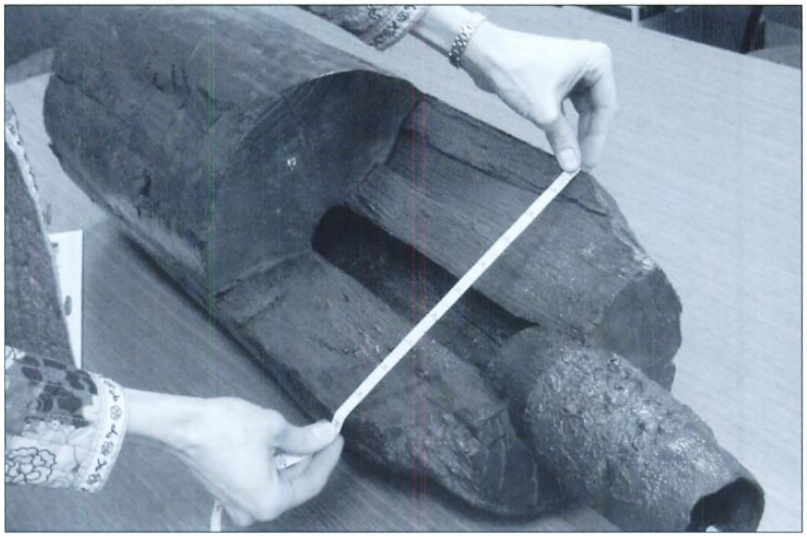


Figure 3.8.36 The first Winchester water system was installed in 1808. Wooden water pipes are still being found during road work in the city. Dale Lehnig, city engineer, measures this main system pipe, 10 inches wide with a two-inch bored hole. Service lines to private property had a one-inch hole. An iron sleeve, shown at the end of this cutaway pipe, was inserted in a second pipe, and they were pounded together. The pipes were further secured by an iron band on the outside joint. Text and photographs courtesy of Kathryn Parker, author of an excellent book entitled *Winchester* (Acadia Publishing, 2006),

Discharge was measured approximately 11 times at Old Town Spring between August 2001 and December 2002. The mean discharge was 0.5 cfs with a minimum of 0.3 cfs and a maximum of 0.8 cfs (Orndorff and Harlow, 2002).



Figure 3.8.37 *Left*: Springhouse of Old Town Spring on historic *Hawthorne* estate, locally well-known as the Civil War-era residence of diarist Cornelia Peake McDonald *Right*: Outcrop of Conococheague Limestone (below the stone retaining wall) at Old Town Spring.

Vaucluse Spring, Frederick County

Vaucluse Spring is a large spring that discharges from the Middle and Lower Ordovician Rockdale Run Formation dolomite and provides a major component of flow to Meadow Brook. Intense fracturing is observed in the Rockdale Run outcrop at the spring, which is adjacent to the Vaucluse Spring fault where rocks of the Conococheague Limestone (Lower Ordovician and Upper Cambrian) are thrust over rocks of the Rockdale Run Formation (Harlow et al., 2005).

The mean discharge of 12 measurements at Vaucluse Spring (USGS station 01635070) was 1.8 cfs with a minimum of 1.3 cfs and a maximum of 3.2 cfs (Orndorff and Harlow, 2002).

The original Federal-style Manor House on a hill above the spring was built in the late 1780s by Revolutionary War Captain Strother Jones. He aptly named the estate "Vaucluse" after the famous village and spring in Provence, France where the 13th century poet Petrarch penned his immortal amorous verses to Laura. Vau-Cluso means closed valley in the Provençal Occitan dialect of the medieval troubadours, such as Frédéric Mistral.

The existing mill structures stand directly on the original stone foundation of a historic 18th-century grist mill. The water is still rushing through the historic millrace, which was once used to channel water directly from the spring to power the mill's wheels.

In 1963, the property was purchased by the renowned Shenandoah Valley realist painter, John Chumley. Chumley reconstructed a two-story home over the original mill's stone footprint, utilizing it as his personal art studio and creative haven for the rest of his life. The 100-acre historic family estate was subsequently restored and first established as a modern bed-and-breakfast destination in the mid-1990s. The Inn at Vaucluse is currently undergoing an extensive renovation project led by Jan Van Haute. While it is temporarily closed for these updates, it is scheduled to re-open its doors to the public with a re-imagined experience at the end of 2026.

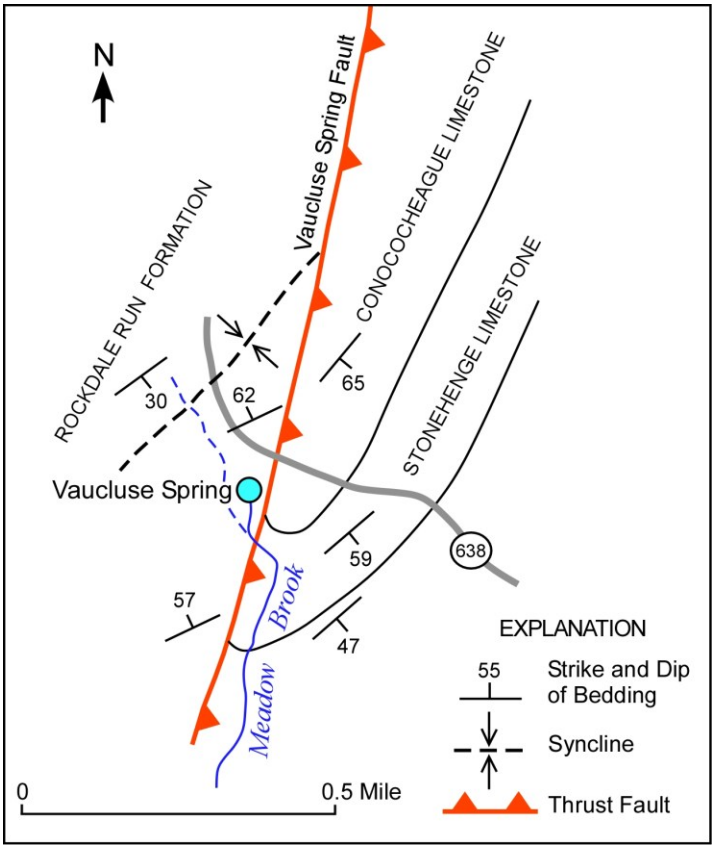


Figure 3.8.38 Schematic showing the geology around Vaucluse Spring, Frederick County. Modified from Harlow et al., 2005.



Figure 3.8.39a Vaucluse Spring



Figure 3.8.39b Vaucluse Spring

Marlboro Spring, Frederick County

Marlboro Spring is in a small village of Marlboro, southwest of Stephens City and Winchester, and just northwest of the town of Middletown, near the intersection of Middle Road (State Route 628) and Cedar Creek Grade (State Route 622). The spring issues from the Conococheague Limestone at contact with the underlying Elbrook Formation.

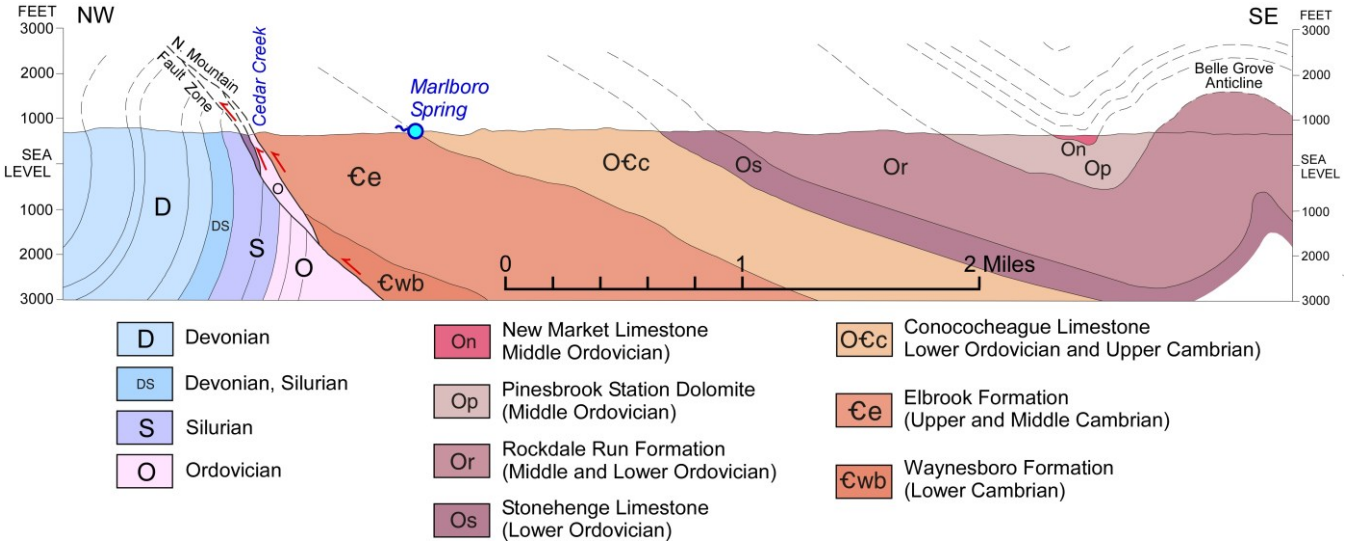


Figure 3.8.40 Geologic cross section over Marlboro Spring. Based on cross section B-B', Geologic Map of the Middletown quadrangle, Frederick, Shenandoah, and Warren Counties, Virginia; Modified from Orndorf et al., 2007. The location of Marlboro Spring is offset.

Discharge was measured approximately 12 times at Marlboro Spring between August 2001 and December 2002 (Orndorff and Harlow, 2002; USGS station 01635005). The mean discharge was 2.6 cfs with a minimum of 1.5 cfs and a maximum of 6.5 cfs. Marlboro Spring was the start of flow for Fawcett Run during this period, and concurrent discharge measurements downstream, at the mouth of Fawcett Run (USGS station 01635008), indicate that it was contributing all the flow in the stream. Fig. 3.8.41 is a graph of historic measurements by USGS at the spring showing that the average discharge rate between October 1949 and September 1956 was around 5 cfs.

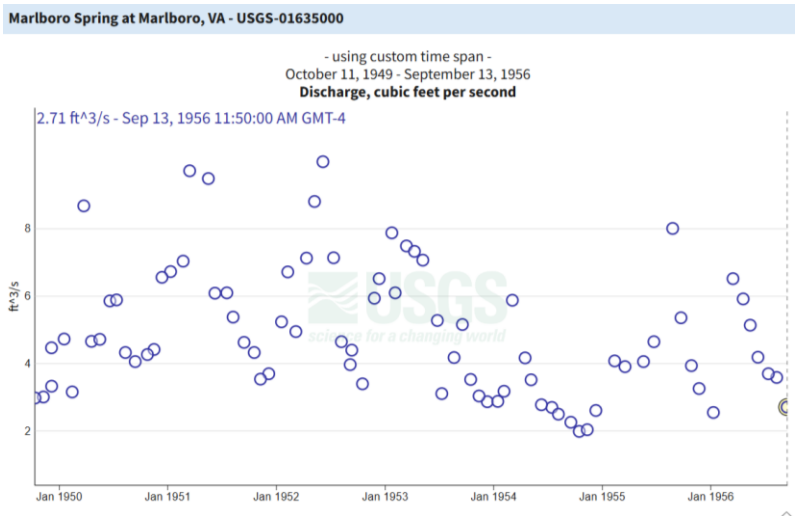


Figure 3.8.41 Available field measurements of Marlboro Spring historic discharge rate, USGS Station 01635000. The average is 4.9 cfs, the minimum is 1.99 cfs, the maximum is 9.99 cfs.



Figure 3.8.42 Pool of Marlboro Spring where groundwater from the underlying karst aquifer discharges under pressure, creating numerous gas bubbles.

Marlboro Spring has a very rich history. In the mid-18th century, industrialist Isaac Zane built massive iron works here, powered by the spring and waterfall. The complex included a blast furnace, forge, sawmill, gristmill, and whiskey distillery. The Shenandoah Valley had an abundance of the three ingredients needed to make iron: rich beds of brown hematite ore, abundant tracts of woodland and vast local source of "marl" deposited by the cold, calcium-carbonate rich water of the spring. Note that "marl" is a colloquial but inaccurate name for the local deposits of tufa – **marl** is unconsolidated carbonate mud with high fraction of clay and organic matter. In comparison, **travertine** is geologic term for dense, crystalline, and sometimes banded calcium carbonate rock, but usually refers to deposits from thermal springs, as opposed to **tufa** which is deposited from cold water springs and streams, and is much softer and highly porous, with visible molds of mosses, leaves, and small branches.



Figure 3.8.43 Sculpture *Stone Memorial* by British sculptor Henry Moore in the National Gallery of Arts, Washington, D.C., is made in Roman travertine. Inset: closeup of the sculpture surface, one foot across. Known to the ancient Romans as *lapis tiburtinus*, this stone was heavily quarried in the region of Tivoli (just east of Rome). Geologically, it is a terrestrial sedimentary rock formed by the rapid chemical precipitation of calcium carbonate from hot, mineral-rich thermal springs. Ancient volcanic activity in the hills surrounding Rome heated these groundwaters, which then rose to the surface and cooled, releasing carbon dioxide and leaving behind the massive, durable stone deposits used to build iconic Roman structures like the Colosseum.

The presence of the abundant spring and "marl" deposits gave the rural community of Marlboro its name. It was once a booming, self-sustaining village of furnace men, colliers, blacksmiths, and wood wrights. During the colonial era, water from Marlboro Spring was piped east by gravity from the top of the falls directly to the village, providing drinking water and supporting the town's health.



Figure 3.8.44 *Left*: Faucet Run cascades into Cedar Creek over thick tufa deposits which extend for several hundred yards along the banks of Cedar Creek. *Right*: Closeup of tufa deposits showing molds of mosses, leaves, and small branches.

During the Revolutionary War, Zane's Marlboro Iron Works became a munitions factory and evolved into one of the largest suppliers of ordnance to the Continental Army and Navy producing four and six-pound cannon, boxes of shot, swivel balls and chain shot. Shipments also included everything from cooking utensils, camp kettles, and stoves to a caboose (a free-standing deck house where seamen cooked meals in a galley). The Marlboro Furnace was the lifeblood of the village as the ironworks peaked at 200 employees.

The production of iron commodities at Marlboro Furnace became greatly diminished due to the declining health and death of Isaac Zane in 1795. The downsizing had an immediate effect on the blacksmiths, wood wrights, wagon wrights and other skill-mixes employed there. History reflects that some of the families from the Marlboro community later became directly associated with the wagon-building industry in Stephensburg (now Stephens City).



The core of the former industrial village is preserved as a private residence and working farm known as Old Forge Farm which was listed on the National Register of Historic Places (NRHP) in 2004. This estate and the old mill on the waterfall are privately owned and closed to the public.

Figure 3.8.45 The original mill at Marlboro, powered by Fawcett Run and waters of Marlboro Spring, suffered major fires in the late 1800s and on May 15, 1930. It was rebuilt on the partial original stone foundations in the 1930s. The mill's water wheel was one of the largest in the Shenandoah Valley at the time.

Carter Hall Spring, Clarke County

Carter Hall Spring is a powerful artesian spring discharging from the Cambrian-Ordovician Conococheague Limestone. It is located on a magnificent 87-acre plantation estate in Clarke County, built around 1797 for Virginia planter Colonel Nathaniel Burwell. The estate is listed on the National Register of Historic Places, and located just outside Berryville, in the neighboring village of Millwood. It famously served as a Civil War headquarters for Confederate General Stonewall Jackson in 1862.

Carter Hall Spring is the largest spring in Clarke County and feeds a massive reflecting pool and bridge system that flows between the historic Carter Hall property and the neighboring Apple Hill estate (built circa 1937). It also serves as a primary headwater that feeds directly into Spout Run, a local waterway known for native trout populations. Carter Hill Spring and the reflective pool are on private properties and access is restricted.



Figure 3.8.46 *Left*: Outflow, under the bridge, from the Carter Spring discharge basin to the reflecting pool shared by Carter Hall and Apple Hill estates. *Right*: View of the Apple Hill Estate and the reflecting pool formed by the waters of Carter Hall Spring. Photographs courtesy of Redfin.

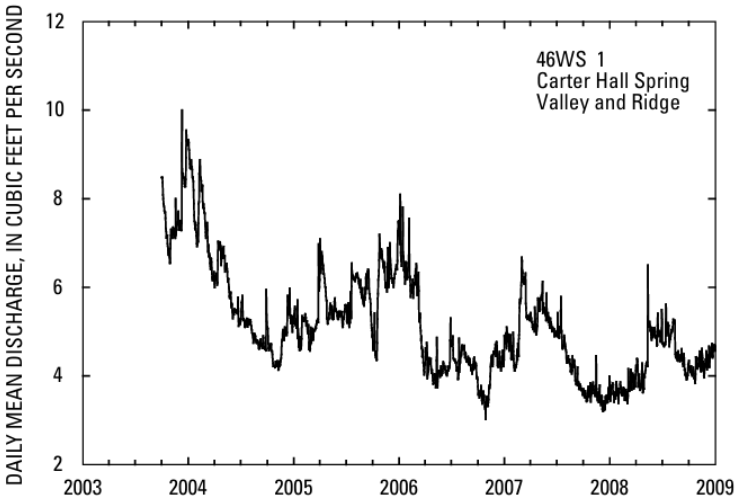


Figure 3.8.47 Pressure transducers were installed by USGS at three karst springs in Clarke County including the largest—Carter Hall Spring—to estimate continuous spring discharge. The Carter Spring discharges ranged from 3.02 to 10.0 cfs, with a mean annual discharge of 5.16 cfs, which indicates that the drainage area is approximately 5 mi^2 based on an estimated average discharge of 1 cfs of flow per 1 mi^2. Of the 36 springs studied and monitored by the USGS during the Clarke County hydrogeologic study, Carter Hall Spring had the smallest water temperature variation of only 0.5°C (between 12.5 and 13.0°C), indicating a deeper groundwater flow not influenced by seasonal air temperature variations. From Nelms and Moberg, 2010.

A prolonged drought between 1999 and 2002 drew attention in Clarke County, to the quantity and sustainability of groundwater resources. More than 20 wells in Clarke County reportedly went dry during this drought, which brought into question whether these failures were related to increased demand or the result of natural fluctuations of the water table. USGS (Nelms and Moberg, 2010), in cooperation with Clarke County, conducted a multi-year

project to provide for an improved understanding of the complex aquifer systems in the county, required to effectively develop and manage them as sustainable water supplies because 54 percent of water use in the county is obtained from groundwater for domestic purposes (Hutson et al., 2004).

A long-term monitoring network was established by USGS to measure water levels, streamflows, and spring discharges. Hydrogeologic information collected during this investigation has been used to address questions about (1) the quantity of water available for use, (2) the effects of increased pumpage on groundwater levels and instream flows, and (3) the quality of the groundwater supply and its vulnerability to current and potential future sources of contamination.

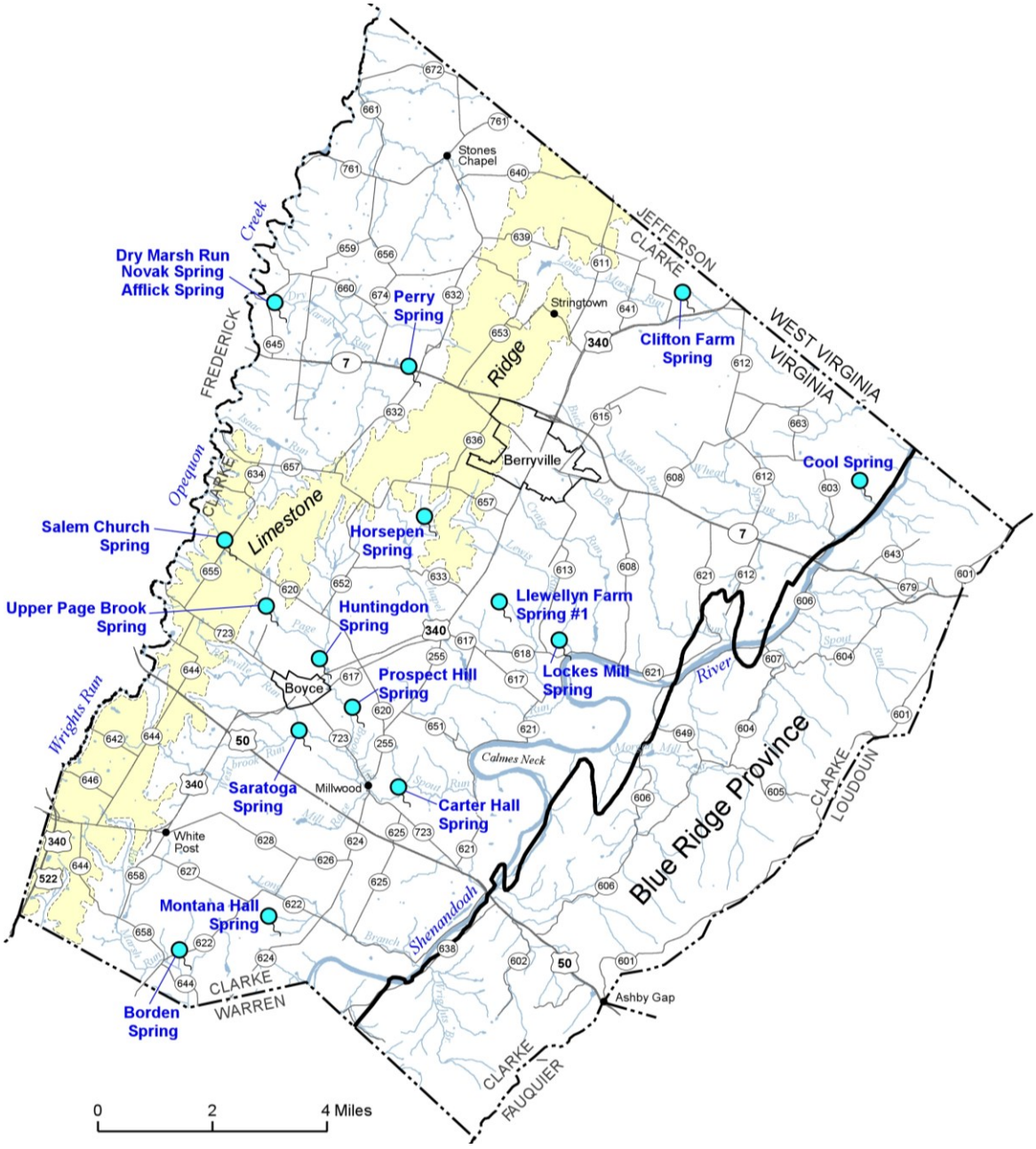


Figure 3.8.48 Map of larger springs studied by USGS in the Shenandoah Valley portion of Clarke County underlined primarily by carbonate rocks. Modified from Nelms and Moberg, 2010.



Figure 3.8.49 Burwell-Morgan Mill in Milwood is powered by Spout Run, the baseflow of which is reliably maintained by several large karst springs upgradient, even during the most severe droughts (Saratoga Spring, Huntingdon Spring, Prospect Spring, and Upper Page Brook Spring; see Fig. 3.8.50). The mill, with its elaborate original mechanism, is one of the oldest still operating mills in the country where visitors can buy a variety of flour types grinded in the old-fashioned way. The mill also serves as an art gallery and hosts two highly regarded annual art shows. https://www.clarkehistory.org/mill.html

The Shenandoah Valley portion of Clarke County is predominantly underlain by soluble carbonate rocks that form numerous karst features such as sinkholes, caves, springs, estavelles, swallet holes, periodic (ebb-and-flow) springs, and sinking streams. Less soluble siliciclastic rocks (sandstone, siltstone, and shale) underlie the western edge of the Shennandoah Valley section of the county. The Valley section of the county encompasses two major basins within the Potomac River watershed: Opequon Creek to the west and the Shenandoah River on the east. The drainage divide between these two basins is present in an area of the County that is frequently referred to as the Limestone Ridge. The Limestone Ridge is delineated as an area higher than the contour 630 ft above sea level (National Geodetic Vertical Datum 1929).

3.8.1 Thermal Karst Springs of Virginia

As explained by Lange (1973), seventy-two springs and groups of springs in the Appalachians of Virginia and West Virginia discharge thermal waters whose temperatures exceed 15°C (59°F) , at least part of the year. Most of the springs issue from Ordovician and Silurian carbonate rocks in anticlinal valleys of the Valley and Ridge and the Appalachian Plateau physiographic provinces. The center of the thermal activity is located in Warm Springs anticline (Allegheny, Bath and Highland Counties), where a chain of spas has utilized the waters for over 200 years.

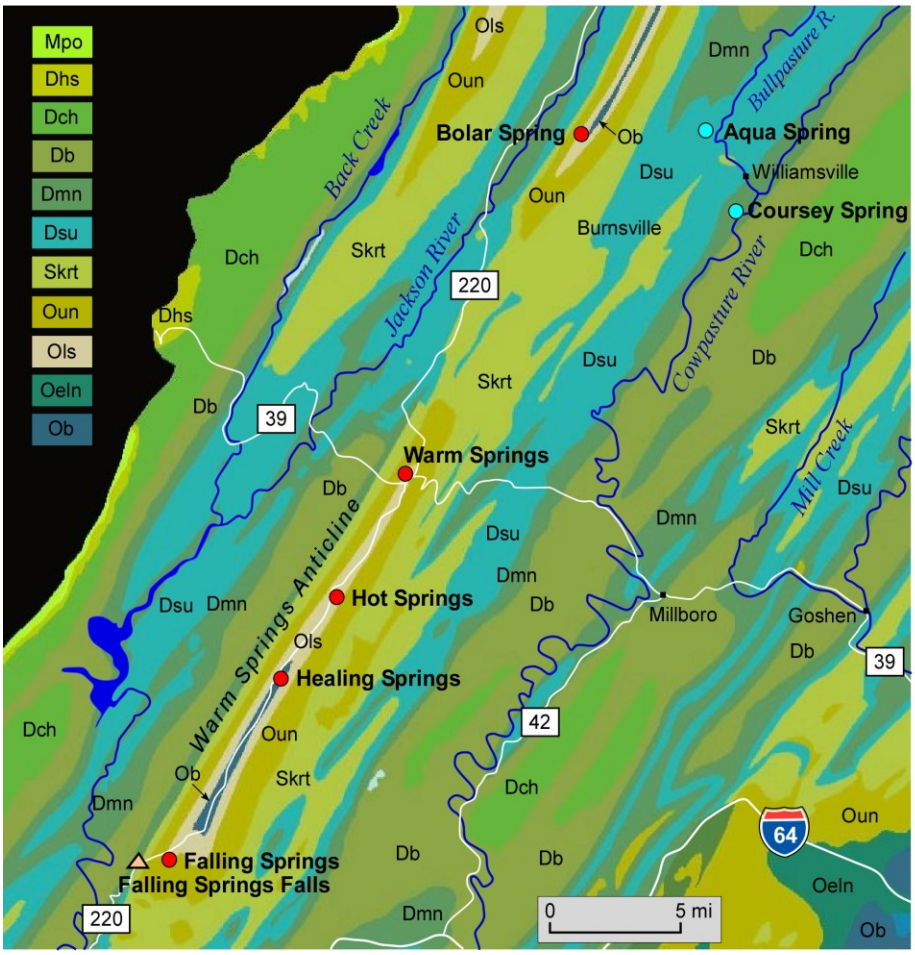


Figure 3.8.50 Geologic map of a wider area of the Warm Springs Anticline. From Virginia Department of Energy, available online at DGMR. Major thermal springs are denoted with red dots, major cold springs with blue dots. Geologic units, from youngest to oldest: Mpo: Mississippian Pocono Formation. Dhs: Devonian Hampshire Formation. Db: Devonian Brallier Formation; primarily shale. Dmn: Devonian Millboro Shale and Needmore Formation; primarily shale, with several carbonate intervals. DSu: Upper Silurian and Lower Devonian; primarily Helderberg, Keyser, and Tonoloway Limestone. Skrt: Silurian Keefer Sandstone, Rose Hill and Tuscarora Formations; primarily arenite. Oun: Ordovician Juniata, Oswego, Martinsburg and Eggleston Formation; primarily shale., Ols: Ordovician Mocassin Formation and Bays Formation; primarily limestone and shale. Oeln: Ordovician Edinburg Formation, Lincholnshire and New Market Limestones. Ob: Ordovician Beekmantown Group dolostone.

The Warm Springs Anticline has been eroded into an elongated northeast-southwest trending valley called Warm Springs Valley (Figs. 3.8.50 and 3.8.51). The oldest Ordovician strata exposed in the area, the core of the anticline, is the dolomitic upper part of the Beekmantown Formation (Lower Ordovician) which is flanked by the younger, mainly siliciclastic rocks on the limbs. Warm Springs Valley is the location of the only three known caves in the eastern United States with thermal waters flowing in some of their passages

The wider thermal area overlies an estimated 6-mile thick sequence of Paleozoic sediments laid down in the Appalachian eugeosyncline. Subsequent thrusting associated with the uplift of Blue Ridge Precambrian rocks to the east has contorted the beds into a series of parallel NE-SW-trending folds undercut by low angle decollements and splay faults dipping toward the southeast. Whether or not the underlying basement has experienced folding and faulting is yet to be resolved (Lange, 1973).

A number of regional geophysical anomalies centered around the thermal area suggest a causal relationship with the springs. These include an unusual thickening of the crust to 60 km (greatest in the U.S.), deduced from travel-time delays of seismic waves; broad gravity and magnetic lows; an absence of seismicity; and an extreme damping of response from distant earthquakes. In addition, geomorphic evidence points to an uplift of the Eocene erosion surface in the vicinity of the springs. The evidence is corroborated by the presence of outcropping volcanics of Eocene age (47 million years) at the north end of Warm Springs anticline. These are the youngest igneous rocks found east of the Mississippi. Dennison and Johnson (1971) conclude that a heated pluton underlies the area.

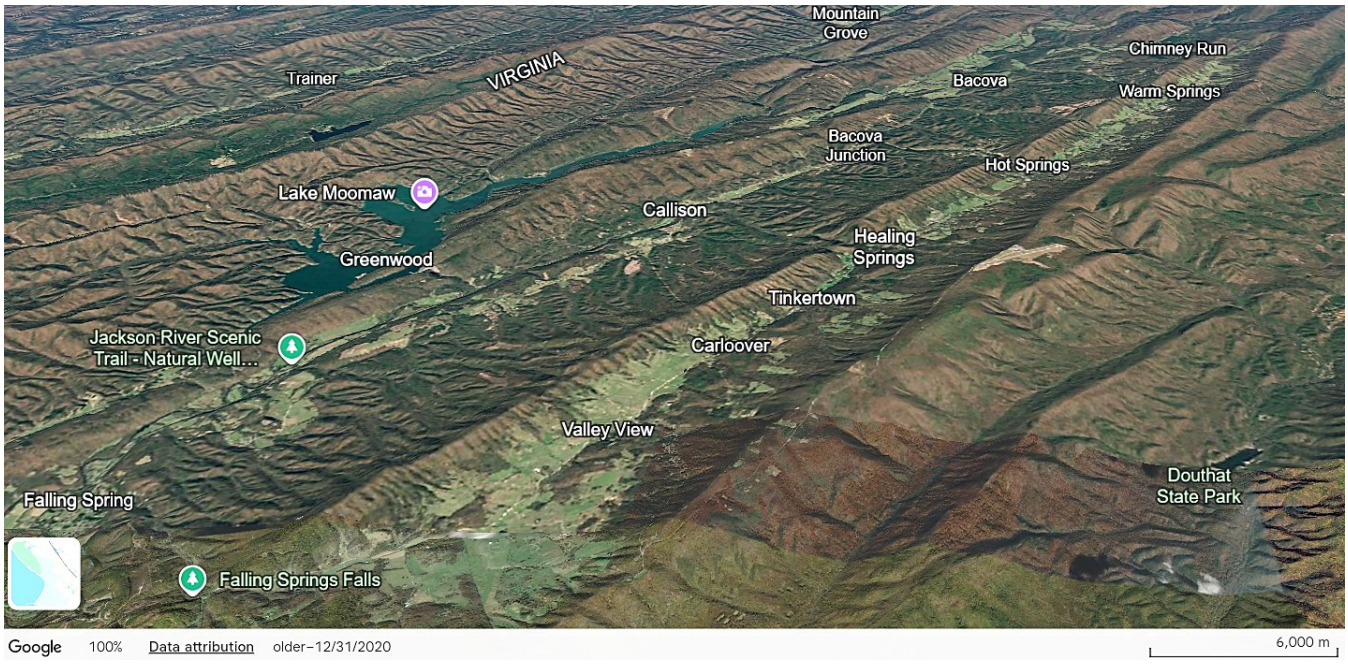


Figure 3.8.51 3D Google Earth image of the Warm Springs Valley and its surroundings.

Lange (1973) argues that examination of the consequences of crustal thickening leads to the deduction that, even under conditions of a typical low Eastern-type geothermal gradient (13°C/km), molten granite or partially molten basalt should be present below crustal depths of 35 to 45km. Local upward migration of magma in the past would account for the presence of the volcanic outcrops. Such ascendants today would result in localized heating of the subsurface and deeply penetrating groundwater. Rising magmatic waters may also contribute to the temperature and composition of the springs. The likely seat of a geothermal reservoir is the buried paleokarst of the dolomitic Ordovician Beekmantown formation which forms the core of the Warm Springs Anticline.

According to Lange (1973), the multiple lines of evidence at least suggest an alternative to the century-old explanation that the thermal groundwaters are heated by the normal geothermal gradient at depth, without abnormal heat sources being involved.

Hobba et al. (1979) note that the Virginia thermal springs are in valleys at or near the crests of anticlines, where any bedding planes open to depth would be expected to permit flowlines of upward moving water to converge at the crest of the anticline. Fig. 3.8.53 shows inferred paths of groundwater movement through the consolidated folded rocks, in a plane normal to the strike of the rocks and at a place where the anticline crest forms a topographic low. To complete the picture, add low angle thrust faults at depth, a vertical fault or fracture at the spring, and possibly a fault or fracture in the plane of the cross section. Any such factors would contribute to the development

of a system of conduits that permits groundwater circulation to great depths where hydraulic head is sufficient to drive the system. The overall flow system may look something like that in Fig. 3.8.53, but with much of the flow being into the plane of the figure along open tension fractures, bedding, or fault planes and upward beneath the spring. The occurrence of springs along the crests of anticlines in valleys or in water gaps in the Valley and Ridge Province of Virginia and West Virginia has been noted by various researchers previously. Clark et al. (1976) made statistical analyses of the yields of wells in various geologic and topographic situations. Working mainly with wells in limestone, they determined that yields along the axes of anticlines are significantly better than those along axes of synclines.

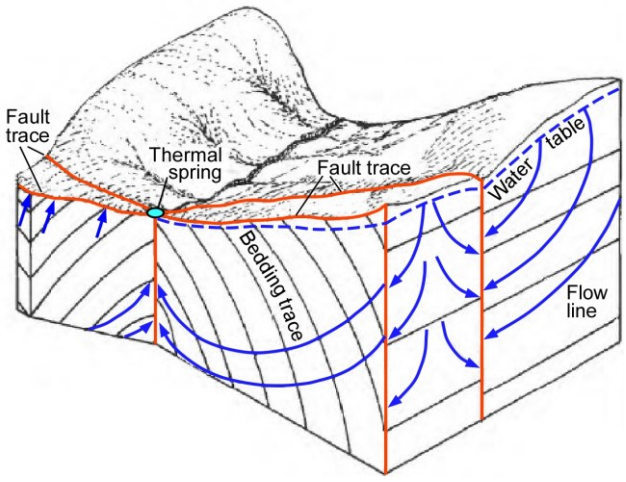


Figure 3.8.52 A cave in Virginia with thermal water where, a few decades ago, cavers liked to relax, often wearing only boots and helmets. Courtesy of Phill Lucas.

Thermal Falling Springs, Healing Springs, Warm Springs, Hot Springs, and Bolar Springs are all at or near the crests of two distinct anticlines—Warm Springs Anticline and Bolar Spring anticline (Fig. 3.8.50)—and flow from the Ordovician Lowville Limestone according to Hobba et al. (1979) who sampled the springs as part of a regional study. Two deep hot wells (#607 and #702) in the area were completed in the Lower Ordovician Beekmantown Group and drew water from elevations below those of nearby springs in the Lowville Limestone.

In Virginia, the Ordovician Lowville Limestone and Beekmantown group carbonates are related through a significant regional gap in the geologic record known as the Knox Unconformity. The Beekmantown Group forms a sequence of older, mostly Lower Ordovician dolostones and limestones.

The Lowville Limestone—a younger, Middle Ordovician unit belonging to the Black River Group—was deposited directly on the eroded surface of the Beekmantown. The Lowville Limestone (first named and described in New York), and Moccasin and Bays Formations in Virginia are related as lateral, time-equivalent facies (depositional variations) of the same Middle-to-Late Ordovician sedimentary system.



Samples from the thermal springs at Hot Springs and Warm Springs contain no tritium. Water from these springs was thus at least 20 years old in 1975. Tritium in the thermal springs at Bolar and Falling Spring was about 25 TU in 1975. If the tritium content of the thermal component of these springs is zero, the proportion of thermal (T) to shallow cool water is about 60% (Hobba et al, 1979).

Figure 3.8.53 Possible circulation of water to a warm spring located near the crest of an anticline at the intersection of two faults. Much of the flow is into the plane of the figure along open tension fractures, bedding, or fault planes and upward beneath the spring. From Hobba et al., 1979; modified for clarity.

Falling Springs, Alleghany County

The Warm Springs Anticlinorium in Alleghany County is a unique thermal karst system characterized by its complex geology and hydrogeological features which includes only three known caves in Virginia that contain thermal springs. Dye trace tests conducted on six sinking streams across the eastern and western limbs of the anticlinorium indicate a predominantly southwestward flow of groundwater. Specifically, traces from sinks on the western limb show a hydrologic connection with Rushing Waters Cave and Warm River Cave, eventually resurfacing at Falling Spring. However, the dye bypassed Mot Pot Cave, which is located almost directly between Rushing Waters and Warm River Cave. On the eastern limb, the dye also flowed southeastward ultimately reaching Warm River Cave and reemerging at Falling Spring. These findings suggest that the subsurface water flow from each sinking stream eventually connects within Warm River Cave and is influenced by the structural orientation of the anticlinorium. Moreover, the thermal waters in Mud Pot Cave and potentially Warm River Cave may be significantly older or sourced from different areas, highlighting the complex hydrogeology of this thermal karst system (Whitlock et al., 2025).



Figure 3.8.54 Falling Springs Falls. Courtesy of Zoran Stevanovic.

The waters from Warm River Cave discharge from rubble at the base of a hill of Ordovician limestone, 11 miles SW southwest of Hot Springs, at the southern end of Warm Springs anticline. Reeves (1932) reports a discharge as high as 7,000 gpm (15.6 cfs) in February of 1928. VDEQ spring database reports the following discharge characteristics in December 2012: flow rate of 1660.6 gpm (3.7 cfs) and temperature of 27.2 ^{o}C.



Figure 3.8.55 Falling Spring (in the past also referred to as the Warm River Cave Spring) is where water from Warm River Cave emerges. Warm River Cave is one of the longest known caves with thermal water in the country. The spring is shown during a dye tracing test (green color is from the dye released in the cave). After about 0.8 miles, the stream from the spring falls over 80 feet high travertine waterfall called Falling Spring Falls, shown in Figs. 3.8.54 and 3.8.56. Photo courtesy of William Jones.

The spring fills a small pond which flows out as a surface stream along the valley floor about 0.8 mi before plunging over a waterfall. The waterfall was naturally built of travertine formed by degassing of the thermal spring water (loss of carbon dioxide to the atmosphere) and the subsequent precipitation of calcium carbonate.

The volume of travertine was such that it was quarried for agriculture lime in the 1920's. To facilitate their mining operations and harness the water for a small hydroelectric power plant, the companies rerouted the creek and physically relocated the waterfall. This artificial diversion permanently cut into the landscape and reduced the modern plunge drop to roughly 80 feet.



In 1781, Thomas Jefferson personally surveyed the waterfall and famously detailed its impressive scale in his manuscript, *Notes on the State of Virginia*. He described it as a "remarkable cascade... falling over a rock 200 feet into the valley below." At the time, its dramatic drop made it even taller than Niagara Falls.

Figure 3.8.56 Falling Springs Falls. 1857 color lithograph on wove paper by German artist Woldemar Rau, after Edward Beyer.

Warm Springs, Bath County

The thermal springs called Warm Springs are in the town of Warm Springs, seat of Bath County, 93 miles west of Charlottesville via I-64 and VA-42S (VA-39), at the intersection of two major transportation routes: the north-south corridor of US-220 (Sam Snead Highway) and the east-west corridor of VA-39 (Mountain Valley Road). Warm Springs Bath Houses (Gentlemen's and Ladies' Pools) were listed on the National Register of Historic Places in 1969.



All who have described this noble fountain, write with enthusiasm; nor is it indeed to be wondered at, for the world may well be challenged for its equal. Its temperature, buoyancy, refractive power, transparency – all invest it with indescribable luxury to the feelings and to the sight.

William Burke

Figure 3.8.57 Edward Beyer's print of Warm Springs published in 1857. The largest building is the Warm Springs Hotel which served as a Confederate Hospital from July 1861 until June 1863.

The history of Warm Springs from the very beginning is explained in detail in the updated nominating form for a listing in the National Register of Historic Places which was approved in 2019.

Here is just one of many interesting details that abound in the nominating form:

At the Warm Springs, many went to their own cabins to cool down: in the same document, Prolix advised visitors how to handle the Warm Springs bath: Stay in the bath fifteen minutes, using very little exercise whilst in the water. As soon as you come out, hurry to your cabin, wrap yourself in a dry night-gown, go to bed, cover up warm, go to sleep, get into a fine perspiration, grow cool by degrees, wake up in half an hour, dress and go to dinner with what appetite you have.

Equally resourceful is a collection entitled *Medicinal Springs of Virginia in the 19th Century* housed at Historical Collections at The Claude Moore Health Sciences Library, University of Virginia.



Figure 3.8.58 The Warm Springs thermal spa pools were completely renovated in 2022-2023. Both pools are open to public for a fee. Reservations are required well in advance because of a great deal of interest from out-of-state and international tourists boosting the local economy. Ladies' Pool is on the left, Gentlemen's Pool is on the right.

Reeves (1932) lists the following for the Warms Springs discharge characteristics, based on 3 measurements in 1928: combined flow rate of Ladies' and Gentlemen's Pools – 1,000 to 1,200 gpm; water temperature – 94 to 96.2 ^{O}F. VDEQ springs database lists 1,377.82 gpm (3.07 cfs) for the flow measurement taken in August 2011, directly west of Bath County information kiosk at confluence of both spring houses and surface drainage that might have contributed 1-5 gpm.

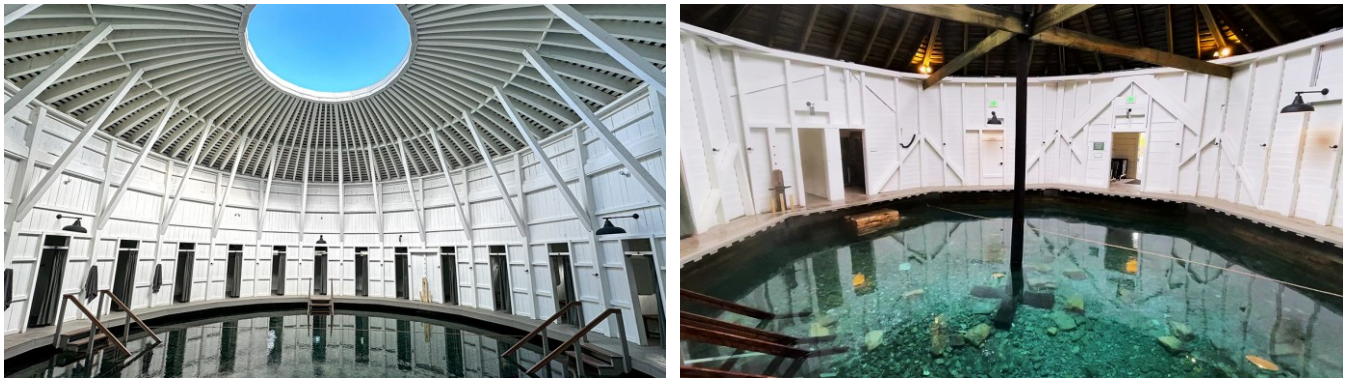


Figure 3.8.59 Ladies' Pool (left) and Gentlemen's Pool (right) at Warm Springs. Left photo courtesy of Omni Homestead (https://www.omnihotels.com/hotels/homestead-virginia/wellness/warm-springs-pools).

Hot Springs, Bath County

Thermal springs in the town of Hot Springs are on the property of Omni Homestead Resort, about 5 miles southwest of the town of Warm Springs via US-220. The Homestead, together with the thermal springs, was listed on the National Register of Historic Places in 1984. In the nominating form for the listing, one can read the following:

"The Homestead is one of the finest resort hotels in the nation. Situated at Hot Springs, Virginia in the Alleghany Mountains, the Homestead provides luxurious accommodations, excellent cuisine, and beautiful natural scenery for its internationally famous guests. Although the present hotel dates from the first decades of the twentieth century, the Homestead had its beginnings in the mid-eighteenth century as a health resort. As early as 1766, a small hotel, also known as the Homestead, was built to accommodate travelers who visited Hot Springs hoping to procure health from the thermal springs.

As a health or pleasure resort, Hot Springs suffered in competition with nearby Warm Springs until the hotel was purchased by Dr. Thomas Goode in 1832. Dr. Goode was responsible for promoting the resort chiefly as a health spa by placing large ads in popular periodicals of the day such as Mr. Godey's Lady Book and Harper's Weekly, claiming the waters at Hot Springs were recommended for any number of maladies from gout to spinal irritations.

During the first half of twentieth century, the Homestead enjoyed a national reputation as an outstanding year-round resort. It received additional notoriety as the site of the International Food Conference in 1943. This conference, attended by representatives of forty-four countries, can be regarded as a precursor to the later founding of the United Nations.

The Homestead has attracted many of America's most prominent twentieth-century citizens including Henry Ford, John D. Rockefeller, Paul Mellon, Mrs. William K. Vanderbilt, and Mrs. Cornelius Vanderbilt, the famed New York City social queen, who made the Homestead her summer headquarters in the 1930s. All but three twentieth-century American presidents have been guests at the Homestead."



Figure 3.8.60 The Hot Springs resort was drawn by Porte Crayon in 1857. The large hotel, the Homestead, was built by Dr. Thomas Goode in 1846. Courtesy of *Medicinal Springs of Virginia in the 19th Century*, Historical Collections at The Claude Moore Health Sciences Library, University of Virginia.

https://wayback.archive-it.org/18731/20250701185013/https://exhibits.hsl.virginia.edu/springs/



Figure 3.8.61 Omni Homestead Resort in 2024. Courtesy of The Omni Homestead Resort.



Figure 3.8.62 *Left*: Famous Octagon Pool Spring before it was redesigned by Omni Hotels and incorporated into a modern pool facility. Text on a metal plate by the former spring pool read: "*The Octagon Pool enjoys the longest recorded history of the many natural mineral springs that abound throughout our mountains and valleys. Native Americans began appreciating its virtues some nine thousand years ago as they explored, hunted, fished and relaxed among the forests, rivers and meadows. Colonial surveyors and settlers found it to be a perfect source of relaxation after arduous journeys. The Octagon Pool was our original soaking pool, and in Colonial times, Homestead guests simply walked up to it, disrobed and enjoyed "taking the waters." The modesty of Victorian times brought an end to that practice, and The Octagon Pool became an attraction of purely historic interest. We invite you to divest yourself of the bonds of shoes and socks, and soak your feet in its soothing waters.*" *Right*: Former historic Octagon Pool was (unfortunately) torn down and converted to a modern octagon-shaped pool shown in the center right. Photo courtesy of https://wanderlust-tours.com/spa-omni-homestead/



Figure 3.8.63 *Spring on the Left*: "The Boiler Spring's naturally hot mineral waters have made The Homestead internationally renowned as a Spa Resort since 1766. These clear waters emerge from deep beneath the earth, flowing constantly at 105°F year-round, and have been greatly favored for their "curative" powers. In 1832 Dr. Thomas Goode began to direct these waters into pool houses through underground pipes made of hollowed-out Chestnut logs. This natural, thermal spring water continues to be conveyed underground to our historic Spa, where it provides today's Homestead guests with the very same absolute relaxation that was described by a noted physician in 1867 as "exceeding all expectation." (Text on metal plaque by the spring). *Spring on the Right*: "Hot Sulphur Spring. The crystal waters of this natural mineral spring are actually warm, rather than hot as its name suggests. They flow constantly at 97° F, and enjoy a mild Sulphur content, which made them popular for both bathing and as a drinking spring. From the earliest recorded uses of springs in America, through the early 20th century, physicians routinely advised patients to drink certain types of waters, as well as soak in them. Although consuming warm sulfur water is no longer popular, this spring house will help you enjoy the heritage of Taking the Waters at The Homestead, a tradition that began in 1766." (Text from metal plaque by the spring).

Measurements performed in 1928 at 7 individual springs at Hot Springs (Table 3.8.1; Reeves, 1932) show that the combined average flow rate of all springs is approximately 500 gpm, and the temperature varies between 72.2°F (Soda Spring) and >90°F for all other springs. Boiler Spring is the hottest (104.9°F) and the most prolific (168 gpm).

Table 3.8.1 Portion of Table 4 from Reeves (1932) which shows individual springs at Hot Springs with date of sampling, flow rate in gallons per minute, and temperature in degrees Fahrenheit. From Lange and Andrews-Jones, 1973.

Octagon Spring, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22, 1928	67	95.1°
	Sept. 12, 1928	67	98.6°
	Nov. 2, 1928	67	98.6°
Boiler Spring, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22, 1928	168	104 °
	Sept. 12, 1928	168	104.9°
	Nov. 2, 1928	168	104.5°
Hot Sulphur Springs, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22, 1928	40	97.3°
	Sept. 12, 1928	40	98.5°
	Nov. 2, 1928	40	97 °
Magnesia Spring, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22, 1928	30	95.8°
	Sept. 12, 1928	30	96.5°
	Nov. 2, 1928	30	95.9°
Spout Spring, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22, 1928	36	103 °
	Sept. 12, 1928	36	105 °
	Nov. 2, 1928	36	105.8°
Soda Spring, Homestead Hotel, Hot Springs, Bath Co.	Dec. 4, 1928	140	72.2°
Warm Spring, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22, 1928	15	90 °
	Sept. 12, 1928	15	91.8°

Bolar Spring, Highland County

Bolar Spring is in the village of Bolar, about 18 miles northeast of Warm Springs via Route 220, and a short distance to the east on local State Route 694. The spring is in Little Valley, right at the border with Bath County.

The Little Valley resides in the axis of the breached Bolar Anticline, which is bordered to the southeast by Jack Mountain and to the northwest by Little Mountain. The karst bearing units in the valley include the Ordovician Moccasin and Bays formations which are present along the central portion of the axis of the anticline, and the overlying Dolly Ridge and Eggleston Formations which are the western equivalents of the Lower Martinsburg and Edinburg Formations (GeoConcepts Engineering, 2017). Large discharge of the spring is likely facilitated by the prevailing fracture sets, perpendicular to the axis of anticline (Fig. 3.8.64). Notably, the Bolar Anticline is on strike with the Warm Springs Anticline to the south (see Fig. 3.8.50).

From 1949 to 1955 flow and temperature measurements were made at Bolar Spring by the Virginia District of the U.S. Geological Survey. Figure 3.8.65 shows that there is generally an inverse relationship between discharge and temperature. This indicates that the spring water probably is a mixture of deep circulating warm water and shallow circulating cool water.

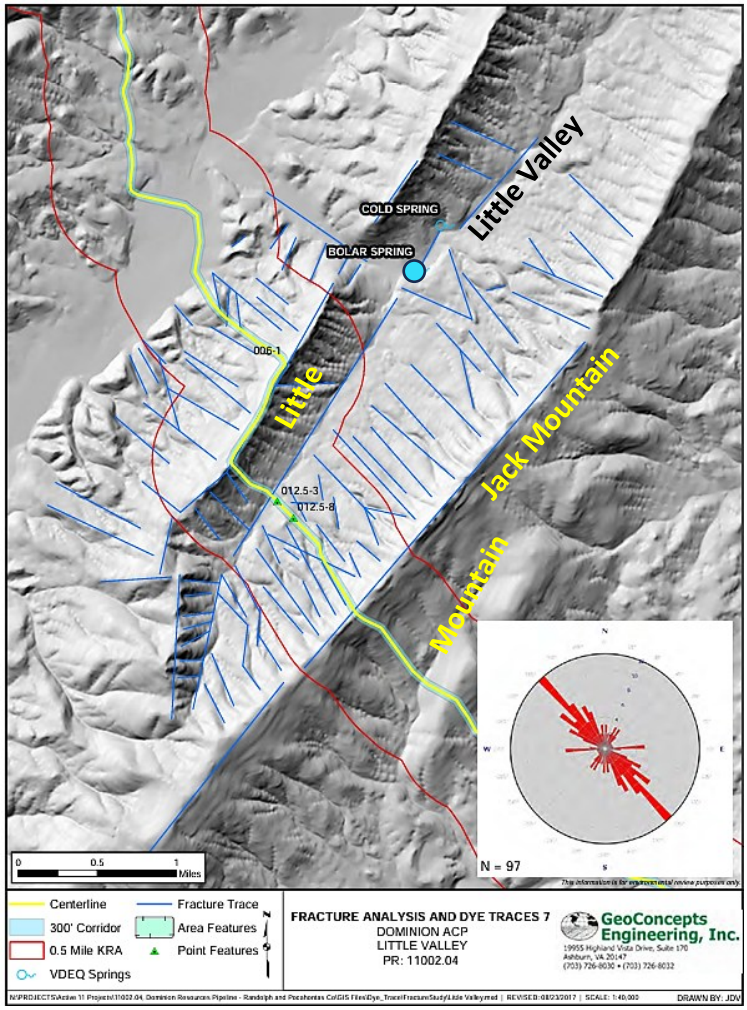


Figure 3.8.64 Map showing location of Bolar Spring (large blue dot) and fracture traces for the Little Valley section of Atlantic Coast Pipeline. From GeoConcepts Engineering, 2017, geographic annotation added.

As pointed out by Hobba et al. (1979), an impressive amount of heat is carried to the earth's surface and released by the thermal springs of Virginia. Computations based on flow and temperature data show that the heat released at larger but cooler springs such as Falling Spring and Bolar Spring, is much greater than that released at smaller but warmer springs such as Hot Springs. Since the discharge at these cooler springs is a mixture of warm and cold water, the components of hot water must be either larger or hotter than that emerging at the smaller warmer springs.

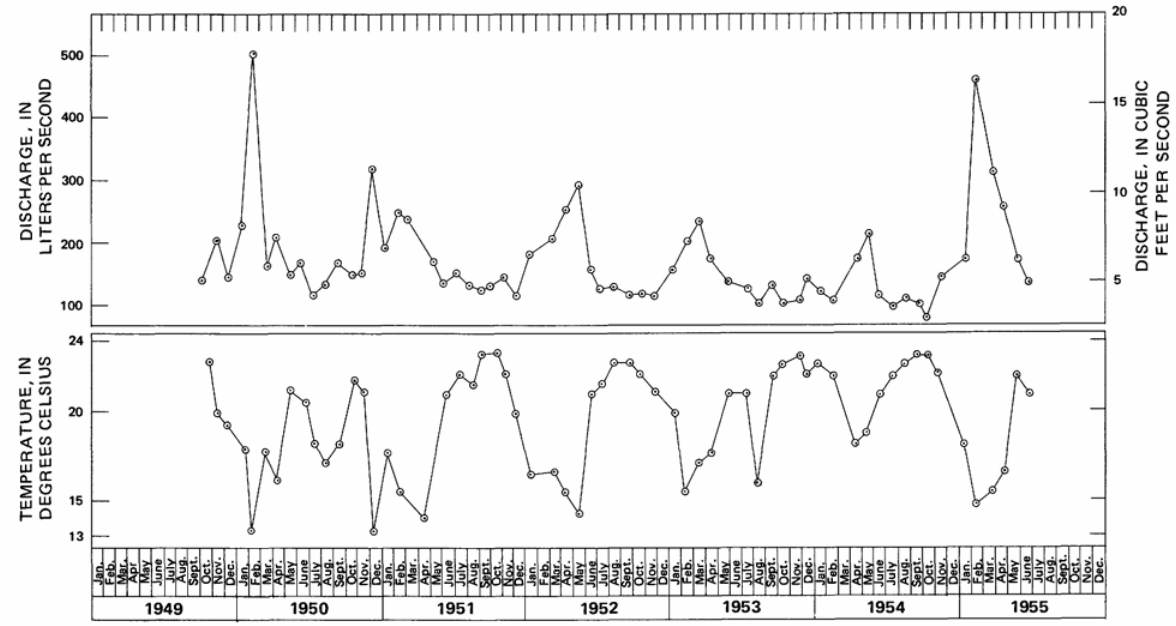


Figure 3.8.65 Temperature and discharge measurements at Bolar Spring. From Hobba et al., 1979.



Figure 3.8.66 Bolar Spring.

3.9 West Virginia

As explained by William Jones in his seminal publication *Karst Atlas of West Virginia* (Jones, 1977), followed by *Hydrology of the Greenbrier Karst* (Jones, 2018), the most spectacular karst and cave features in West Virginia have formed in the Mississippian Greenbrier Group limestones. Studies of the karst drainage systems of the Greenbrier limestone began in the early 1960s and were the first to make extensive use of water-tracing techniques and cave mapping in the United States. The carbonate aquifer is about 400 ft thick in the Swago Creek area west of Marlinton (Pocahontas County), increasing to 1000 ft in southern Monroe County. The basic hydrogeologic setting for the region consists of relatively flat-lying limestones exposed in valleys or plateaus and surrounded by higher elevation clastic units. Recharge to the conduit aquifer system is by capture of surface streams originating on the clastic rocks (allogenic recharge) and water infiltrating through the extensive areas of sinkholes (autogenic recharge). Only a few surface streams cross the carbonate outcrop, and even these tend to lose water into the karst drainage systems. Much of the flow through the aquifer is through conduits under open channel conditions much like a surface stream with a roof. Discharge is concentrated at large springs that typically display rapid response to storm events, and the ratio of maximum to minimum discharge exceeds 100:1 for most of the springs.

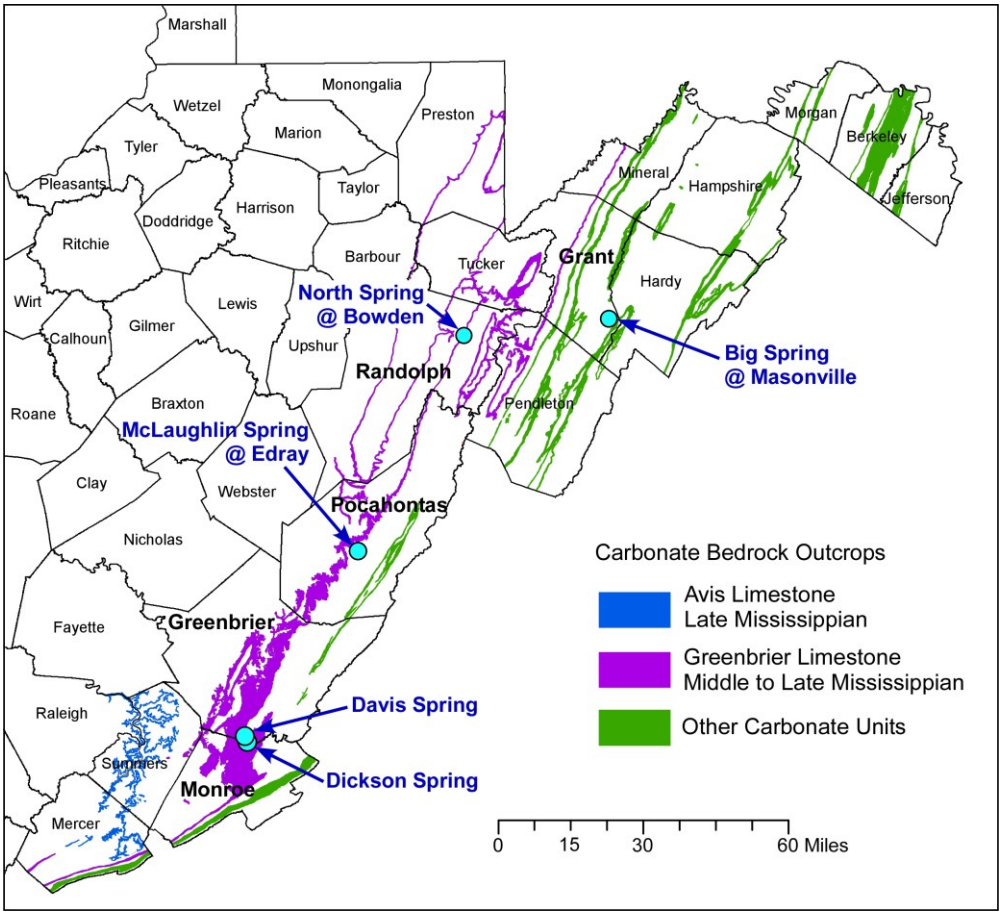


Figure 3.9.1 Map of carbonate bedrock outcrops in West Virginia with locations of largest karst springs in the state. Principal karst-forming carbonate rocks in West Virginia are within the Mississippian Greenbrier Group (purple color); Devonian and Silurian Helderberg Group and Tonoloway Limestone; and Cambrian and Ordovician Tomstown Dolomite, Elbrook Formation, Conococheague Formation, Beekmantown Group, Saint Paul Group, and Black River Group (green color). Based on recent geologic mapping in southern West Virginia, the Mississippian Avis Limestone, also known as the Little Stone Gap, can be added to this list (blue color). Modified from Hohn et al., 2017.

The karst caves and conduits are generally decoupled from surface topographic features, and the patterns of mapped cave passages are influenced by structural and stratigraphic characteristics. Insoluble beds within the Greenbrier Group may perch underground streams well above the apparent base level, and the underlying Maccrady Shale acts as an aquitard with several large caves developed along the contact of the shale and the overlying limestone. Much of this area can be considered a "contact karst" with the clastic rocks delivering concentrated recharge water onto the soluble limestones and the underling shales eventually forcing the return of conduit flow to the surface. The available data on water wells in the limestone suggest that most are actually producing from shaley units with the limestones acting as confining beds.

The Greenbrier River and its tributaries represent base level for most of the area, and the relief of several hundred feet provides the hydraulic gradient. The area is underdrained by a well-integrated network of caves.

The oldest carbonate units in the state are the Cambrian and Ordovician limestones and dolomites which are exposed in a synclinorium in the Shenandoah Valley in Jefferson and Berkeley Counties. A total carbonate thickness of almost 10,000 feet is exposed in a highly folded and faulted setting. The very high-density fracture pattern of these rocks encourages a fracture-diffuse flow aquifer and karst and cave development is rather limited in this part of the Shenandoah Valley. Ordovician carbonates also crop out on the eroded crest of the Wills Mountain anticline in Germany Valley, Pendleton County, and along the southeastern border of the state in Monroe and Mercer Counties. The higher relief in these areas has provided a more favorable setting for cave and karst development than found in the lower relief areas of the Shenandoah Valley. Silurian and Devonian carbonates are exposed in Pendleton, Grant, Hardy, Mineral, Hampshire, and Morgan Counties, and in the eastern parts of Greenbrier, Pocahontas, and Monroe Counties. Some of the limestone units are highly cavernous, but their outcrop areas are frequently well above present base level and little data are available on the properties of these units as aquifers. Several of these formations are thin bedded with a high percentage of clay that limits the potential for solutional development (Jones, 1977).



The Greenbrier River and its valley follow the distinct geological hinge line separating two provinces—the Valley and Ridge Province lies directly to the east, while the Appalachian Plateau Province stretches to the west.

Figure 3.9.2 Greenbrier River.

Geologists often place the karstic Greenbrier Limestone outcrop in a specific sub-zone called the Folded Plateau or the Allegheny Mountain Section. This zone features the broad, open, gentle folds typical of the Appalachian Plateau's eastern edge rather than the tightly compressed, sharply folded, and faulted rock layers that strictly define the Valley and Ridge Province.

Because it acts as a transition point, the region shares characteristics of both provinces. The Valley and Ridge limestone has eroded into a rolling, low-lying fertile valley floor bound by sharp mountain ridges to the east, mimicking standard Valley and Ridge topography. The Appalachian Plateau rock layers dip very gently to the northwest (usually less than 10 degrees), retaining the structural flatness characteristic of the plateau. This specific intersection of slightly folded carbonate rock and heavy rainfall is exactly what allowed the Greenbrier Karst to develop, creating the densest concentrations of massive cave systems in West Virginia, together with numerous sinking streams, springs, and large sinkhole areas (White, 2018).

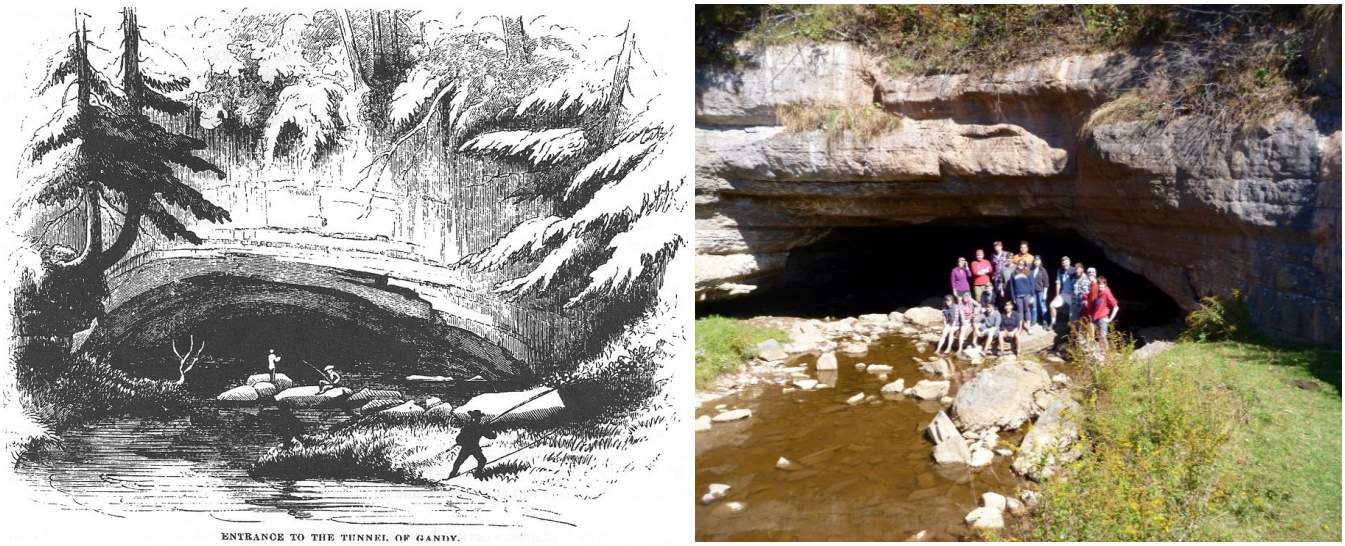


Figure 3.9.3 *Left*: "Tunnel of Gandy", now called Sinks of Gandy Creek, is in eastern Randolph County, near the ghost town of Osceola. Illustration from Strother, David Hunter, "The Mountains", Harper's New Monthly Magazine, 46:669-675, 1873. *Right*: Sinks of Gandy Creek. Photo courtesy of Professor David Goodwin, Department of Geosciences, Denison University, Granville, Ohio. https://personal.denison.edu/~goodwind/



Figure 3.9.4 *Left*: A caver stands in the main underground stream in the Culverson Creek Cave System (CCCS). *Right*: The famous Culverson Log Jam. Photographs courtesy of Phil Lucas. CCCS has a total surveyed length of 21 miles and a depth of 300 feet. CCCS is listed on The West Virginia Speleological Survey's West Virginia Significant Cave List for history, recreation, aesthetics, geology, biology, hydrology, paleontology, length and depth. CCCS is the premier water cave in West Virginia and is the main drainage for a surface basin of over 42 square miles. The passages range from large trunk to small crawls and vertical drops. The cave is very susceptible to flash flooding so watching the weather is imperative. The Wild Cat Entrance to the Culverson Creek System is owned and managed by West Virginia Cave Conservancy. It is maintained in an "open" condition to visitors, regardless of any organizational affiliation. https://wvcc.net/wildcat/



Figure 3.9.5 *Left*: Karst spring in Greenbrier County. *Right*: Sinking stream and cave at the end of a blind valley in Greenbrier County.



Figure 3.9.6 Greenbrier limestone karst features. *Left*: Typical sinkhole. *Right*: Sinkhole (front) and karst window.



Figure 3.9.7 *Left*: Beautifully decorated Lost World Caverns near Lewisburg offers self-guided tours. *Right*: Silurian Tonoloway Formation Limestone south of Franklin on Rt. 220

Davis Spring, Greenbrier County

The privately owned Davis Spring is the only first-magnitude spring in the Eastern United States outside Florida. The spring drainage area of approximately 73 square miles is entirely in Greenbrier County (Fig. 3.9.7) and contains one of the most developed karst terrains in the country. The only surface water perennial stream in the drainage area is Milligan Creek which originates in the Richland area, flows for 6.8 miles and sinks into the karst, only to surface again at the Davis Spring. Water from the spring flows along an unnamed surface channel for about 1200 feet before emptying into the Greenbrier River.

As explained by Tudek (2010) in a master's thesis which remains the definitive work on the hydrogeology of Davis Spring, Milligan Creek parallels the eastern slope of the mountain, receiving discharge from the mountain as it progresses towards Davis Spring. At any given point in location or time Milligan Creek can either flow on the surface, completely underground or a combination of both. This gives Milligan Creek a disjointed appearance. At approximately 6 mi north of Davis Spring, Milligan Creek sinks in its bed a final time, leaving only a paleo-channel on the surface. This paleo-channel is clearly traceable until it joins with the Davis Spring channel less than 50 meters downstream. Under flood conditions, the sinking point is unable to accommodate all the water from Milligan Creek and the channel backs up into a long lake, for hours or days.

Other surface drainage in the basin comes from allogenic water to the east flowing off clastic deposits and into integrated, explorable cave systems. The largest of these feeds a cave called Maxwelton Sink Cave which is at the downstream end of a very large blind valley at the base of 100+ feet high cliff. Dozens of miles of cave passages have been mapped in the eastern portion of the drainage basin.

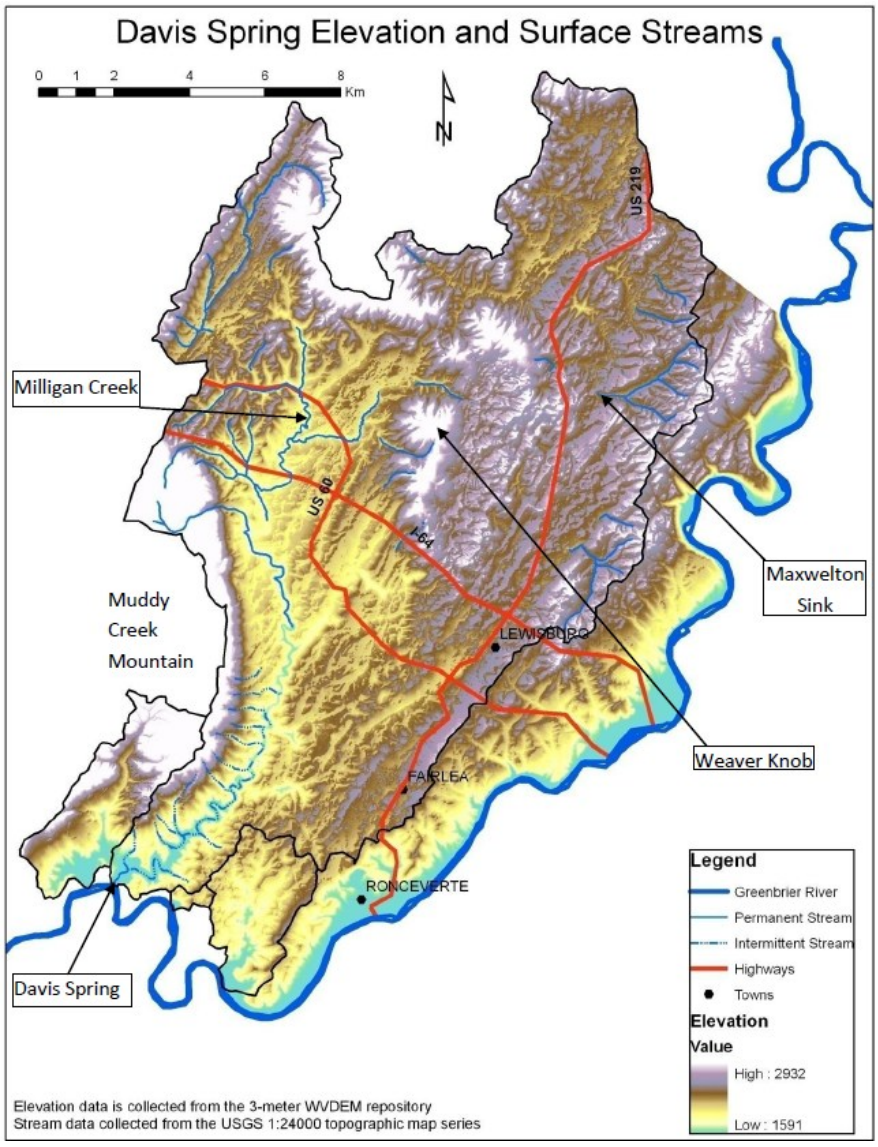


Figure 3.9.7 Elevation and surface streams of the Davis Spring and some surrounding basins. Milligan Creek is the drainage in the upper left. The paleo-Milligan Creek drainage is indicated by dashed lines in the lower left. Drainage feeding the contact caves is in the upper right, with Maxwelton Sink identified. Weaver Knob is the high peak in the center. Meandering Greenbrier River is in the east. From Tudek, 2010.

Some of the more telling points in Tudek's thesis include references to previous investigations performed by other researchers and the USGS. For example, William Jones , in conjunction with others, traced several routes of groundwater flow in the 1960s and 1970s, providing rough estimates for tracer travel time from different locations to Davis Spring (Jones, 1997). These investigations also established the basic shape and size of the drainage basin. In the early 1960s, a USGS staff gauge was placed a few hundred feet downstream from the spring. Jones measured stages at the spring in 1972 and 1973 at regular intervals. Discharge measurements by Jones and others placed the average flow of the spring at 110 cfs (Jones, 1977). Peaks of over 1000 cfs were estimated based on stage–discharge relationships and occurred most frequently during the winter – spring months. However, the actual peaks were lost as the USGS arbitrarily cropped the peak flow at 1000 cfs (Jones, 2009; see graph in Figure 3.9.8). Jones estimates that the highest flow may have approached 2000 cfs during that year (Jones, 2009, personal communication).

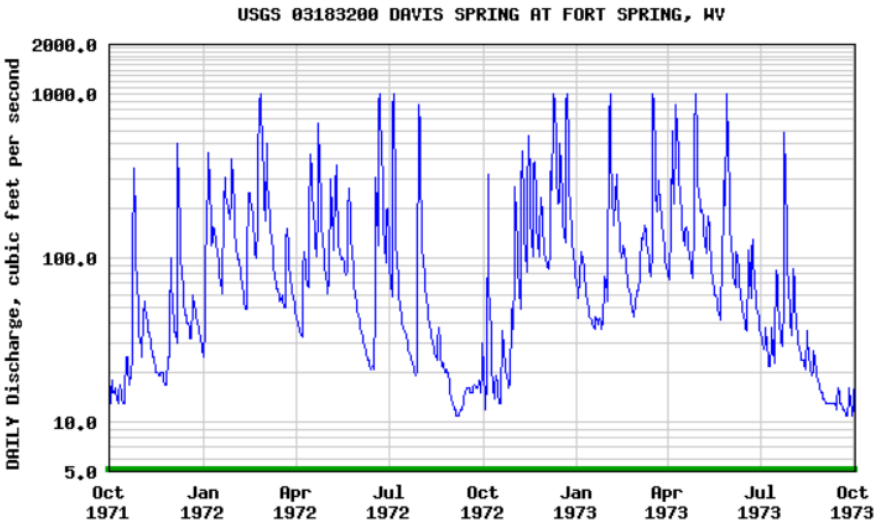


Figure 3.9.8 Daily discharge rate of Davis Spring, West Virginia for the period of record. The average is 124.6 cfs, with a minimum of 11 cfs and maximum >1,000 cfs (the graph is truncated at 1,000 cfs for reasons that are not clear.)



Figure 3.9.9 Aerial photograph of Davis Spring during high flow conditions and muddy water; Greenbrier River is in the lower left; photo courtesy of William Jones.

As explained by Tudek (2010), datalogger evidence and tracer tests both suggest that most of the Davis Spring conduit system must have open flow throughout most of the year. The Davis Spring basin is a particularly flashy system. During fieldwork, discharge at Davis Spring was as high as 30 m^3/sec (January 2009) and as low as 0.4 m^3/sec (August 2008). Throughout the entire study hydrograph peaks at Davis Spring were sharp and tall. Consistent with an open flow system, tracer travel times from Milligan Creek to Davis Spring decreased substantially from the dry season (246 hours in August 2008) to the wet season (96 hours in March 2009).

The Davis Spring basin is underlain by Mississippian age carbonates and clastics, most notably the Greenbrier Group. These strata generally dip gently to the northwest between 5 and 10 degrees, except at faults or near folds. Where these structures are present, the local dip can be steeper, frequently more than 45 degrees. The Greenbrier Group in the basin are a thick accumulation of limestone of the middle Mississippian age. It corresponds in age to the massive limestones in the Mammoth Cave region as well as the limestones in Indiana (Bennison, 1989).



Figure 3.9.10 Davis Spring during average flow conditions, November 2024.

Dickson Spring, Monroe County

Dickson Spring, with a drainage area of 24.68 square miles, is the largest of all karst springs in central Monroe County. High flows of up to 107 cfs were observed during 28 sampling periods in 1974-1975 but flows much higher than this probably occurred. The lowest flow observed was 6.6 cfs and the mean was 30 cfs (Ogden, 1976).

Dickson Spring emerges at the base of a cliff in Middle Mississippian Patton Limestone of Greenbrier Group, on the western limb of the Hurricane Ridge syncline where the beds are dipping 13 degrees to the southeast. The spring flows from a pile of rock debris, but during high flow also boils up from a pool in front of these rocks. There is no cave entrance that allows exploration of the spring system from its place of emergence.

The drainage basin features at least eight significant caves, with passages developed in the Patton, Sinks Grove, and Hillsdale limestone units. At least five sizable insurgences have been traced to Dickson Spring. Many other

smaller insurgences are assumed also to emerge at this spring. The insurgence at Rehobeth Church was traced by W.K. Jones (oral communication, 1973) during low flow (September 1972); it took 19 days to travel 7.3 miles, assuming a straight-line distance (Ogden, 1976).

Based on comprehensive, bi-weekly chemical analyses of the spring over a 13-month period, Ogden (1976) concludes that Dickson Spring is a deep system with a large basin that has the most constant seasonal chemistry and water temperature of all the other springs investigated in the central Monroe Karst. The spring is usually undersaturated with respect to calcite and has relatively higher amounts of dissolved dolomite from insurgent streams. It is also probably primarily phreatic (it has closed conduit flow).

The spring shares its name and location with the historic Spring Valley Farm, widely known as the Richard Dickson Farm, along U.S. Route 219 and Second Creek, just outside Union. Settled in 1776, the Dickson family farm features a 1793 log cabin and an 1837 brick extension. The home once served as a stagecoach stop for travelers visiting nearby 19-century healing spring resorts. The working agricultural property is permanently protected via a conservation easement held by the West Virginia Land Trust, ensuring the pristine nature of the Second Creek headwaters is preserved. Because the spring and the surrounding basin lie on private working farmland, access is restricted.

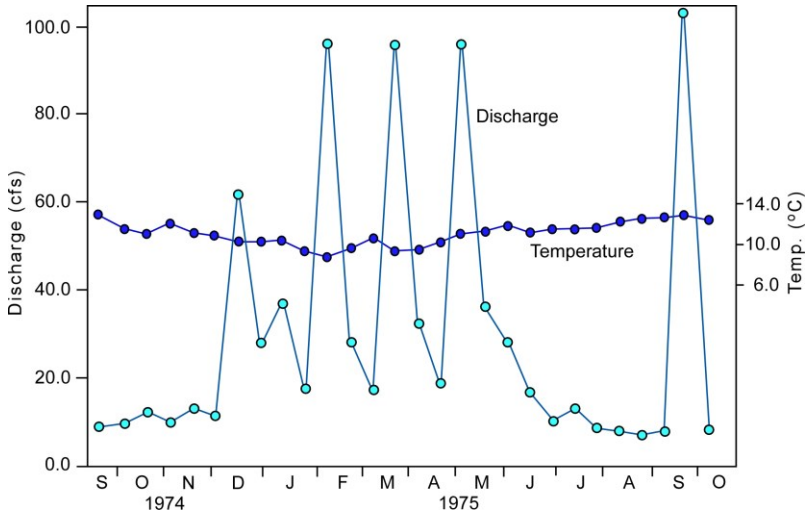


Figure 3.9.11 Bimonthly measurements of discharge rate and temperature for Dickson Spring. Modified from Ogden, 1976.



Figure 3.9.12 Aerial photograph of Dickson Spring's short run flowing to Second Creek on the left. Courtesy of William Jones.

McLaughlin Spring and Averill Spring, Pocahontas County

McLaughlin Spring and Averill Spring (sometimes spelled Avrill), located just up the road from Marlinton, are captured for the water supply of Edray State Trout Hatchery. In this area the entire sequence of the Mississippian Greenbrier Group limestones is exposed in valleys in the Edray and Clover Lick Creek areas of central Pocahontas County. Most runoff from the area originates as streams draining from the higher surrounding clastic rocks. Most of the subsurface flow routes underdrain the surface valleys, and the average hydraulic gradients are generally higher than found in other West Virginia karst areas (Jones, 1977).

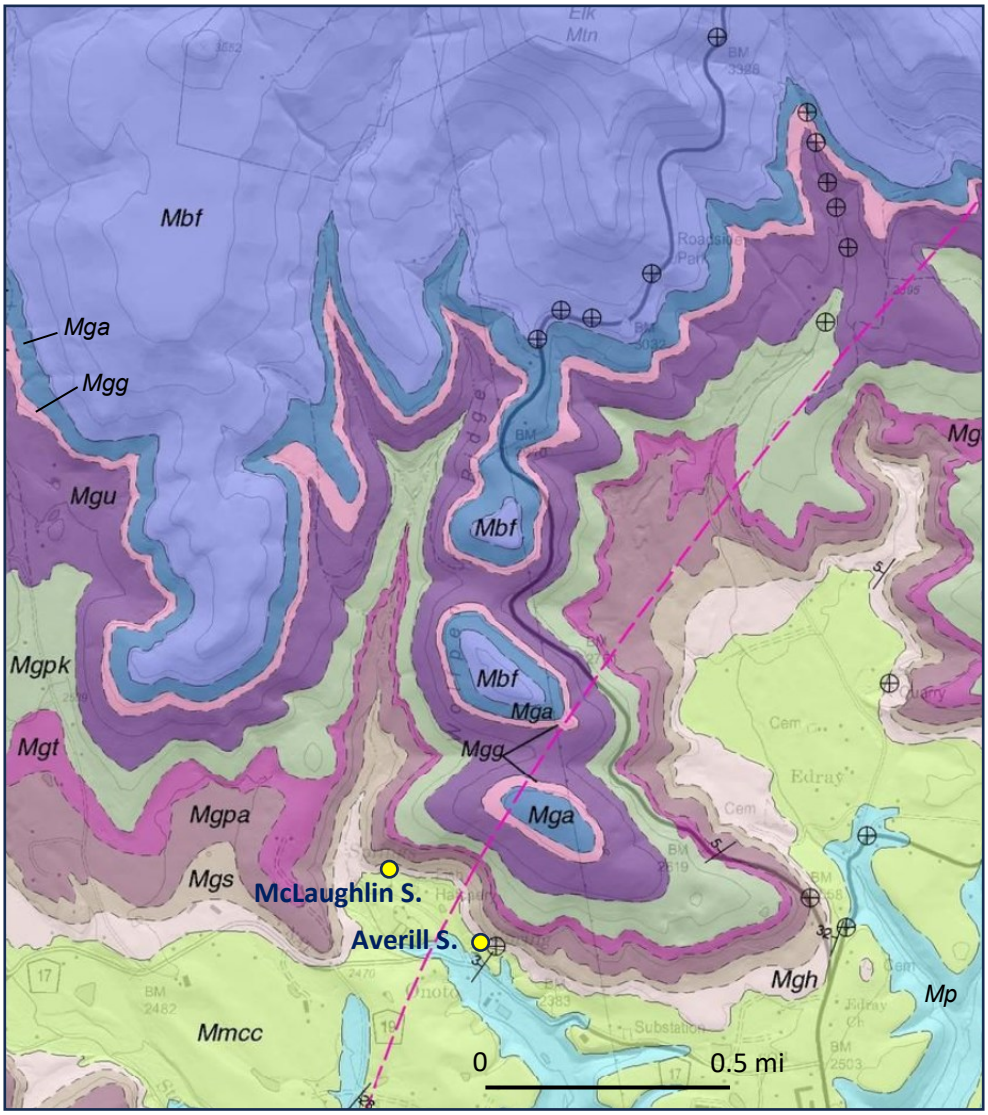


Figure 3.9.13 Part of bedrock geologic map of the Edray 7.5' Quadrangle, West Virginia, in the vicinity of McLaughlin and Averill Springs. From Hunt et al., 2019, West Virginia Geological and Economic Survey. Bedrock units from youngest to oldest: *Mbf*: Bluefield Formation (730-800 ft); shales and mudstones. Mississippian Greenbrier Group (450-500 ft total): *Mga*: Alderson Formation limestone. *Mgg*: Greenville Formation calcaresous siltstone. *Mgu*: Union Formation limestone. *Mgpk*: Pickaway Formation limestone. *Mgt*: Taggard Formation limestone. *Mgpa*: Patton Formation limestone. *Mgs*: Sinks Grove formation. *Mgh*: Hillsdale Formation limestone. *Mmcc*: Maccardy Formation mudstone and sandstone. *Mp*: Price Formation sandstones, siltstones, and shales. Dashed pink line is approximate axis of Stony River Syncline. Circle with crosshair is horizontal bedding.

A detailed study of the geomorphology of the region was presented by Werner (1972). Three sinking surface streams were traced to the hatchery springs, and three additional tracer tests in the Stony Creek Valley area helped to define their recharge area (Fig. 109 in Jones, 1977). Discharge records are available for McLaughlin Spring from 1945 to 1958 (USGS #1810, Mclaughlin Spring at Edray, WV). The mean annual discharge was 9.22 cfs (4,138 gpm) with a maximum flow of 152 cfs (68,222 gpm) and a minimum flow of 0.27 cfs (121 gpm).

Both springs are descending gravity springs, emerging at a nearly horizontal contact between the Greenbrier's Hillsdale Formation Limestone (*Mgh* on the map in Fig. 3.9.13) and the underlying mudstone of Maccrady Formation (*Mmcc*).



Figure 3.9.14 McLaughlin Spring has two permanent orifices, about 25 yards apart, captured to supply Edray Hatchery by gravity. On average, they provide approximately 2,000 to 2,500 gpm or 2/3 of the total flow used by the hatchery. One third, or approximately 1,000-1,200 gpm, is supplied by Averill Spring, located about 1200 feet to the southeast. Pictured is Tom Provezis of the Edray Hatchery, explaining various details about the spring.



Figure 3.9.15 Catch basin for capture of Averill Spring, built in 1932 by Civilian Conservation Corps (CCC) and still in excellent condition. The spring has 2 orifices, both of which are captured for supply of the Edray Hatchery by gravity (providing on average about 1,000 to 1,200 gpm or 1/3 of the hatchery's current use). The overflow from the basin creates a nice cascading waterfall (Fig. 3.9.16).

Edray Fish Hatchery, one of seven West Virginia cold-water hatcheries, is responsible for stocking 134,000 pounds of trout annually that have gone into the 70 streams in Pocahontas and surrounding counties. The purpose of the hatcheries is to supplement fish populations so West Virginia can provide what many say is the best trout fishing on the East Coast, without negatively impacting native fish populations.



The Edray hatchery stocks brook, brown, rainbow, golden, and tiger trout. It starts stocking trout in the streams early in the spring and, by the end of May, the stocking pools will be empty. The smallest trout stocked are between one and one-and-a-quarter pounds, with the largest weighting five pounds.

Figure 3.9.16 Overflow from the Averill Spring catch basin creates a nice waterfall, especially attractive during high flow conditions. Photo by L.D. Bennett, courtesy of The Pocahontas Times. https://pocahontastimes.com/



Figure 3.9.17 Water from McLaughlin and Avrill Springs is brought to the Edray Hatchery by gravity piping and delivered to multiple fish basins in a variety of ways to maximize aeration.

Minnehaha Spring, Pocahontas County

Lessing et al. (1991) state that Minnehaha Spring discharges from the Oriskany Sandstone (shown as Du on Figs. 17 and 18 of their report) at the contact with the overlying Marcellus Shale. The authors postulate that most of the water discharging in the spring probably enters the Oriskany Sandstone outcrop and flows downdip and down plunge to depth in the Oriskany before moving upward to the spring. Backthrust faults may control the depth of circulation to the spring. Upward migration of water probably occurs along highly fractured, nearly-vertical permeable zones, as suggested by lineaments at or near the spring (Lessing et al., 1991).

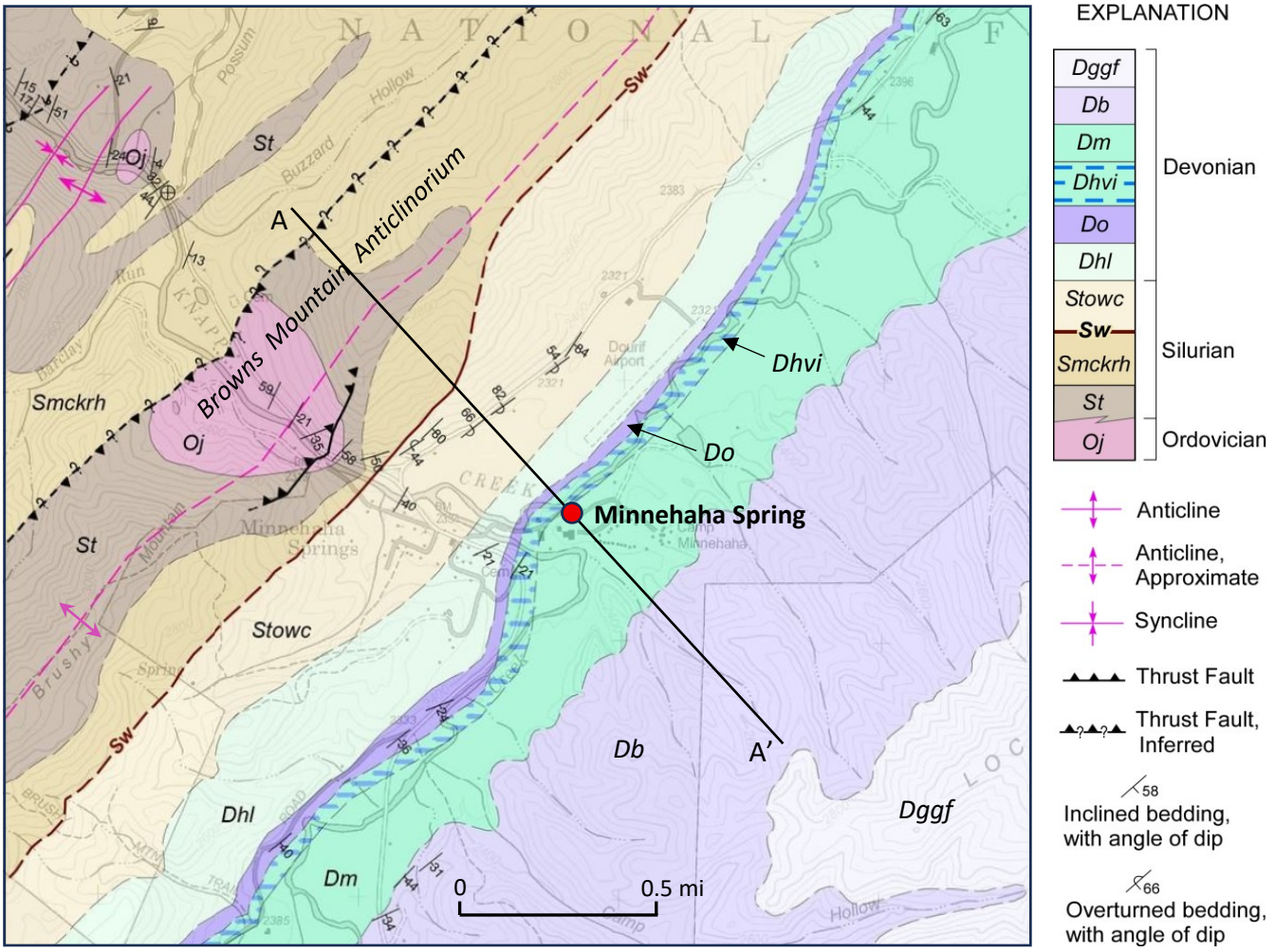


Figure 3.9.18 Geologic map of the Minnehaha Spring area. Geologic units, from oldest to youngest: *Oj*—Juniata Formation (75 ft); quartz sandstone interbedded with mudstone. *St*—Tuscarora Sandstone (200 ft); extremely resistant quartz sandstone. *Smckrh*—McKenzie, Keefer, and Rose Hill Formations (300 ft, undifferentiated); shale and siltstone, with interbedded sandstone. *Sw*—Williamsport Sandstone (20 ft); quartz sandstone. *Stowc*—Tonoloway Limestone/Will Creek Formation (575 ft, undifferentiated); limestone, interbedded with calcareous shales. *Dhl*—Helderberg Limestone (300 ft), carbonates, with some degree of recrystallization. *Do*—Oriskany Sandstone (100 ft); quartz sandstone, weakley or not cemented where observed. *Dhvi*—Huntersville Chert interval (120 ft). *Dm*—Milboro Shale (200 ft); shale and silty shale, with calcareous layers and concretions. *Db*—Braillier Formation (1400 ft); silty shale and sandstone. *Dggf*—Greenland Gap Group, Foreknobs Formation (1600 ft); quartz sandstone, mudstone, and silty shale. Line AA' denotes cross-section in Fig. 3.9.19. From McDowell et al., 2013, some annotation added.

However, the most recent, detailed geologic mapping of the Minnehaha Springs quadrangle (Fig. 3.9.18, McDowell et al., 2013) shows that the Oriskany Sandstone is very thin. Together with the hydrogeologic characteristics of the exceptional thermal artesian spring, this indicates that the primary aquifer is almost certainly in the underlying karstified Devonian Helderberg Limestone and the Silurian Tonoloway Limestone. These two limestones have a combined thickness of up to 875 ft and are deeply seated below the Devonian clastic rocks on the southeastern flank of the Browns Mountain Anticlinorium (cross section in Fig. 3.9.19). The overlying Devonian Oriscany Sandstone, Huntersville Chert, Marlboro Shale, and Brailer Formation shale and sandstone likely provide, through the prominent fracture sets described by Lessing et al., (1991), for a slow downward

recharge of the primary karst aquifer. However, the Devonian clastics cannot serve as any significant groundwater storage/reservoir and cannot have highly transmissive preferential flow paths that would allow flow integration needed for the emergence of a single, high flow, ascending (artesian) spring such as Minnehaha Spring.

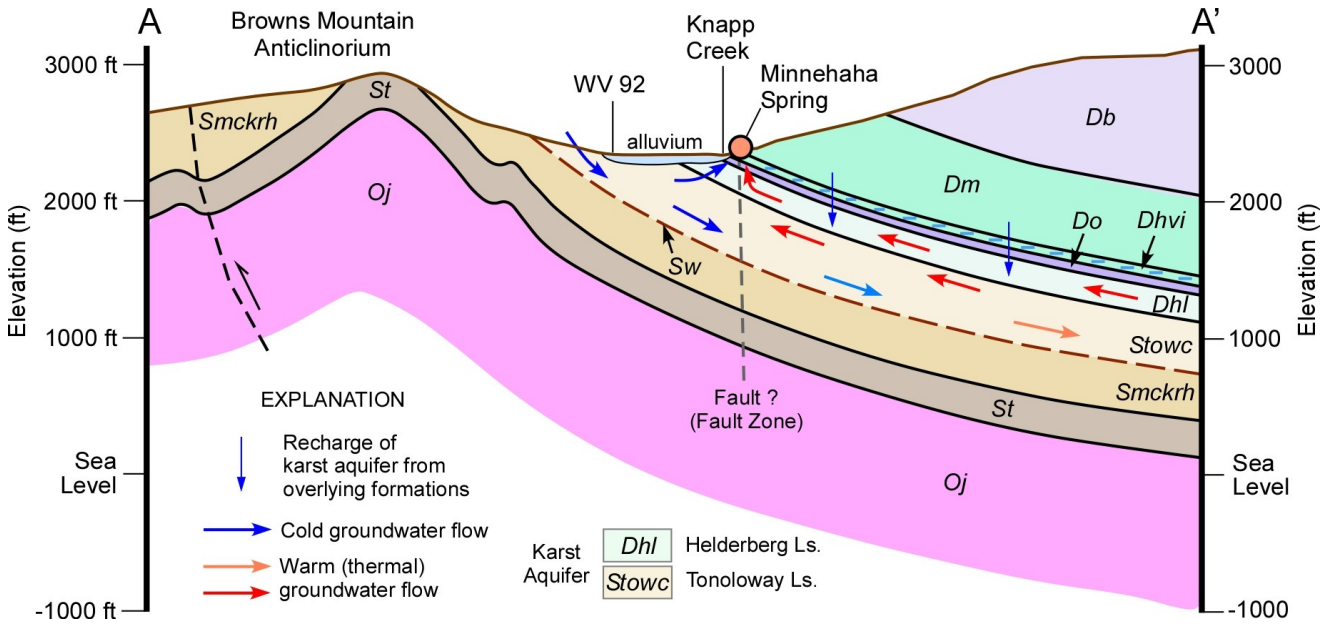


Figure 3.9.19 Hydrogeologic cross-section AA' for the line shown on geologic map in Fig. 3.9.18. Geologic units are the same as on the map.



Figure 3.9.20 From an excellent blog by Callan Bentley, Associate Professor of Geology at Piedmont Virginia Community College in Charlottesville, Virginia: *In the Valley & Ridge province of eastern West Virginia, my favorite formation is the Silurian-aged Tonoloway Formation. Here's an outcrop on Corridor H, right on the Grant/Hardy County line. The Tonoloway was deposited in the passive margin setting between the late Ordovician Taconian Orogeny (lots of clastics shed into this basin) and the Devonian Acadian Orogeny (lots more clastics shed into this basin). There are no significant clastics in the Tonoloway: it's instead composed of crystallized seawater! It consists of carbonate rock (limestone and dolostone) that shows numerous indications of shallow water deposition under arid conditions. Much of the formation looks like this: Super thin laminations of limestone and dolostone* (right photo). https://mountainbeltway.all-geo.org/2017/05/23/silurian-tidal-flat-carbonates-tonoloway-formation/

As presented in Lessing et al., 1991 (Fig. 3.9.21), the broad northwest and northeast maxima for lineaments detected by using SLAR images of the Minnehaha Springs area roughly correspond to the two maxima for systematic fractures, with a slight shift. Systematic fracture orientations have been measured in a variety of rock types in this area. The nearly horizontal Silurian Age Tuscarora Sandstone, which crops out in the core of Browns Mountain Anticlinorium, shows excellent fractures. On the limbs of the anticlinorium, fractures in the Oriskany Sandstone, in the limestones in the Helderberg Group, and in the Marcellus Shale show the same northeast and northwest azimuths. (Author's note: Marcellus Shale is mapped as Milboro Shale on the most recent geologic map by McDowell et al., 2013). This indicates a fracture signature that persists in both the Silurian and Devonian rocks (Lessing et al., 1991).

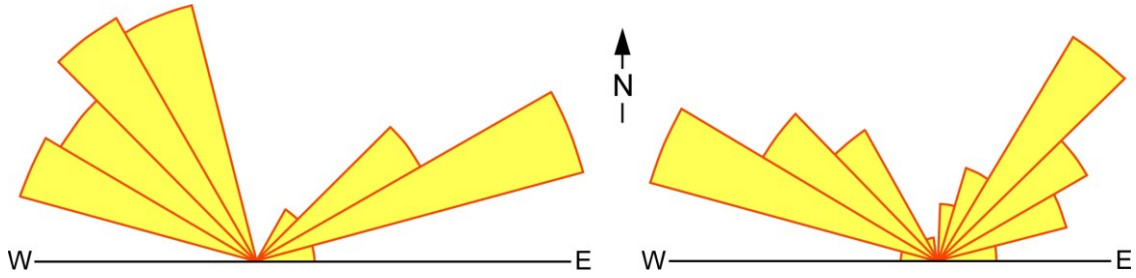


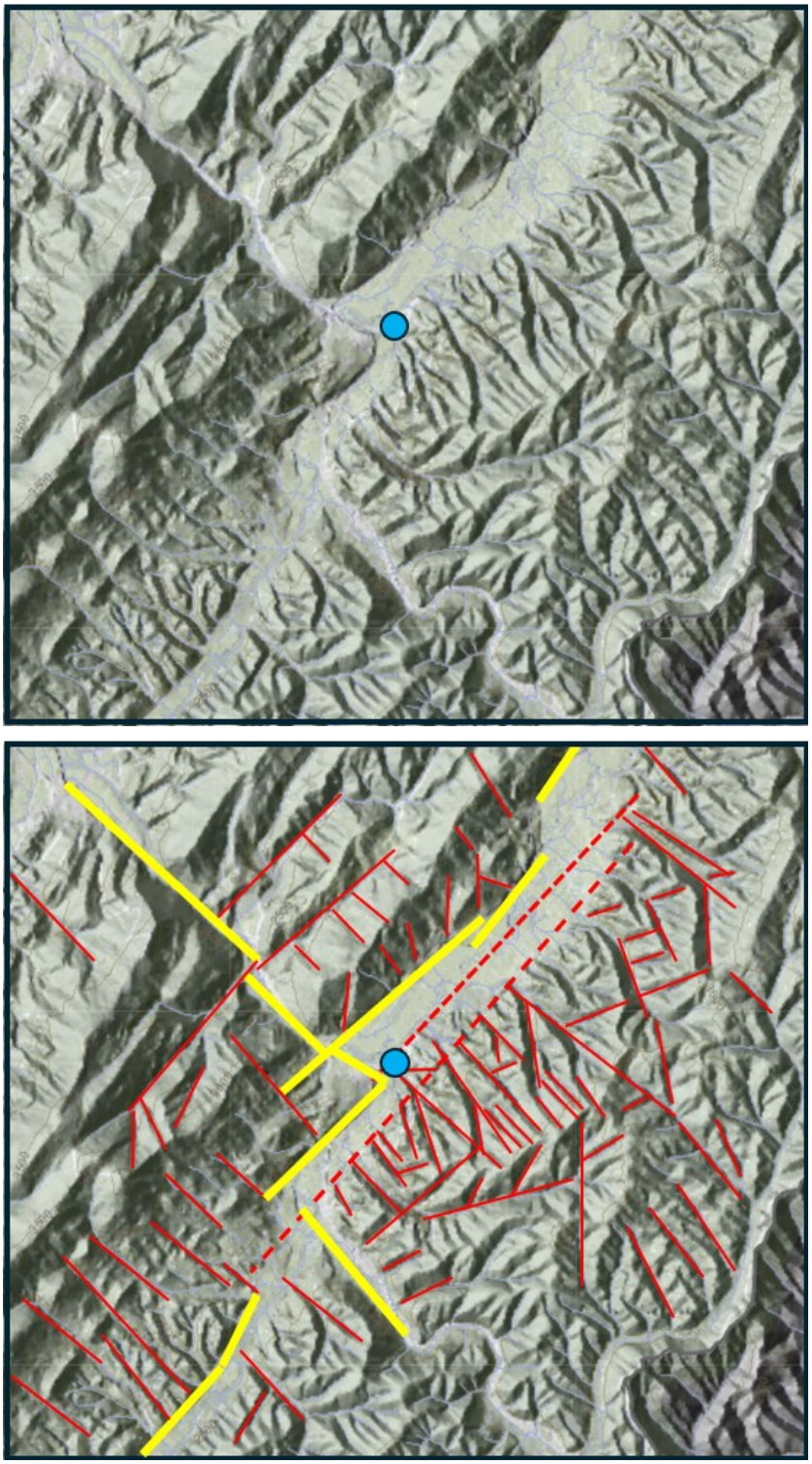
Figure 3.9.21 Rose diagrams of cumulative length of lineaments mapped on side-looking airborne-radar images (left) and cumulative frequency of fracture trends in the rocks at Minnehaha, Curry, McCarty, and Dunmore Springs (warm-springs) area (right). From Lessing et al., 1991.



Figure 3.9.22 Road cut on Rt. 39 in the town of Minnehaha Springs, west of intersection with Frost Road/Rt.92, exposing an overturned contact between Tonoloway Limestone (*Stowc*) on the left, and Williamsport Sandstone (*Sw*) on the right.

It is somewhat mystifying that neither old nor new geologic maps of the wider Minnehaha Springs area show any consideration for (literally "screaming") breaks in the topography that all point strongly to the underlying structural geologic fabric. Instead, all mapped geologic contacts between different bedrock units are smooth and continuous. The topographic breaks are particularly obvious on shaded relief maps such as the one shown in Fig. 3.9.23. In the karst terrain of the Minnehaha Spring area, as well as in any other similar hydrogeologic environment consisting of limestones, such obvious breaks are prime candidates for converging preferential flow paths that cross regional and local topographic divides and integrate dissolutionaly enlarged fracture networks (conduits) which

accompany them by default. The cross section in Fig. 3.9.19, and Fig. 3.9.23 illustrate these points and offer possible clues for the karst hydrogeologic framework of the strong thermal Minnehaha Spring.



Lessing et al. (1991) list the discharge rate of Minnehaha Spring at 655 gpm, recorded in May 1983, and water temperature of 20.4 ^{O}C. Hobba et al., (1979) list flow rate of 220 gpm, recorded in November 1975, and temperature also of 20.4 ^{O}C. More frequent, systematic measurements of the Minnehaha Spring are not available.

Tritium content of water from Minnehaha (1.1 TU) suggests that more than 97 percent of the water is more than 30 years old. Lessing et al. estimate the minimum depth of circulation to the springs to be 1,500 feet. This is somewhat puzzling since the Oriskany Sandstone, which according to the authors is the aquifer providing water to Minnehaha Springs, is only about 100 feet as shown on their cross section in Fig. 18 (p.30). However, when considering that the principal aquifer consists of the thick underlying karstified Helderberg and Tonoloway Limestones, such depth does make sense.

Figure 3.9.23 Shaded relief map of the Minnehaha Spring area and observed lineaments based on sharp contrasts. Not all possible lineaments are denoted, and the interpretation is subjective by default. Thick yellow lines are major breaks in the relief, indicating possible large faults and/or fault zones. Red lines are likely fracture sets and/or small faults which influenced development of the small-scale drainage pattern. Base map from online version of Geologic Map of West Virginia (1968 GeMS).

As noted by Hobba et al. (1979), although Minnehaha Spring issues from the Oriskany Sandstone, the water is saturated with calcite. This spring is in the vicinity of the Virginia thermal springs, all of which are associated with limestone. The fact that Minnehaha Springs is saturated with calcite suggests that, unlike the other sandstone springs, its water has been exposed to carbonate rock (Hobba et al., 1979).





As explained by Stan Cohen in *Historic Springs of the Virginias* (1981), the water of the spring, on the farm of the Lockridge family, was analogous to the water of Hot Springs in Virginia. The name Minnehaha Springs was given to it because of Indian relics found nearby. There is also conjecture that Pocahontas, the Indian princess, might have lived in the area. A company known as the Pocahontas Mineral Water Development Company was organized; a hotel was completed on top of the hill above the spring in 1914, and a bath house with an inside pool was built at the bottom. Management was turned over to the owners of the Casa Ybel, a winter resort in Florida.

Figure 3.9.24 *Top*: Overflow from the retention basin of Minnehaha Spring. The concrete basin was constructed in the early 1920s and first served as a swimming pool for the resort. Today, the spring is used for the entire water supply of *Camp Twin Creeks*, including a modern swimming pool on the property. *Bottom*: Spring house is in the lower left of the photo.

The two-story hotel had 24 bedrooms. A 1914 brochure states that it had its own electric and water plant, modern plumbing, running water and call bells in each room and was comfortably furnished throughout. There were automobiles to drive guests to and from Marlinton, the nearest railroad station. Fishing, horseback riding, tennis, dancing, pool and cards were optional amusements along with bathing in the mineral water. The brochure stated, however, that it should be clearly understood that the resort was not intended for the treatment or cure of serious ailments, but was strictly a summer resort. It was also advised that patients consult their own physician before using the springs for medicinal or therapeutic reasons (Cohen, 1981).

It is not certain when the resort was closed to the public but in 1944 a summer camp for boys was established and named Camp Minnehaha. On Feb. 4, 1945, the hotel burned to the ground destroying all its contents. The bath house was moved to a place opposite the pool. It is now used as a gym and recreational hall for the current coed camp named Camp Tween Creeks.

North Spring, Randolph County

The Bowden State Fish Hatchery, situated 10 miles east of Elkins in Randolph County, was built in the early 1960's by the U.S. Fish and Wildlife Service. The West Virginia Division of Natural Resources (WVDNR) took over operation and ownership of the hatchery on July 1, 1997. Historically, the hatchery obtained its water from North Spring, South Spring, and Shavers Fork River for a combined flow somewhere between 2,000 and 4,000 gallons per minute. However, as reported by Garton (1977), construction of part of Interstate highway 79 in West Virginia uncovered pits and caverns overlying a karst aquifer which was the source of springs used as a water supply for the Bowden National Fish Hatchery (the hatchery's name at the time). Large quantities of clay and silt were washed into the caverns, resulting in very turbid springflow during storms. During one event, more than 150,000 trout died due to silt build-up on their gills. Other fish kills were the result of poisoning by diesel fuel which was spilled on the construction site and washed into the caverns. In addition, damage to the hydrogeologic environment occurred because the construction beheaded the aquifer resulting in reduced flow and re-channelization of water away from the springs (Garton, 1977).

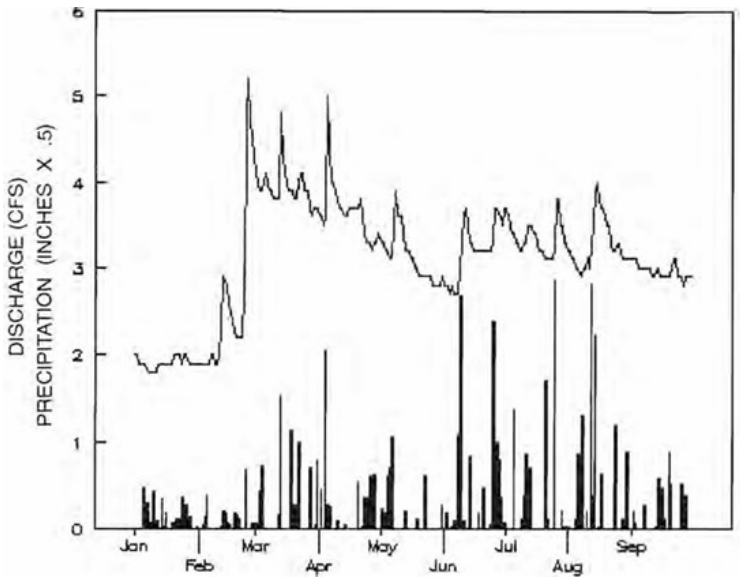


Figure 3.9.35 Graph of discharge rate of North Spring for year 1977. From Jones, 1977.

The more prolific, and surviving North Spring, currently the primary source of water for the hatchery, typically provides clean, cold water that stays at a stable temperature year-round. This is critical for breeding cold-water species like rainbow, golden rainbow, brook, and brown trout. Unlike surface water from the Shavers Fork River, the spring water is clean and lacks the pathogens or wild diseases that can devastate young fish populations.

Following a massive, $10 million state-of-the-art renovation completed in 2022 by the WVDNR, the facility drastically changed how it utilizes its water. Because the highway permanently limited the volume of the natural spring flow, engineers designed a Partial Reuse Aquaculture System. The hatchery now recycles 80% of its water. Pure spring water enters the system, travels through a mile of fish-rearing raceways, and is then pumped into a purification building. There, it passes through massive drum filters and UV disinfection cylinders before being re-oxygenated with liquid oxygen and pumped right back to the fish. Thanks to maximizing the high-quality water from the springs, the hatchery has completely stopped using river water, boosted its trout production capacity by 50%, and now successfully stocks over 300,000 pounds of trout annually across North Central West Virginia.

North and South Spring issue from the base of the Mississippian Greenbrier Group limestone, at nearly horizontal and partially covered (with Quaternary alluvial sediments) contact with the underlying low-permeable clastics of the Mississippian Price Formation.



Figure 3.9.36 A bird's eye view of the Bowden Fish Hatchery with renovations complete (2022). Photo courtesy of West Virginia Governor's Office

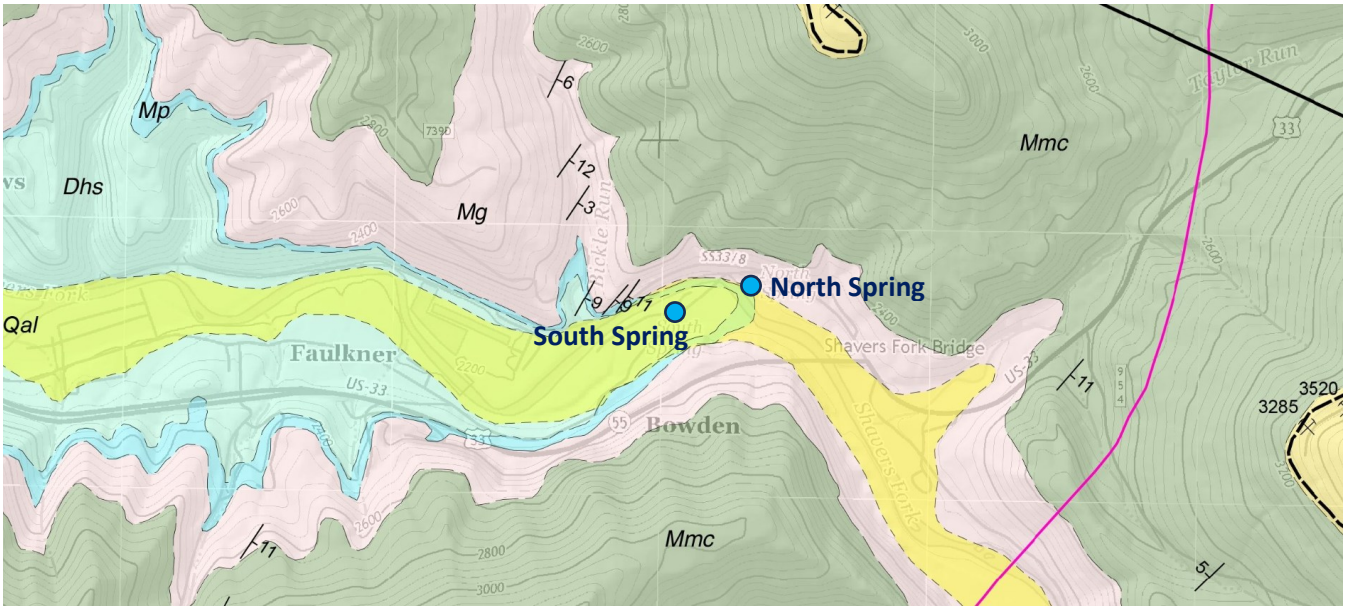


Figure 3.9.37 Geologic map of the general area of North and South Springs. *Qal*: Quaternary Alluvium. *Mmc*: Mississippian Mauch Chunk Group (undifferentiated), shales, sandstones, siltstones, mudstones and limestones. *Mg*: Mississippian Greenbrier Group limestones. *Mp*: Mississippian Price Formation sandstone, conglomerate, shale, and siltstones. *Dhs*: Devonian Hampshire Formation mudstones, shales, siltstones and sandstones. Pink line in the east denotes axis of North Potomac Syncline with gently sloping bedding dip angles of 5 to 12 degrees. From Chapman et al., 2016.

The Big Spring, Grant County

According to Jones (1977), The Big Spring at Masonville in Grant County has a mean discharge of 13 cfs and an estimated annual runoff of 12 inches/year. This suggests a catchment of about 14 square miles. The apparent catchment based on topographic divides is only about 2 square miles. Jones (1977) states that no information about the shape or position of the watershed can be deduced from this calculation.



Figure 3.9.38 *Top left*: Spring box of Big Spring. *Top right*: Steep limestone beds at a waterfall caused by a fault on Spring Run downstream from the spring. *Bottom left*: Water from the spring is transferred to the hatchery by gravity via two 12-inch mains. *Bottom right*: Holding basin on Spring Run as part of hatchery waterworks. The visible overflow is what comes from the spring via Spring Run (bottom left photo) and is not piped to the hatchery at this time.

While no dye tracing was performed in the general area of Big Spring, maps in Figs. 3.9.29 and 3.9.30 do offer some clues as to the possible drainage area of the springs and the hydrogeologic framework for the emergence of one of the largest karst springs in West Virginia, and the Valley and Ridge Province of the Appalachians as a whole.

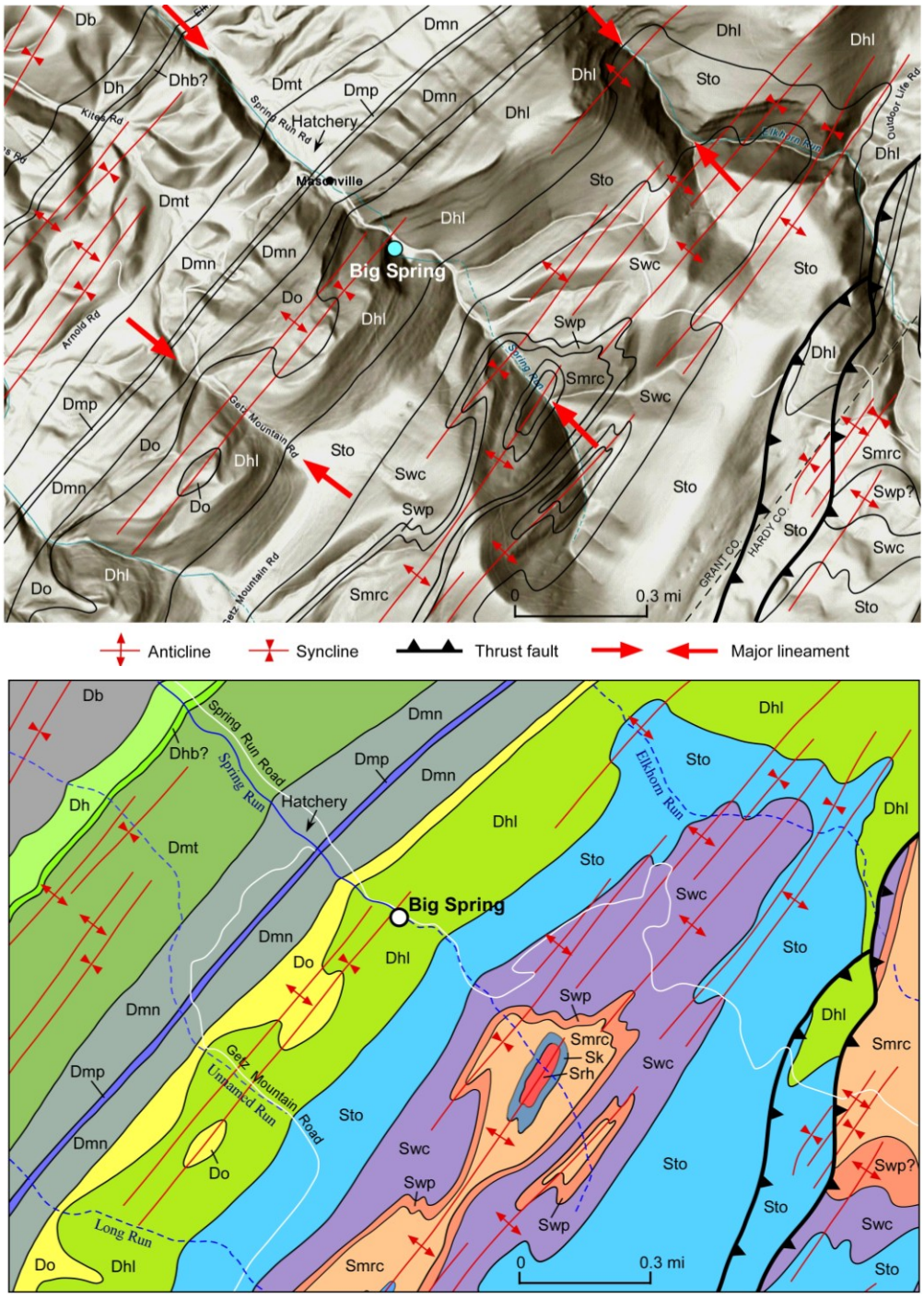


Figure 3.9.39 Shaded relief and bedrock geologic maps of the Big Spring area. Modified for clarity from Dean et al., 2001. Geologic units from oldest to youngest: Srh—Silurian (S) Rose Hill Formation (400-450 ft); shale with thin siltstone and sandstone. Sk—Keeler Sandstone (0-15 ft). Smcr—McKenzie Formation (300-325 ft); calcareous marine shale and argillaceous limestone. Swp—Williamsport Sandstone (???-???). Swc—Will's Creek (300-375 ft); shale with some thin beds of limestone. Sto—Tonoloway Limestone (400-500 ft). Dhl—Devonian (D; lower part is Silurian) Helderberg Group (400-500 ft); massive-bedded limestone. Do—Oriskany Sandstone (100-140 ft). Dmn—Marcellus-Needmore Shale (500-600 ft). Dmp—Purcell Member (25-30 ft); argillaceous limestone in middle of Marcellus. Dmt—Mahantango Formation (1200-1300 ft); siltstone and shale. Dhb—Burket Member (??-??). Dh—Harrell Shale (250-300 ft). Db—Brallier Formation (1400-1500 ft); shales and siltstones.

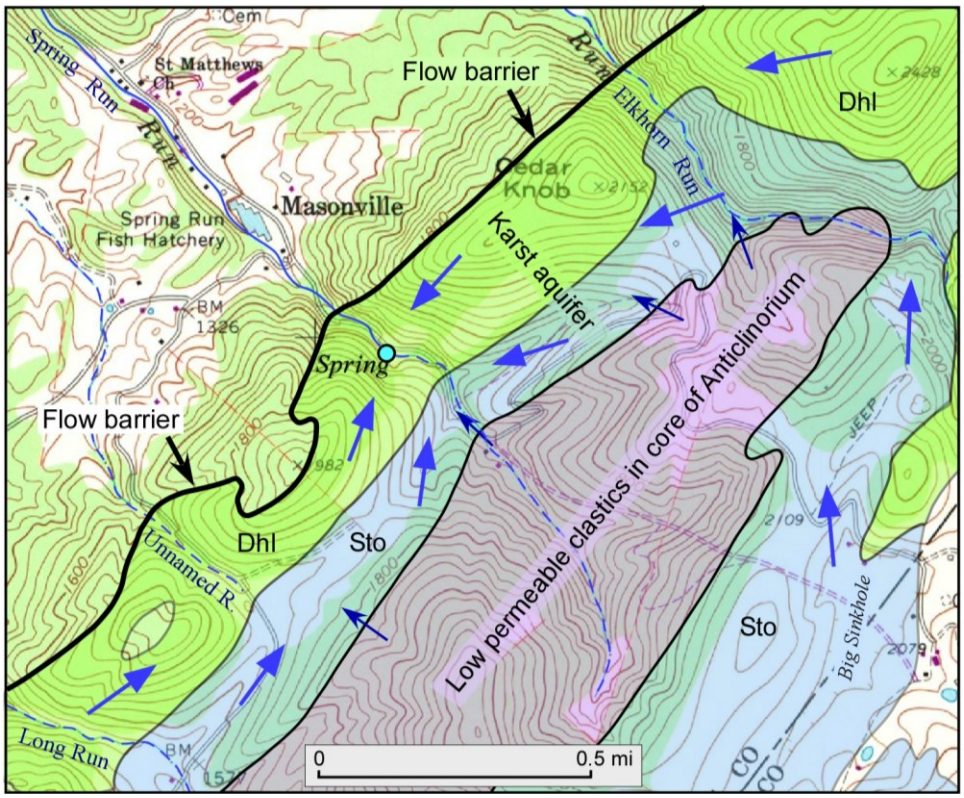


Figure 3.9.40 Schematic of likely general groundwater flow directions (large blue arrows) in the karst aquifer consisting of Tonoloway (Sto) and Helderberg Group (Dhl) limestones that feed Big Spring. The entire area east of the flow barrier formed by Oriskany sandstone and younger clastic rocks (see map in Fig. 3.9.39) is topographically higher than Big Spring. This includes valleys of four streams ("runs") that all trend generally SE-NW and cross geologic boundaries. Recharge of the karst aquifer, (in addition to precipitation) is by runoff from the topographically higher clastics of the Elkhorn Mountain Anticlinorium (smaller blue arrows), and from the four losing streams. Some portions of the highly karstified limestone areas east of the anticlinorium may also be part of the Big Spring drainage area. Note that the limestones also continue to the south, off the map. Topographic base map is from the USGS Petersburg East Topographic Quadrangle, West Virginia.



Notably, as in the case of the Minnehaha Spring geologic map (see Figs. 3.9.18 and 3.9.23), authors of the geologic map of the Big Spring area show no consideration for several major lineaments that are obvious on the shaded relief and topographic maps. There also are unmapped smaller faults and fault zones that are visible in the field, such as the ones shown in Figs. 3.9.38 (*top right*) and 3.9.41. These discontinuities are certain to play significant roles in development of preferential flow paths and conduit networks in the underlying karst aquifer.

Figure 3.9.41. Fault scar in the Helderberg Group limestone near Big Spring.



Figure 3.9.41 Operated by the West Virginia Division of Natural Resources (WVDNR), Spring Run Trout Hatchery serves as one of the state's largest cold-water trout production facilities. Water from the spring is delivered to multiple raceways in a variety of ways to maximize aeration.

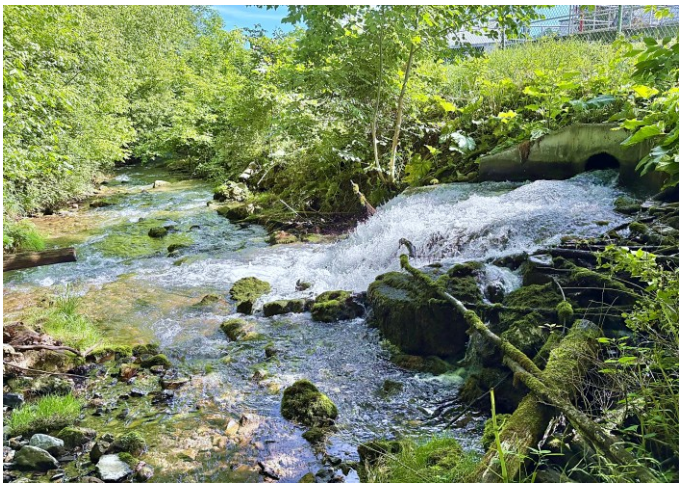


Figure 3.9.42 Outfall of Big Spring water from the hatchery.

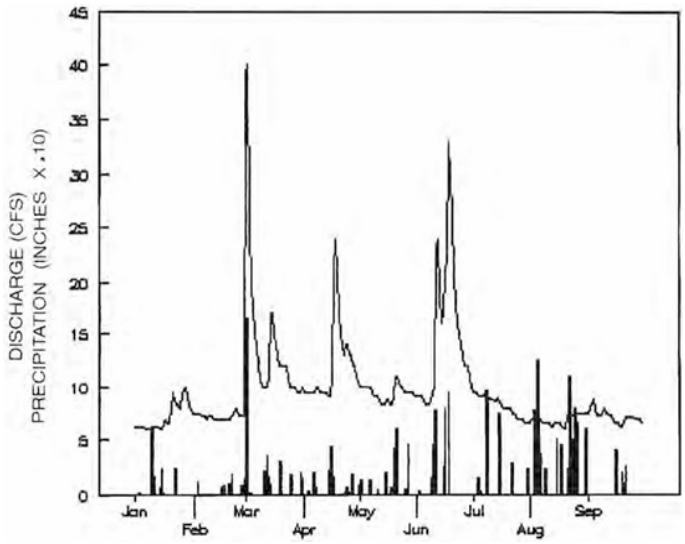


Figure 3.9.43 Discharge rate (in cubic feet per second, cfs) of Big Spring for year 1964. From Jones, 1977.

3.10 Maryland

Maryland spans an area, from east to west, of Atlantic Coastal Plain, Piedmont, Valley and Ridge, and Appalachian Plateaus physiographic provinces. In the Maryland Piedmont, the Cockeysville Marble crops out in Howard and Baltimore Counties, and the Wakefield Marble occurs in Frederick and Carroll Counties. Caves and sinkholes are reported in these units (Franz and Slifer, 1971; M notification on map in Fig. 1.10.1).

Frederick Valley, in Frederick County, is an inlier of Valley and Ridge-type rocks and Triassic and Jurassic basin rocks in the Piedmont Province. Triassic and Jurassic limestone-clast conglomerates of the Leesburg Member of the Bull Run Formation extend northward along the western edge of the Culpeper basin from Loudoun County, Virginia through the southern half of Frederick County. These conglomerates are known to be karstic (TJB; Triassic and Jurassic aged basin-fill calcareous sedimentary rocks.)

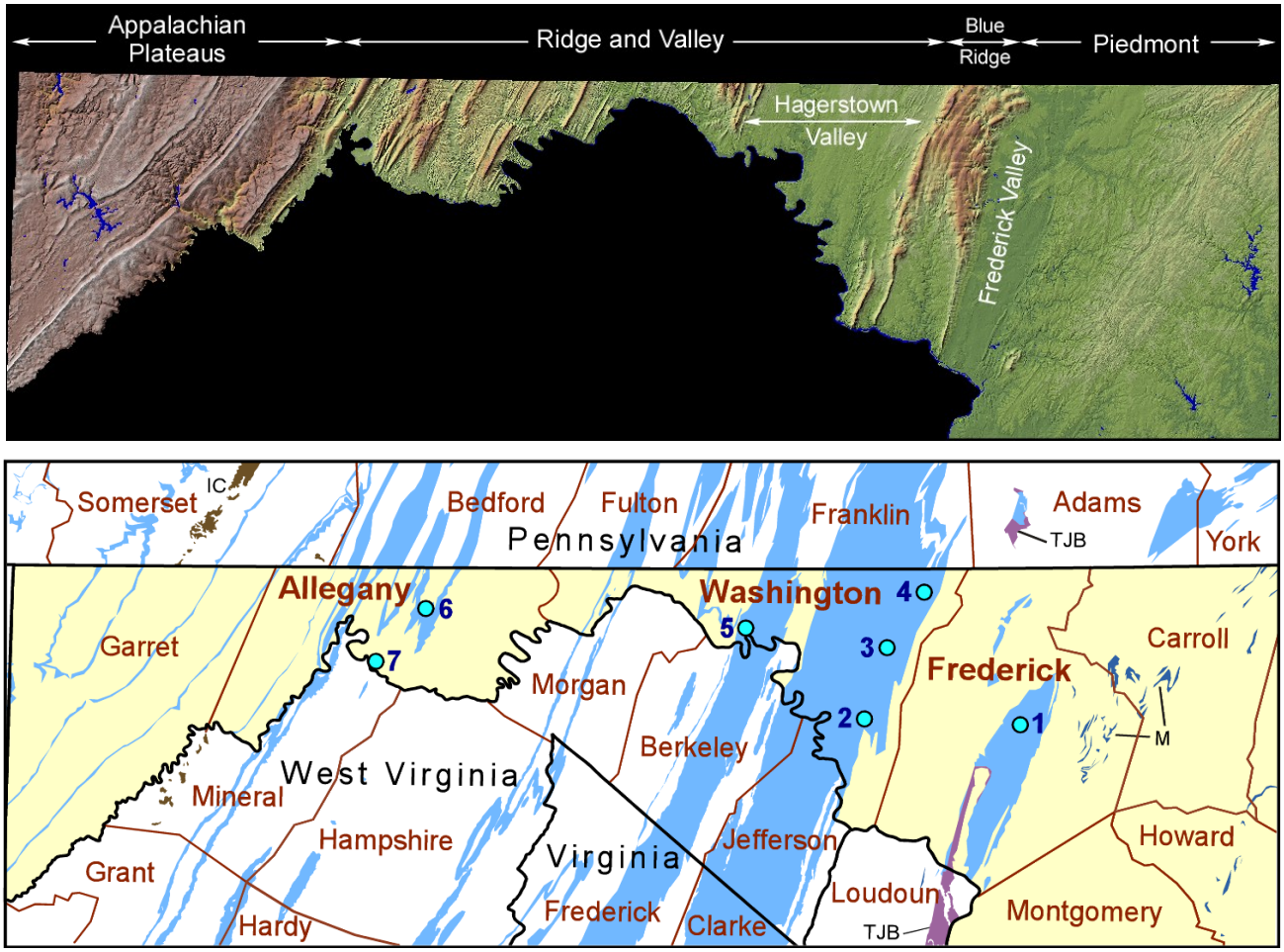


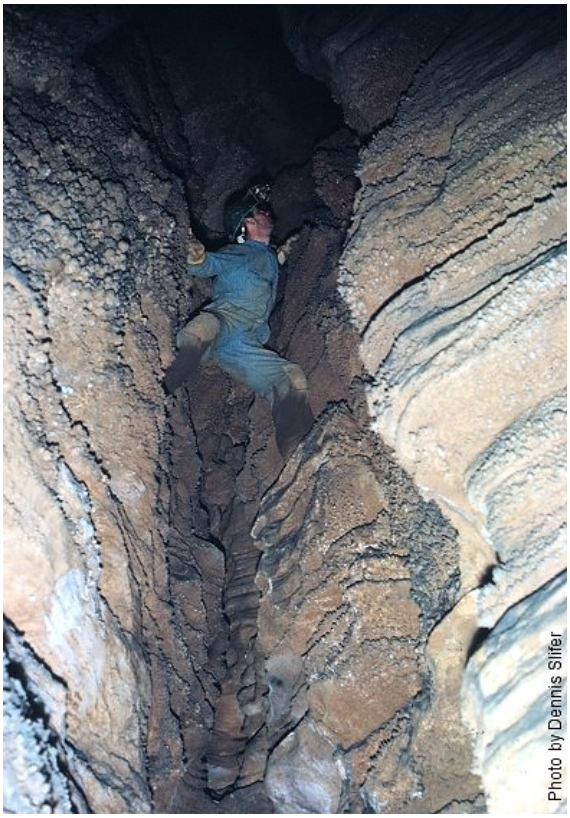
Figure 3.10.1 *Top*: Physiographic provinces of western Mayland. Shaded relief map courtesy of USGS. *Bottom*: Outcrops of karstified rocks in western Maryland and adjacent portions of Pennsylvania, West Virginia, and Virginia. Frederick, Washington, and Allegany Counties have the most developed karst and the largest karst springs in Maryland: (1) Fountain Rock Spring; (2) Keedysville Spring; (3) Albert Powell Hatchery Spring; (4) Unnamed ("Hauver") Spring; (5) Big Spring; (6) Murley Branch Spring; and (7) Blue (Potomac) Spring. Karst areas from Weary, 2008.

The Cambrian Frederick Formation is the primary karstic unit in the Frederick Valley. It is overlain by the Grove Formation which has a smaller areal extent but develops a higher density of karst than the Frederick

Formation (Brezinski, 2004). In the Valley and Ridge Province, karstic units include: the Tomstown Dolomite, the Waynesboro Formation, Elbrook Limestone, Conococheague Limestone, Stonehenge Limestone, Rockdale Run Formation, Pinesburg Station Dolomite, Chambersburg Limestone and St. Paul Group undivided (previously called the Stones River Group), Tonoloway Limestone, and the Helderberg Group. The Tomstown Dolomite in the Hagerstown Valley of Washington County contains more caves than any other formation in Maryland (Franz and Slifer, 1971).

Hagerstown Valley is a part of the Great Valley, which is a continuous, nearly 800-mile long basin spanning the eastern side of the Valley and Ridge province from Georgia to New Jersey. It is known by different names in different states, and includes the Lebanon Valley (Pennsylvania), the Shenandoah Valley (Virginia), and the Great Valley of East Tennessee.

A general description of karst in the Valley and Ridge Province is provided by Weary, 2008: *Folded, faulted carbonate rocks: Limestone and dolomite in areas flanking and in orogenic zones. May be intensely folded and faulted, commonly well jointed, commonly with cleavage. Most of these rocks are Paleozoic in age. Dissolution may produce solution, collapse, and cover-collapse sinkholes. Caves range from small and simple to long and complex systems. Geometry of cave passage patterns tend to show at least some structural control producing "network" caves (Palmer, 1991)*



The Late Mississippian Greenbrier Limestone is the primary karst forming unit in the Appalachian Plateaus Province. Maryland's largest cave, Crabtree Cave, in Garret County, is developed in it. Crabtree Cave is also the largest bat hibernaculum in Maryland and shelters eastern pipistrel, little brown, big brown, northern long-eared and Keen's bats. The cave is permanently closed to the public by The Nature Conservancy to protect wildlife and prevent the spread of white-nose syndrome (Crabtree Cave, Garrett County).

Figure 3.10.2 Crabtree Cave is not only the largest cave in Maryland, with 4200 feet of passage, but is also perhaps the most difficult to explore. The cave can be traversed as a circuit or loop, via the connection tube, by competent and thin explorers in an average time of 6 to 10 hours. Photo by Dennis Slifer. Courtesy of Maryland Geological Survey.

Caves of Maryland (Franz and Slifer, 1971) is the classic state cave publication, superseding an earlier book by Davies (1950). The Maryland Geological Survey has karst information on their web site, as well as detailed bedrock geologic maps for various quadrangles, often including karst features, that can be downloaded in a high-resolution pdf format (https://www.mgs.md.gov/publications/maps.html).

Below are several excerpts related to springs and caves from the planning document *Managing Maryland's Growth, Models and Guidelines, Sensitive Areas,* and published by The Maryland Office of Planning in 1992.

The largest Maryland spring is Potomac Blue Spring in Allegany County, which has produced a measured volume of 9,750 gal/min, although its normal production may only be half that volume (Otton and Hilleary, 1985).

Springs can provide dependable sources of potable water. As such they were of considerable importance to early residents of Maryland. Without question, springs flowing today were also utilized by the first native Americans to reach this region more than ten thousand years ago. Later, as European settlers moved into and through Maryland, strategically located springs became important stopover localities for travelers. These locations then became the sites of early settlements. Such sites are documented by place names like Green Spring Valley, Bentley Springs, Big Spring, Clear Spring, Cool Spring, Fountain Rock, Indian Springs, Silver Spring, and Springdale. Unfortunately, although some of these local springs have been preserved, many have become polluted and no longer provide water suitable for human use. In some rural areas of Maryland, springs are still utilized for drinking water or other purposes. Typically, these springs are relatively small and have been walled in to increase the depth of the pool, primarily to make the filling of containers easier. Others have been encased in spring houses.



Figure 3.10.3 Crystal Grottoes is the only commercial cave in Maryland, and one of the largest in the state. Nearly one half mile of passage was mapped in 1968. In 1920, a construction crew was working to quarry limestone for road material near Boonsboro. As they dug into the earth, they uncovered something completely unexpected: a hidden cave system full of breathtaking formations. https://www.crystalgrottoescaverns.com/

Prior to the availability of mechanical refrigerators, spring houses were important facilities for storing and extending the life of butter, milk, and other perishables. Certain large volume springs have found use as sources of pure, cool water suitable for cold water fish hatching operations. A fine example of this use is the large spring that feeds the Albert Powell State Fish Hatchery near Hagerstown. Several other very large springs in this same area have been harnessed to feed commercial watercress ponds. Springs and seepage areas also provide habitat for a variety of sensitive plants and animals, many of which are quite rare and restricted in their distribution. Some of these are highly specialized residents of groundwater.

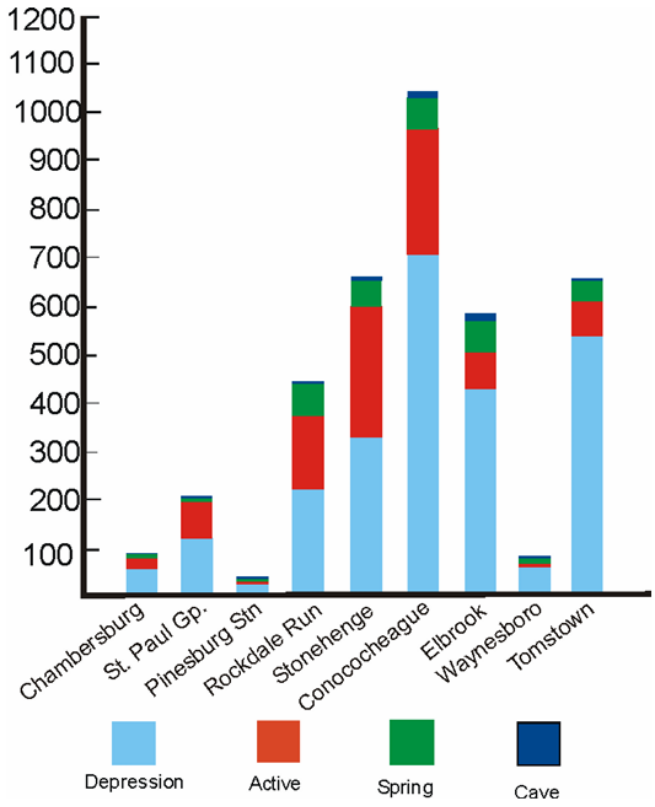
Since springs and seeps represent the resurgence of pure groundwater, protective measures must include keeping pollutants out of the groundwater, ensuring that the aquifers supplying them will continue to be recharged and will not be diverted, and preventing the destruction or covering of a spring or seep as a result of construction or development.

Known Maryland caves have been destroyed (Busheys Cavern, Washington County) or severely damaged (King Quarry Cave, Washington County) by quarrying or mining operations. As indicated previously, most local caves are developed in limestone or dolomite rocks, both of which are utilized locally for construction purposes. No quarrying or blasting activity should be conducted above or in close proximity to known caves.

Karst geology and hydrogeology of the Hagerstown Valley is described by Nutter (1973), Duigon (2001), and Brezinski (2018), while the stratigraphy and karst development in the Frederick Valley have been described by Nutter (1973), and Brezinski (2004). Following are some illustrative excerpts from these outstanding publications which are available for download from the Maryland Geological Survey webpage.

The Hagerstown Valley is formed on Cambrian and Ordovician limestone and dolomite. These rocks were formed in shallow marine waters on an ancient carbonate platform, similar to today's Bahama Banks. For many years limestone formations have been used as local sources of agricultural lime and building stone. Modern uses include crushed stone for aggregate and cement.

The Valley represents a broad down warp or fold in the Earth's crust known as the Massanutten Synclinorium. It is bordered on the east and in fault contact with, a large up-fold known as the South Mountain Anticlinorium. The South Mountain Anticlinorium comprises the northern part of the Blue Ridge Physiographic Province. To the west, the Great Valley is in fault contact with the folded Appalachian mountain section of the Ridge and Valley Physiographic Province.



Not all carbonate units exhibit an equal susceptibility to karst development in the Hagerstown Valley stratigraphic succession. Although all of the carbonate units contained at least one type of karst feature, these features were not distributed evenly throughout the Hagerstown Valley geologic units. The Conococheague Formation and Stonehenge Limestone contain significant percentages of three karst features-depressions, active sinkholes, and springs. These two formations contain more than half of all active sinkholes, and along with the Elbrook and Rockdale Run formations contain more than 75% of all springs (Brezinski, 2018).

Figure 3.10.4 Stacked bar chart of numbers of karst features identified in the 2018 Hagerstown Valley karst study by Brezinski.

Based on yields reported at 1,800 water supply wells in the Hagerstown Valley, Stonehenge Formation limestones have the highest mean and maximum yield of 32.6 gpm and 385 gpm respectively (Duigon, 2001).



Figure 3.10.5 Lithologic character of the Conococheague Formation. A, Bedded and sandy dolomite of the Big Spring Station Member. B, Algal thrombolites of the Zullinger Member. C, Ribbony limestone of the Zullinger Member. D, Prism-cracked, laminated, dolomitic limestone of the Zullinger Member. From Brezinski, 2018.



Figure 3.10.6 Stream flowing into a sinkhole at Jugtown, Washington County. From Nutter, 1973. Courtesy of Maryland Geological Survey.

The Frederick Valley is a tightly folded overturned syncline that exposes easily soluble carbonate rocks that range in age from Early Cambrian to Early Ordovician. The valley is bordered on the west by Early Triassic sediments that are primarily clastic in character. A significant part of the Triassic strata is composed of detrital carbonate rocks, and therefore susceptible to karst development. The western limit of the Triassic rocks is observed along a linear fault that is presumably Triassic in age. This presumed Triassic fault trace is nearly straight, indicating it has a steep dip. The strata along the western side of this fault belong to the Cambrian Harpers Formation at the foot of Catoctin Mountain; that is the easternmost unit of the Blue Ridge Province (Brezinski, 2004).

The eastern boundary of the Frederick Valley has generally been in dispute. While the boundary is commonly placed at the contact between the limestones of the Frederick Valley and the subjacent Araby Formation, it seems more appropriate to place it at the Martic Fault. Because the underlying Araby Formation is of similar metamorphic disposition as the Frederick Valley limestones, it seems logical to include it with rocks of similar geologic origin and deformation. The Martic Fault, which can be traced from Pennsylvania to Virginia, places the greenschist facies rocks of the western Piedmont against the virtually unmetamorphosed rocks of the Conestoga Valley in Pennsylvania and the Frederick Valley in Maryland (Southworth, 1996).

While springs account for less than 2% of the mapped karst features in the Frederick Valley, several of them are notable public landmarks. This includes Fountain Rock Spring located within Fountain Rock Park in Walkersville.

Fountain Rock Spring, Frederick County

Fountain Rock Spring, located within Fountain Rock Park in Walkersville, historically supported limestone quarrying, major regional lime kiln operations, watercress farming, and trout rearing and fishing. The surrounding park now features trails and exhibits around the kiln remnants, boardwalk trail system built directly over an old, flooded quarry pond, trails around the spring orifices, and trails around beautiful spring retention basin (former trout pond).



The spring discharges from the Late Cambrian to Early Ordovician Grove Limestone at an average rate of approximately 1,275 gpm (2.85 cfs) and mean water temperature of 12.3ºC (54.1ºF), based on 13 measurements between October 1980 and October 1981 (Otton and Hilleary, 1985).

Figure 3.10.7 Main orifice of Fountain Rock Spring is in a small overgrown depression shown here. During high flow conditions, several additional orifices around the depression, at 2-5 feet higher elevations, become active as well.

Several interesting facts about the spring and the park are: the lime kilns and quarry operated from 1872 to 1955 and produced powdered burnt lime, used for field fertilizer, and crushed stone for road surfacing; during World War II, German prisoners of war were brought in to work at the quarry; the Quarry Pond is home to six different species of turtles, about 50 in total, and several different species of fish, and watercress has naturally grown in the spring water for the past 80 years. The most famous watercress farmer utilizing the spring was Wilson Carmack, who would harvest the watercress with a sharp knife, pack it with ice, and sell it in Baltimore, Philadelphia, and Washington, D.C.



Figure 3.10.8 Fountain Rock Spring discharges to a crystal-clear retention pond.

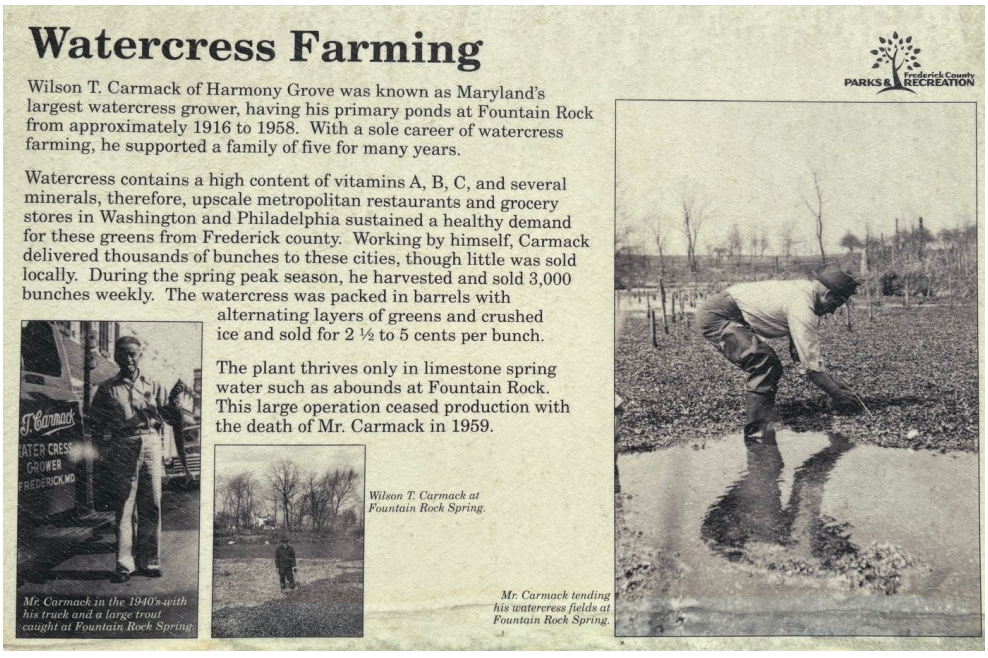


Figure 3.10.9 educational panel by Frederick County Parks & Recreation placed at Fountain Rock Spring.

Keedysville Spring, Washington County

Keedysville Spring, located in the Town of Keedysvile, discharges from the Cambrian Tomstown Formation which consists of dolomite, dolomitic limestone, and limestone. The reported discharge rate is 1,603 gpm (3.57 cfs), and the water temperature varies between 52 and 55ºF; the mean is 53.2 ºF based on 12 measurements between April 1981 and March 1982 (Otton and Hilleary, 1985).

The Spring is utilized for water supply as part of the Boonsboro/Keedysville Regional Water System and the permitted maximum daily withdrawal of 250,000 gallons is shared by the two towns. The system also includes a smaller Warrenfeltz Spring in the Town of Boonsboro and two wells completed in the karst aquifer, all of which are used solely by Boonsboro. The two springs and the wells are considered groundwater under the direct influence of surface water (GWUDI) due to occasional presence of coliform and fecal bacteria and their water is processed at local water treatment plants.

GWUDI is a groundwater source—such as a well, spring, or infiltration gallery—that is located sufficiently near a surface water body (e.g., river, lake, or stream) to receive direct surface water recharge. Because part of the groundwater recharge comes from surface water, these sources are at risk of contamination by pathogens and viruses, such as Giardia and Cryptosporidium, which are typically found in surface water but not in true groundwater. This makes GWUDI sources, such as many karst springs, more vulnerable to waterborne diseases and other health risks.



Figure 3.10.10 Keedysville Spring is utilized as the main source of water supply for the towns of Boonsboro and Keedysville in Washington County.

Boonsboro is close enough to Washington D.C. to experience what seems like an unstoppable boom with all its consequences, the most obvious being an ever-increasing water demand. For example, during a recent drought, the town used the entire discharge from the Warrenfeltz Spring and Boonsboro Branch went dry. After local farmers in Keedysville (located downstream from Boonsboro) went directly to Annapolis (the State capital) and complained to the responsible agency, Boonsboro released water from the spring following the groundwater withdrawal permit requirements.

The aquifers found in the Valley and Ridge Carbonate regions of the Hagerstown Valley are typically plentiful and have larger storage capacity than other areas making them a likely target for additional groundwater supply. These areas have historically been adequate to service public systems and individual wells. While this region is generally the most prolific, it can also be erratic and susceptible to contamination due to the karst nature of the underlying geology. With limitations in the City's treatment capacity and distribution system, the County may investigate options in establishing another public water source within the Urban Growth Area. A new system would likely require the drilling of wells and installation of appropriate water treatment facilities. Depending upon the gallons generated by the wells, the level of service could range from small and localized to modest and regional. No specific locations have been determined at this time.

Washington County, Maryland





The Keedysville USGS topographic quadrangle has long been recognized as one of the most structurally complex areas of Maryland where relationships of the rock units have long perplexed geologists. This includes a number of thrust and vertical faults of which the Keedysville, Beaver Creek, and Eakles Mill Faults are the most prominent (Fig. 3.10.12). The spring emerges right in the middle of the area where these three regional faults converge. According to Brezinski (2009), Keedysville/Beaver Creek Fault can be traced all the way to Virginia in the south and Pennsylvania in the north, and Eakles Mill Fault extends far north to Pennsylvania. This faulting and folding, accompanied by fracturing, created perfect conditions for intensive karst development in this part of Hagerstown Valley (e.g., Crystal Grottoes Caverns is about one mile NE of Keedysville Spring).

Figure 3.10.11 Outcrops of Cambrian Tomstown Formation dolomite in Boonsboro Branch near Keedysville Spring. The dolomite is crisscrossed by dissolutionally enlarged fractures, cleavage, and bedding planes.

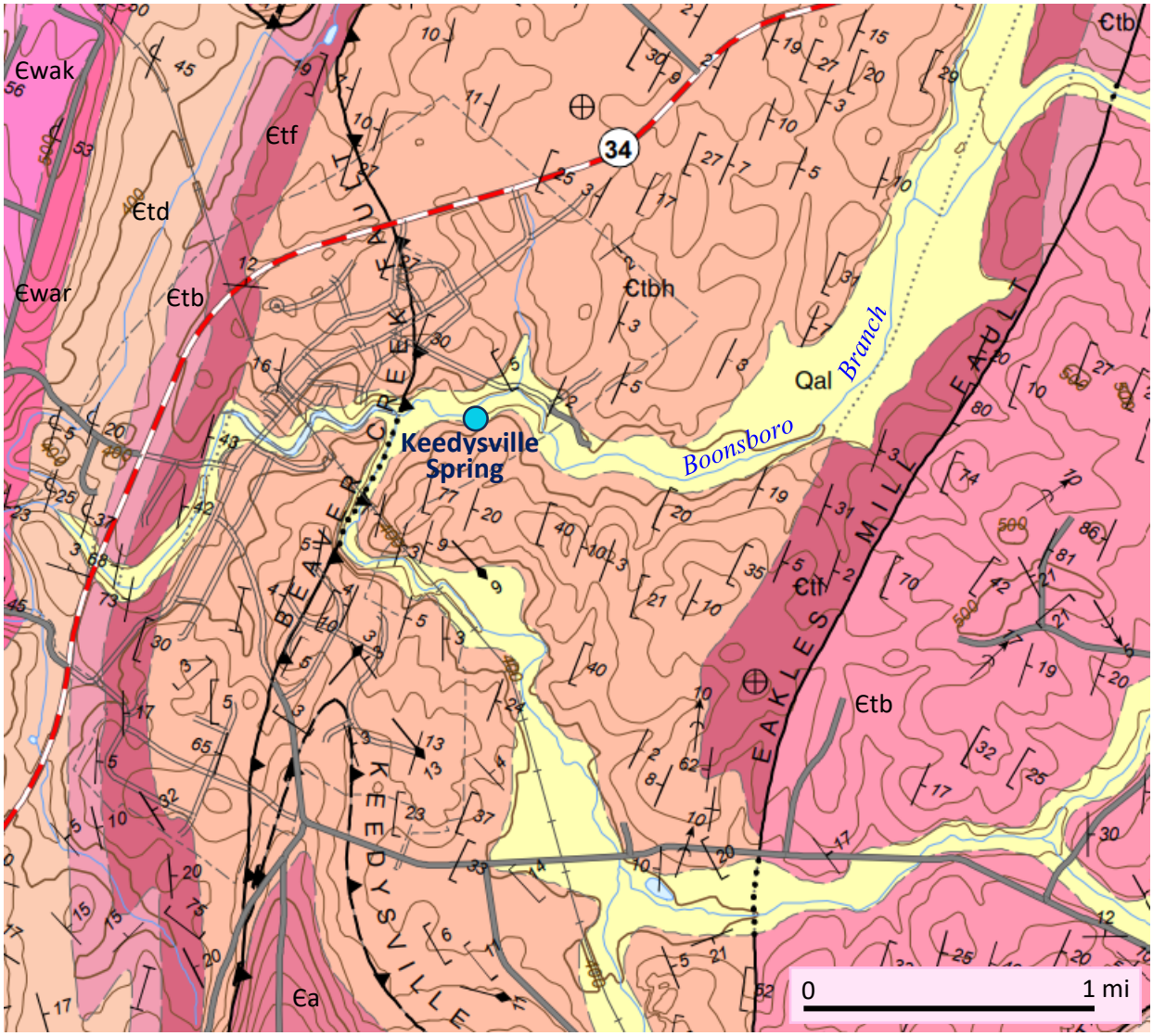


Figure 3.10.12 Geologic map of the Keedysvile Spring area. From Brezinski, 2009 (some annotation added). Geologic units, from oldest to youngest: Ꞓa—Cambrian Antietam Formation; shale and siltstone interbedded with sandstone. Cambrian Tomstown Formation—predominantly dolomite, dolomitic limestone, and limestone are divided into 4 different members: Ꞓtd—Dargan Member; Ꞓtb—Benevola Member; Ꞓtf—Fort Duncan Member; Ꞓtbh—Bolivar Heights Member. Above Tomstown is Cambrian Waynesboro Formation consisting of Cavetown Member (Cwak) carbonates, and Chewsville Member (Cwac) shale, siltstone, and sandstone. Qal—Quaternary alluvial sediments.

Albert Powell Fish Hatchery Spring, Washington County

A karst spring, designated as WA Bj 4 in the MD database and commonly referred to as Albert Powell Hatchery Spring, is the main water supply for the hatchery. It issues from dolomites and limestones of the Middle Cambrian Elbrook Formation. The Albert Powell Hatchery is located along Beaver Creek near the eastern edge of Hagerstown Valley, about 7 miles southeast of Hagerstown via I-70E. The Hatchery raises over 250,000 rainbow trout each year for stocking of the State's freshwater streams. Beginning March 2, 2026, the Hatchery is closed to public due to renovation which is anticipated to be completed in 2 years.

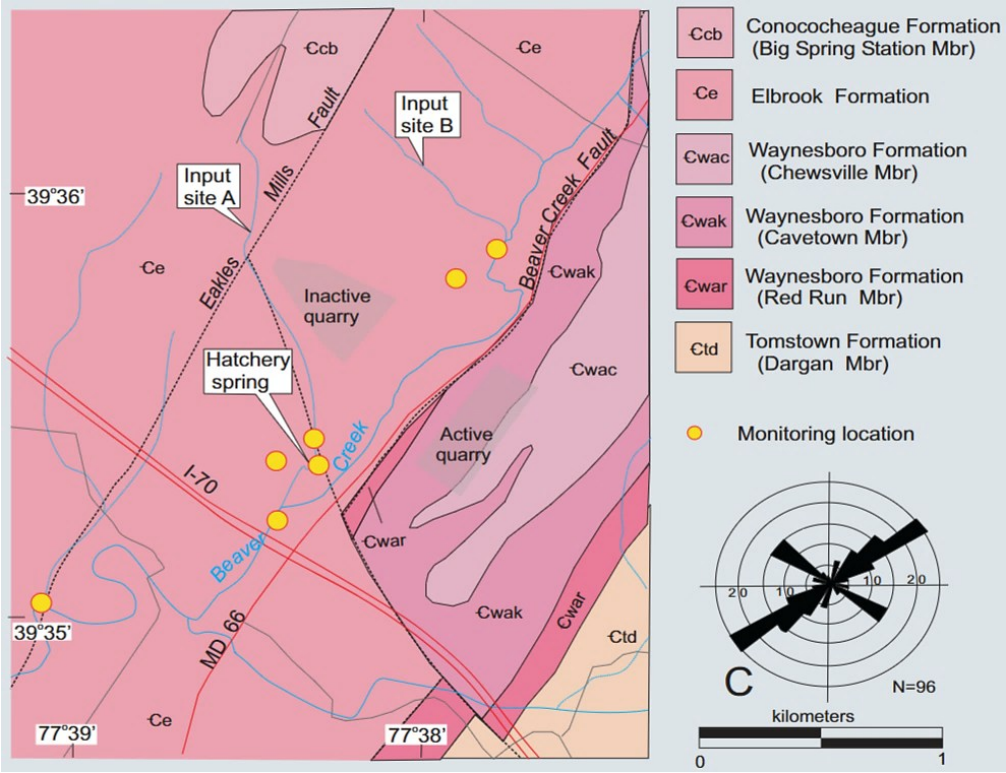


Figure 3.10.13 Geologic map of the area surrounding the Albert Powell State Hatchery (after Brezinski and Bell, 2009 and Brezinski and Fauth, 2009). Predominantly clastic rocks of the Red Run Member of the Cambrian Waynesboro Formation act as a flow barrier for the karst aquifer developed in thick carbonates of the Cambrian Elbrook Formation. From Berzinski et al., 2018.

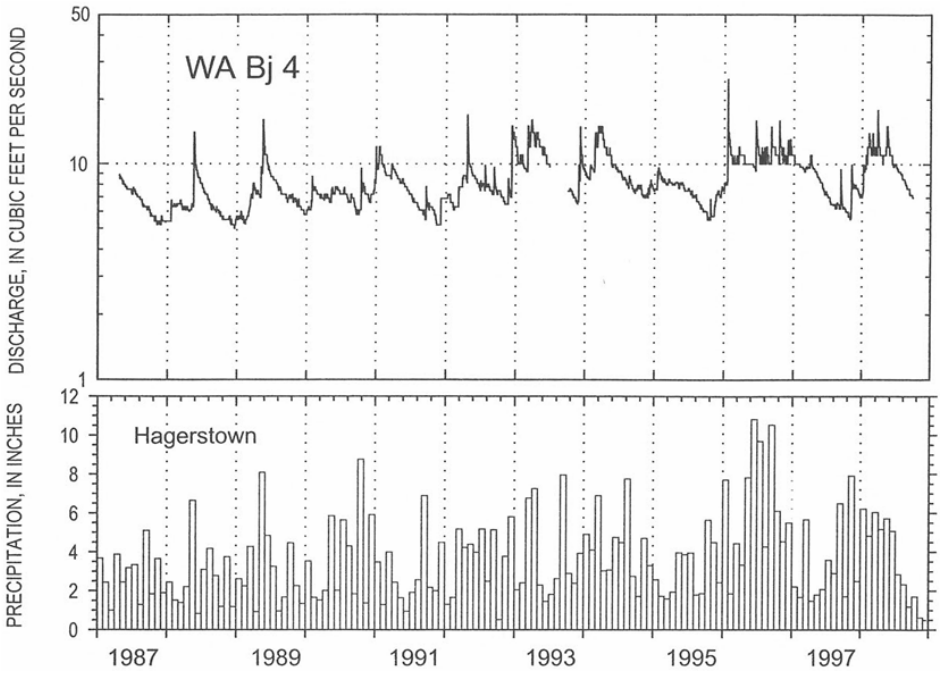


Figure 3.10.14 Daily discharge at Powell State Fish Hatchery Spring (WA Bj 4 in MD database), and monthly precipitation at Hagerstown for the period April 1987-September 1998. Average discharge rate is 8.3 cfs. From Duigon, 2001.

Since the hatchery's founding in 1949, infrequent turbidity events have killed or threatened several late winter fry populations. Two such episodes, in November, 2004 resulted in significant mortality to young fish (Duigon, 2007). Geologic inference and dye tracing of groundwater flow were used to investigate the boundary of the area contributing groundwater to the flow of the Spring and identify possible sources of turbidity. The results of the

study suggested that the contributing area extends about 5 miles northeast from the Spring, broadening to the west from about 1 mile in width at the southwestern end to about 2.5 miles at the northeastern end, covering approximately 8.2 square miles. It is bounded on the east by the Beaver Creek Fault (Fig. 3.10.13), an old, mylonitized thrust fault presumed to be a barrier to groundwater flow. The Eakles Mills Fault on the west is a younger, high-angle fault along which the rock reacted in a brittle fashion, thereby likely becoming a linear zone of enhanced permeability. The Eakles Mills Fault may act as a linear sink draining toward the southwest, intercepting any groundwater flow coming from the west. During periods of high groundwater levels, some of the water draining along the Eakles Mills Fault may be diverted by a cross fault located on the hatchery property to Beaver Creek and, during periods of highest groundwater levels, to the hatchery spring (Duigon, 2009).

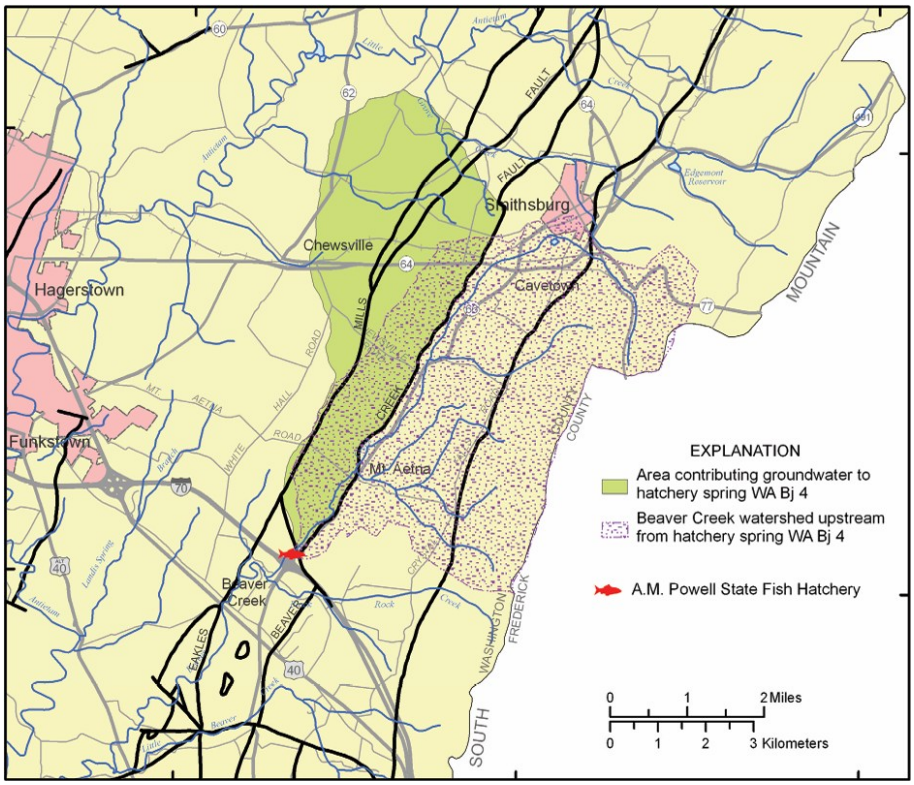


Figure 3.10.15 Area contributing groundwater flow to the Powell State Fish Hatchery Spring as hypothesized based on investigations that included dye tracing. From Duigon, 2009.



Figure 3.10.16 *Left*: Albert Powell Fish Hatchery is one of three cold water fish hatchery facilities owned and operated by the state of Maryland. *Right*: The water used at the Hatchery is supplied by a karst spring that averages 3,725 gpm (8.3 cfs) and is considered the second largest spring in Maryland. Covers are placed on the spring water surface to reduce the aquatic vegetative growth of duckweed, watercress and grasses. Aerators in the spring operate seasonally to increase oxygen and reduce harmful gases, such as nitrogen. Photographs courtesy of Albert Powell Hatchery.

Stone Field Spring, Washington County

Stone Field Spring (WA-AK 3) is on the historic Stone Field Farm located on Route 64 between Bikle Road and Rowe Road on the Greensburg side of Smithsburg. The property is famously recognized for its beautifully preserved 19th-century stone farmhouse which belongs to a regional tradition of building homes directly over springs to provide an indoor water source and cold storage.

Inside the lower level of the house, the water flows through an engineered crawl space under the original stone cabin and out to a walled pond, keeping the area naturally cooled. The stone cabin ("springhouse") structure predates the main house and was built in 1760 by Peter Mong. It is known traditionally as "Peter Mong's Cabin". The main part of the stone house was added in 1810.

Because of its architectural and geographical significance, the property was formally surveyed in 2004 and listed under the Maryland Historical Trust as site WA-IV-029. It is currently undergoing a thorough and historically sensitive renovation by the new owners who bought the farm in 2023.

The spring discharges from the Cambrian Tomstown Formation dolomite at a rate ranging between 0.6 cfs and 7.0 cfs, and water temperature between 45°F and 57°F. The average temperature is 52.3°F based on 13 measurements between Marh 1981 and February 1982 (Otton and Hilleary, 1985).



Figure 3.10.17 The Stone Field Spring was so robust that it eventually transcended private use. Historical site surveys from the Maryland Historical Trust document physical piping infrastructure at the pond, indicating that the spring was previously tapped and utilized by the Town of Smithsburg to supplement the local municipal water supply. The original Peter Mong's Cabin, extending to the left (north) from the main house, is built above the spring. It is one-and-a half-story three bay stone cabin. Photo courtesy of Maryland Geological Survey.



Figure 3.10.18 *Left*: Stone Field Farmhouse facing south. The spring discharges to the walled pond from under the original Peter Mong's Cabin on the left. *Right*: Walled pond, facing west towards Smithsburg Pike. Photographs courtesy of Washington County Zoning Commission.

The constant, cool temperature of the spring water turned the basement into a natural "cold cellar" or springhouse. This environment allowed residents to store highly perishable goods like milk, butter, and meat before the invention of modern refrigeration. Having a freshwater source directly inside the foundation walls meant the family had guaranteed uninterrupted access to clean water. During the mid-to-late 18th century, frontiersmen faced constant security threats. An indoor water source ensured that the home's occupants could survive a prolonged siege or conflict without needing to venture outside to a well or river.

Big Spring, Washington County

Big Spring (WA-BF 3 in MD database) is in the town of Big Spring, about 3 miles south of Clear Spring and I-70, at the intersection of Big Spring Road and Clear Medow Road. Discharge rate of the spring was measured four times between June 1996 and February 1997 and varied slightly: 1,304 to 1,488 gpm (Duigon, 2001, Appendix C, p. 82-83); water temperature was measured more frequently between January 1996 and February 1997 and varied between 11.7ºC and 12.1°C (53ºF and 53.8ºF).



Figure 3.10.19 Big Spring in Town of Big Spring is privately owned; it discharges below the main house shown in the photo and is piped to a small stone springhouse shown in lower right.

Big Spring issues from limestone with laminated dolomite of the middle member of the Ordovician Conococheague Formation. It is believed that the underlying, basal member of the Conococheague Formation, named Big Spring Station Member, is part of the reason for the spring's emergence since it is less permeable, owing to the presence of shale and sandstone beds in less soluble dolomite. The Big Spring Station Member name is credited to J.L. Wilson who measured the type section at railroad cuts north of and in fields west of Big Spring Station on the Western Maryland Railroad (Cloos, 1951).

Geologic map of the wider Big Spring area (Fig. 3.10.29), like most other maps of the Valley and Ridge province, shows less than a handful of faults (discontinuities) crossing or interrupting smooth boundaries of geologic units folded into series of generally parallel synclines and anticlines. The absence of mapped faults is not surprising given many difficulties with their verification in the field. At the same time, the tectonic fabric caused by intense folding of brittle carbonates is virtually certain to include many faults, fault zones, and fractures, all of which provide key foundation for development of preferential and interconnected flow paths in the karst aquifers (Fig. 3.10.21).

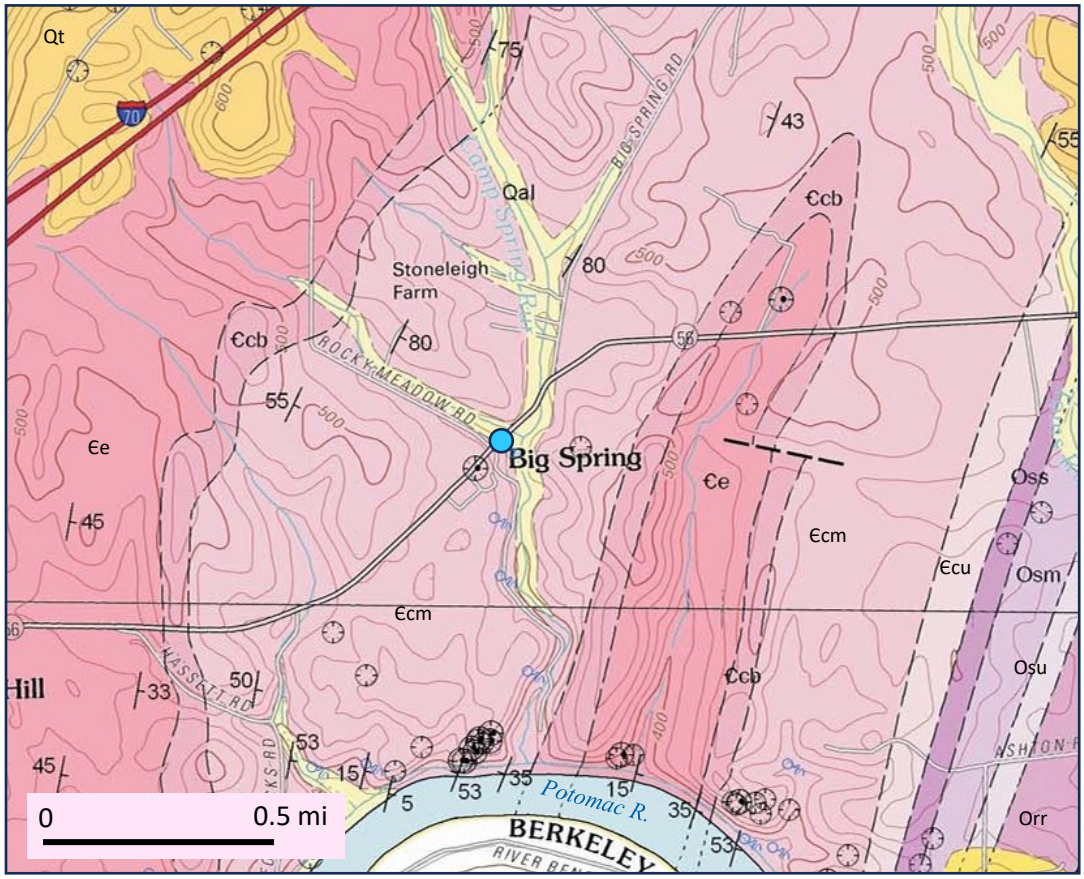


Figure 3.10.20 Geologic map of the Big Spring area (part of Geologic Map of Maryland Portions of the Clear Spring and Hedgesville Quadrangles; from Brezinski and Glaser, 2014; some annotation added.) Geologic units from oldest to youngest: Ꞓe—Cambrian Elbrook Formation limestone and dolomite. Ꞓcb—Conococheague Formation Big Spring Station Member dolomite (base of the formation). Ꞓcm—Conococheague Formation middle member; predominantly limestone with laminated dolomite. Ꞓcu—Conococheague Formation upper member; lime mudstone, locally with marble strata. Oss—Ordovician Stonehenge Formation Stoufferstown Member; lime mudstone with thin beds of lime grainstone and limestone. Osm—Ordovician Stonehenge Formation middle member; massive lime boundstone. Osu—Ordovician Stonehenge Formation upper member; lime mudstone and packstone. Orr—Rockdale Run Formation limestone and dolomite. Qt—Terrace deposits. Qal—Alluvial deposits. Closed circles denote sinkholes.

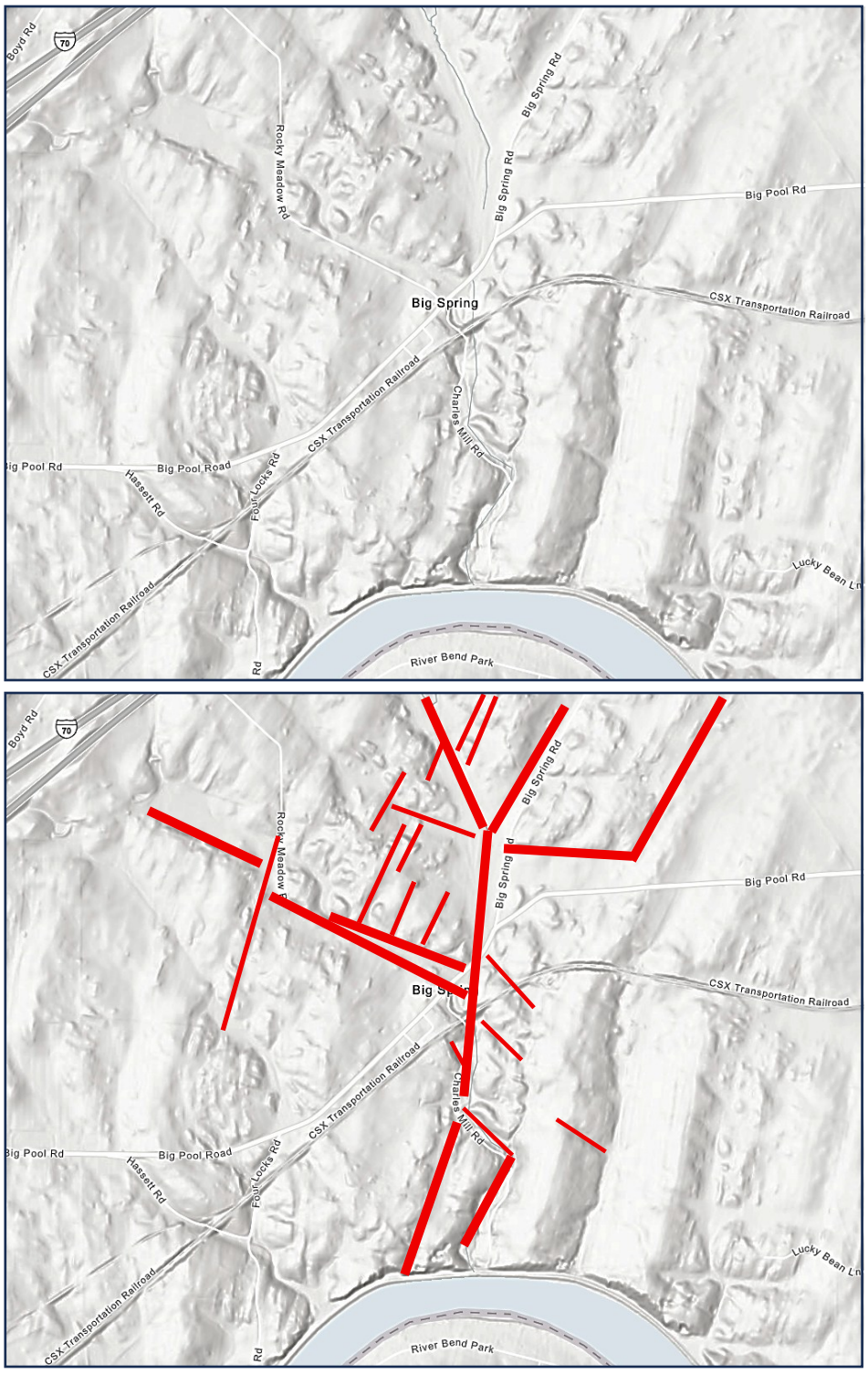


Figure 3.10.21 Shaded relief map of the Big Spring area and observed lineaments based on sharp contrasts. Not all possible lineaments are denoted, and the interpretation is subjective by default. Thick red lines are major breaks in the relief, indicating possible large faults and/or fault zones. Thin red lines are likely fracture sets and/or small faults which influenced development of the drainage pattern. Shaded relief map from The Cooperative National Geologic Map by USGS. [Cooperative National Geologic Map | NGMDB]

Murley Branch Spring, Allegany County

Located in the town of Rush, less than ¼ mile NE of Rush Church on Williams Road, the headspring of Murley Branch is on private property and access is restricted. There is a small dam impounding the immediate discharge from the spring (Fig. 3.10.22). In old reports, as well as locally, the spring is referred to as Big Spring: *"Little need be said concerning the ordinary springs except to speak of their abundance and general distribution. Along the Tuscarora-Clinton, the Oriskany-Eomney, and the Mauch Chunk-Pottsville contact lines excellent springs are particularly numerous. Many good springs occur elsewhere, but throughout the greater part of the county they are not so strong nor so regularly distributed as along the lines indicated. A few important exceptions occur. These are often closely related to disturbed strata, an excellent example of which may be seen to good advantage at the " Big Spring " one mile southwest of Rush. This is perhaps the strongest spring in the county and its waters flow from a local anticline in the Helderberg limestone*." (Maryland Geological Survey, 1900; p.192).

Based on most recent geologic map, the spring issues from the Silurian Tonoloway Limestone at the contact with the underlying Silurian Wills Creek Shale (Brezinski et al., 2025).

Discharge of the spring was measured between October 1957 and July 1959 and varied between 370 and 3,000 gpm (Slaughter, 1962). Otton and Hilleary (1985) report 3 measurements of 850 gpm (Sep 1979), 670 gpm (Sep 1980), and 810 gpm (July 1981). Water temperature varied between 50°F and 54°F, with mean of 52°F based on 12 measurements between June 1981 and May 1982 (Otton and Hilleary, 1985).



Figure 3.10.22 Murley Branch Spring in March 1982. Photo courtesy of Maryland Geological Survey; from Otton and Hilleary, 1985.

Blue Spring (Potomac Blue Spring), Allegany County

Blue Spring (often referred to as Potomac Blue Spring; AL-CE 1 in MD database) is located at Lock 72 of the Chesapeake and Ohio Canal (C&O Canal), almost exactly 10 miles below Cumberland (in the days that the canal was operational Lock 72 was known as "Ten Mile Lock"). Blue Spring is owned by the National Park Service and officially recognized as Maryland's largest spring by the State agencies (e.g., Otton and Hilleary, 1985; The Maryland Office of Planning, 1998). It is featured on various social media including webpages of reputable organizations such as C&O Canal Trust, which sometimes stretch the limits of available information: *Blue Spring*

is one of the largest springs east of the Mississippi. Crystal clear, blue water flows from the spring into the Potomac River (https://www.canaltrust.org/pyv/blue-spring/).

There are less than a handful of officially reported discharge rates of Potomac Blue Spring. An unknown number of measurements were made between October 1957 and September 1959. The maximum of 9,750 gal/min (21.7 cfs) was recorded on 4/17/58, and the minimum of 3,510 gpm (9.4 cfs) on 10/4/57 (Slaughter, 1962, p. 20). Two additional values were reported in Otton and Hilleary (1985): on 9/02/80 the discharge was 4,937 gpm (11.0 cfs), and on 7/23/81 it was 4,623 gpm (10.3 cfs). For comparison, Pennsylvania has at least seven springs with an average discharge rate higher than 10,000 gpm (26.8 cfs; all are springs of second magnitude), Florida has at least forty such springs (including 1st magnitude springs), and other states east of Mississippi have at least a dozen larger springs.



In June 2026, about a week following a small rainfall episode, the spring was flowing at an estimated rate of less than 1,500 gpm (Fig. 3.10.23-*Bottom*). In any case, Blue Spring is substantial so that the city of Cumberland historically evaluated it as a major alternative municipal water supply source.

Based on 12 measurements between February 1981 and February 1982, the mean water temperature is 11.0°C (51.8°F; Otton and Hilleary, 1985.)



Figure 3.10.23 Potomac Blue Spring is officially the largest spring in Maryland. Being a short distance from the North Branch of Potomac River, it is subject to flooding. *Top*: Google Earth map of the spring area. *Bottom*: Photo of the spring in June 2026 when the estimated discharge rate was less than 1,500 gpm. The spring bubbles up through bottom covered with sediment.

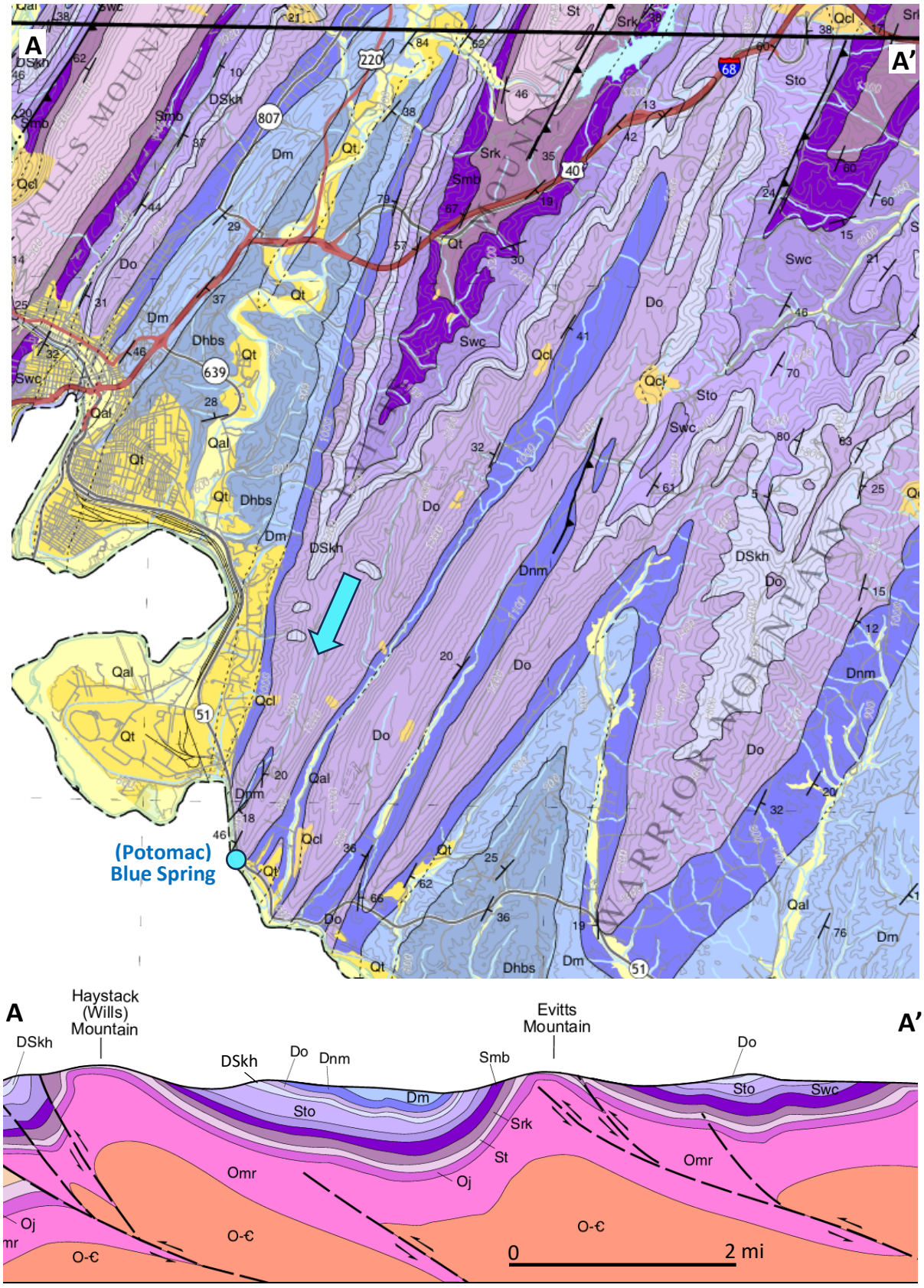


Figure 3.10.24 Geologic map of the Potomac Blue Spring area. From Brezinski et al., 2025; some annotation added.

Figure 3.10.24 (Cont.) Dhbs—Harrell Shale-Brallier-Scherr Formations (Devonian, undivided; 3500 ft); calcareous shale, interbedded shale, siltstone, and sandstone. Dm—Mahantango Formation (Devonian; 1400 ft); siltstone to sandstone, shale. Dnm—Needmore-Marcellus Shales (Devonian, undivided; 500 ft); calcareous shale with thin 1 foot beds of limestone, limestone, and shale. Do—Oriskany Formation (Devonian, 300 ft); interbedded siliceous shale, with sandy and cherty limestone near the base (Shriver Shale Member); overlain by calcareous sandstone (named Ridgely Member at the top). DSkh—Keyser-Helderberg Limestones (Devonian-Silurian, undivided; 380 ft); primarily limestone with some interbeds of calcareous shale. Sto—Tonoloway Formation (Silurian; 400 ft); dolomitic limestone with thin layers of limestone and laminated dolomite. Swc—Wills Creek Formation (Silurian; 400 ft); interbedded calcareous and dolomitic shale, and tan, dolomitic shale containing mud cracks, laminations, and salt and gypsum casts. The thickness of the Wills Creek Formation is approximately 400 feet (120 m). Smb— McKenzie-Bloomsburg Formations (Silurian, undivided; 330 ft); interbedded calcareous shale, thin-bedded, fossiliferous limestone, sandstone, and shale. Srk—Rose Hill Formation-Keefer Sandstone (Silurian, undivided; 300 ft); shale, and sandstone. St—Tuscarora Sandstone (Silurian, 380 ft); sandstone locally interbedded with shale. Oj—Juniata Formation (Ordovician; 300 ft); sandstone, siltstone, and shale. Undifferentiated Ordovician-Cambrian (O-Є) rocks shown only in cross-section. Blue arrow shows a regional groundwater flow direction.

Blue Spring bubbles up through the silty and sandy alluvial sediments of the Potomac River, forming a spring pool and a short run that flows to the Potomac River. It is about 15 feet lower than the C&O canal which is occasionally filled with water after heavy rains but is dry most of the time in the immediate vicinity of the spring. Along the Canal there are outcrops of the Oriskany Formation Ridgley Sandstone which is the main and obvious reason why all related geologic and hydrogeologic reports state that Blue Springs discharges from Oriscany Sandstone.

However, given the high discharge rate of the spring, uncharacteristic of any sandstone aquifer in any state of the Valley and Ridge Province, or indeed the country as a whole, it is almost certain that the main aquifer feeding the spring is karstic as evidenced from Fig. 3.10.24. Devonian-Silurian Keyser-Helderberg Limestones (DSkh) and Silurian Tonoloway Limestone (Sto) are underlying the Oriskany Formation sandstone and shale (Do). Together, they form a karst aquifer that is at least 500-700 feet thick in Allegany County. In turn, the Oriskany is eroded in several locations north of Blue Spring where Keyser-Helderberg Limestones are exposed at the land surface. The karst aquifer limestones outcrop and are directly recharged in a continuous belt on the flanks of the Evitts Mountain Anticline north of the Spring. A general flow direction in the karst aquifer is to the south, towards Blue Spring and the regional erosional basis, the Potomac River. It is also likely that part of the discharge from the karst aquifer and the overlying formations is directly to the river, as a "diffuse discharge".



Figure 3.10.25 *Top*: Outcrop of Ridgely Member sandstone of the Devonian Oriscany Formation along C&O Canal near Blue Spring. *Bottom*: Short run from Blue Spring flows to the Potomac River. Note the contrast between the clear spring water and muddy river water. Photo taken in June 2026.

3.11 Pennsylvania

Pennsylvania spans, from east to west, the Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateaus physiographic provinces and is underlain by chiefly Paleozoic sedimentary rocks. Pleistocene glacial sediments, locally more than 50 ft thick, overlay the bedrock in northern parts of the state (Soller and Packard, 1998). Potentially karstic units for Pennsylvania were derived by Weary (2008) from a digital version of the 1:250,000-scale state geologic map published on the internet by the Pennsylvania Geological Survey (Miles et al., 2001).

In the Piedmont, primarily in Chester County, Lower Paleozoic marbles that may be karstic (denoted with M on the map in Fig. 3.11.1) include the Cockeysville, Franklin, and Wakefield Marbles. Triassic limestone conglomerates are found in Mesozoic basins in a northeast to southwestward-trending belt in Berks, Lancaster, Lebanon, York, and, Adams Counties (TJB).

No karstic units were identified in the Blue Ridge Province of Pennsylvania.

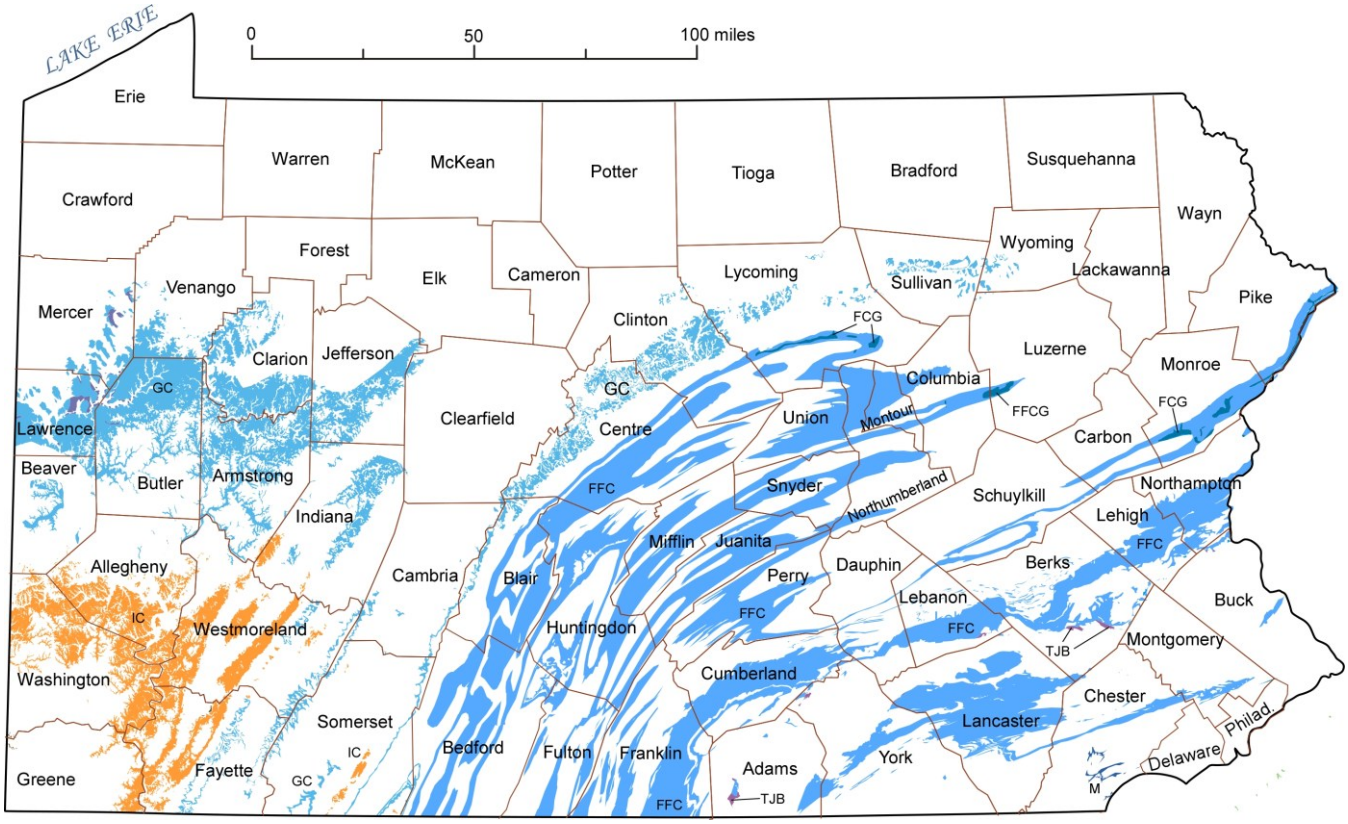


Figure 3.11.1 Karstic rocks in Pennsylvania. FCC: Folded, faulted carbonate rocks of Paleozoic age. FCG: Folded, faulted carbonate rocks with glacial cover. GC: Gently folded and flat-laying limestone and dolomite in interior plateaus and lowlands. IC: Carbonates interbedded with non-soluble sedimentary rocks; karst features are rare. TJB: Triassic and Jurassic calcareous sedimentary rocks. M: Marbles and metalimestones, usually found in thin, linear belts or pods. Karst areas from Weary, 2008.

As described by Weary (2008), in the Valley and Ridge Province, including the Hamburg klippe, karstic rock units range from Early to Late Paleozoic ages (FFC). Many have the same lithology and names as the units described previously in Virginia, West Virginia and Maryland. Some familiar, highly karstified carbonates include Beekmantown Group, Elbrook Formation, Keyser and Tonoloway Formations, limestone of the Martinsburg Formation, Greenbrier Limestone, Stonehenge Formation, and Tomstown Formation. Specific to Pennsylvania are

quite a bit more karstified carbonate units. Confusingly, however, various official sources including authors of Pennsylvania Geologic Survey, sometimes use different names for the same locations. Here is just one example: Flippo (1974) states that Nippono Spring, the largest in Pennsylvania, issues from the Nealmont and Curtin Formations, whereas the geologic map by Lloyd and Carswell, (1981) shows that the spring issues at a contact between the limestones of Rodman Formation and the overlying Salona Formation limestones with thin interbeds of calcareous shales. Rodman Formation is a part of Nealmont Formation, and Curtin Formation, equivalent of Linden Hall Formation, is older than Salona Formation, although both are of Ordovician age.

In any case, when it comes to the hydrogeologic importance of different types of rocks, the most important factor when evaluating karst aquifers and springs is their overall lithology: carbonates (karst) vs. non-carbonates (e.g., clastics). It of course goes without saying that familiarizing with the "local" geologic nomenclature is always beneficial.

In the Appalachian Plateau of Pennsylvania, units that are potentially karstic (GC on map in Fig. 3.11.1) include: the Mauch Chunk, and Allegheny Formations, and Monongahela Group. Areas defined by these formations greatly overstate the potential karst area, as both are primarily clastic units; however, each contains limestone known to be karstic. The Mississippian Mauch Chunk Formation contains the Loyalhanna, Greenbrier, Wymps Gap, and Deer Valley Limestone Members, and the Pennsylvanian Allegheny Formation contains the Vanport Limestone Member. The Loyalhanna and Vanport Limestones are the primary cave-bearing units in western Pennsylvania (White, 1976).

The Pennsylvanian Monongahela Group, which crops out in the southwestern corner of the state, contains the Benwood limestone (informal unit, also called the Sewickley Member of the Uniontown Formation in the past; denoted IC on the map in Fig. 3.11.1) which is significantly thick (as much as 70 ft). No references mentioning the presence of caves were found for the Benwood, but it does contain karst springs and must at least have solutionally enlarged joints and bedding planes, if not minor caves (Weary, 2008).



https://www.springcreekwatershedatlas.org/post/2019/03/14/geologic-history story

Figure 3.11.2 Lower Ordovician carbonate rocks along State Route 144 near Axemann in Centre County. From *The Spring Creek Watershed Atlas, Geologic History* by Robert Schmalz, Professor Emeritus of Geology. Photo by Robert Schmalz.



Figure 3.11.3 The Maple Hill Sinks are a series of limestone sinkholes located in Brady and Washington Townships in Lycoming County. They span about 1.4 miles and are situated in a rural valley near the communities of Allenwood and Elimsport. During heavy rains, these natural sinkholes fill with water to form large, temporary lakes connected via small streams. This pond will be nearly dry by mid-summer. Photo courtesy of The Nature Conservancy, 1993.



Figure 3.11.4 The Allentown Formation is a dolostone [CaMg(CO3)2] originally deposited as limy mud and sand in warm, shallow seas that once covered all the eastern United States during the Late Cambrian Period (515-500 Ma). Underlying much of the southern Lehigh Valley and Saucon Valley, the Allentown Formation outcrops along the Saucon Rail Trail (SRT) near the border of Hellertown and Lower Saucon Township. Courtesy of Department of Earth & Environmental Sciences, Lehigh University (Allentown Formation Rock Outcrop).

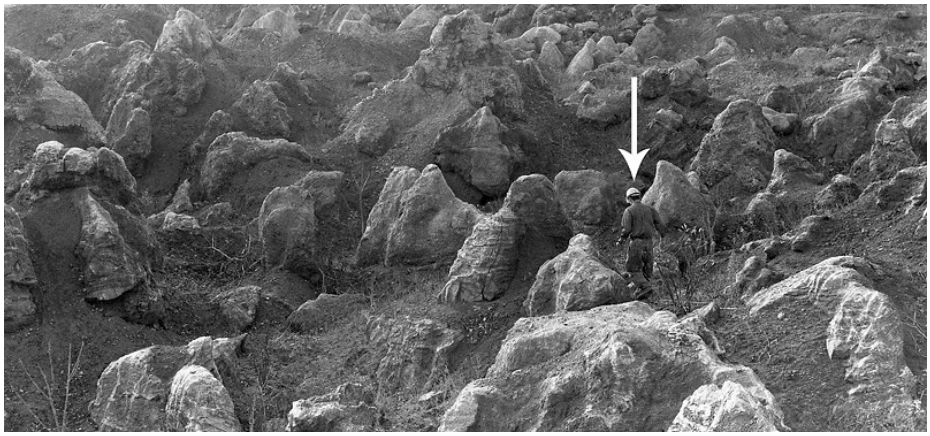


Figure 3.11.5. Pinnacles of limestone exposed on the property of the former J. E. Baker quarry in York County. Man (below arrow) is approximately 6 feet tall. Photograph by Helen Delano. From Kochanov, 2015.



Figure 3.11.6 Tytoona Cave Nature Preserve in Blair County is owned by the National Speleological Society. A permit, which can be obtained online at no cost, is required to enter Tytoona. The cave receives water from a short stream that appears at the other end of the karst window. The downstream portion of the cave system exits at Arch Spring, which is privately owned and not on Tytoona Cave Nature Preserve property.

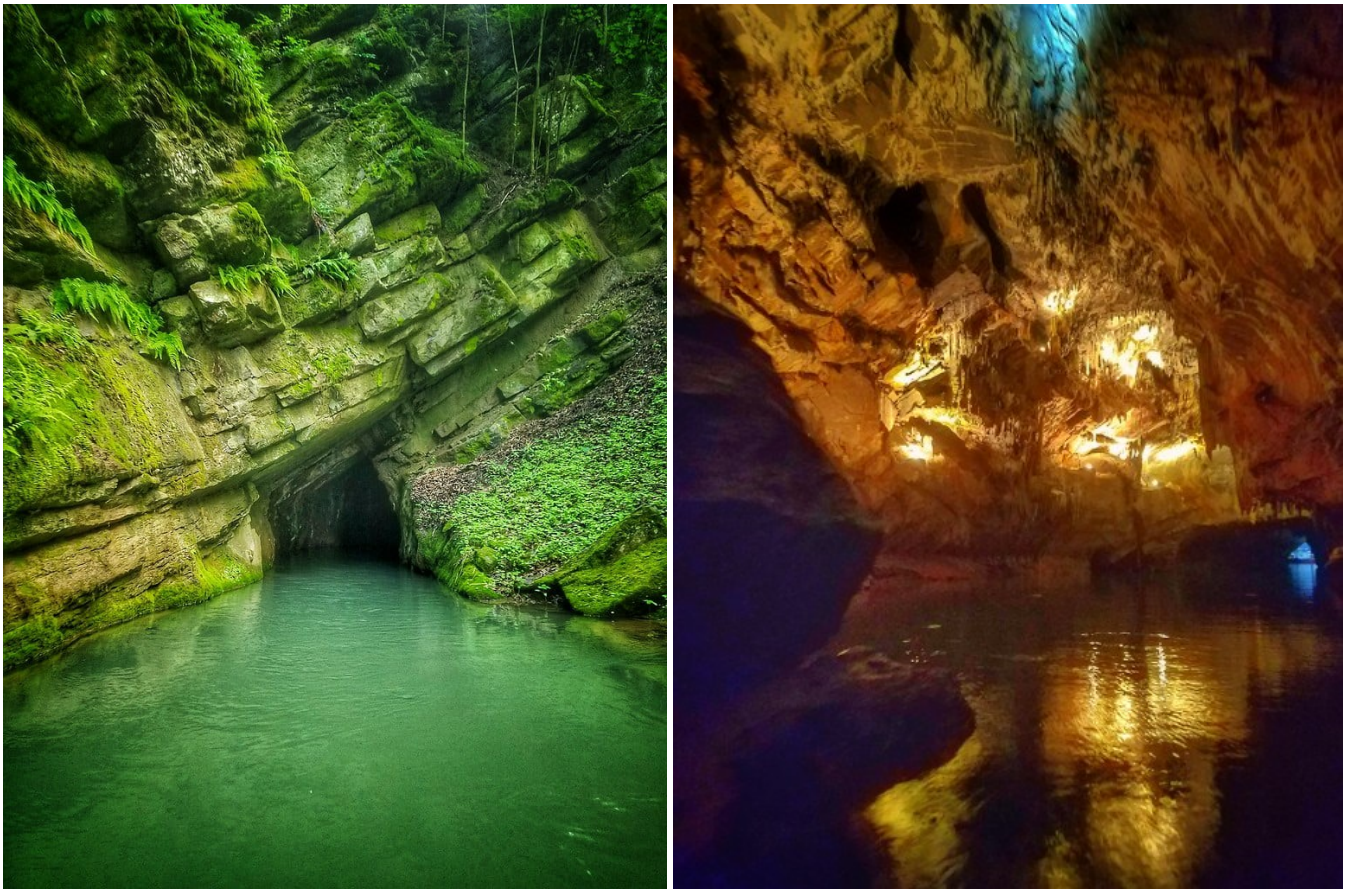


Figure 3.11.7 Penn's Cave in Gregg Township, Centre County is the only cave in Pennsylvania on the National Register of Historic Places. The entire tour of this show cave is conducted by boat, and it features glittering stalactites and stalagmites, often in mysteriously familiar shapes, such as *The Statue of Liberty* and *The Garden of the Gods*. https://www.pennscave.com/history-geology/geology. Penn's Cave Spring shown in the left photo discharges from the Middle Ordovician Nealmont Formation limestone. The state of Pennsylvania is currently in the process of establishing Penn's Cave State Park. Photographs by Terry Tyson, Penn's Cave. | Terry Tyson | Flickr and Penn's Cave opening

As discussed by Saad and Hippe (1990): "*Discharges of some of the larger springs in the Valley and Ridge physiographic province do vary greatly however, and some instantaneous discharges greater than 44,900 gal/min have been reported. Nippono Spring (Ly 1) in Lycoming County, which has a median discharge of 18,000 gal/min (Flippo, 1974), has a reported instantaneous discharge of 66,300 gal/min. Large variations in discharge are characteristic of conduit flow systems and are discussed in detail in the next section. Large variations in discharge also are characteristic of surface streams that enter the subsurface through sinkholes or caves. A conduit spring, such as Arch Spring (Ba 21) in Blair County, that receives recharge from such streams also will have large variations in discharge*."

Deciphering what any spring truly is, when it comes to a reasonable average discharge rate, is not a straightforward exercise when the information behind an official record is not fully explained. For example, Flippo (1974) gave estimates of mean discharge rates for all springs included in his report, even when only one measured value was provided as in the cases of Mammoth Spring in Mifflin County, and Taylersville Spring in Clinton County (see Table 3.11.1, which is based on the original Table 2 in Flippo's report). In a few instances, a note states that estimates are based on daily discharge collected by owner (e.g., Schantz Spring in Lehigh County owned by the City of Allentown and used for water supply). Saad and Hippe (1990) include the information from Flippo (1974) in their report titled "Large Springs in the Valley and Ridge Physiographic Province of Pennsylvania" and add only a handful of newer measurements or clarifications for several springs.

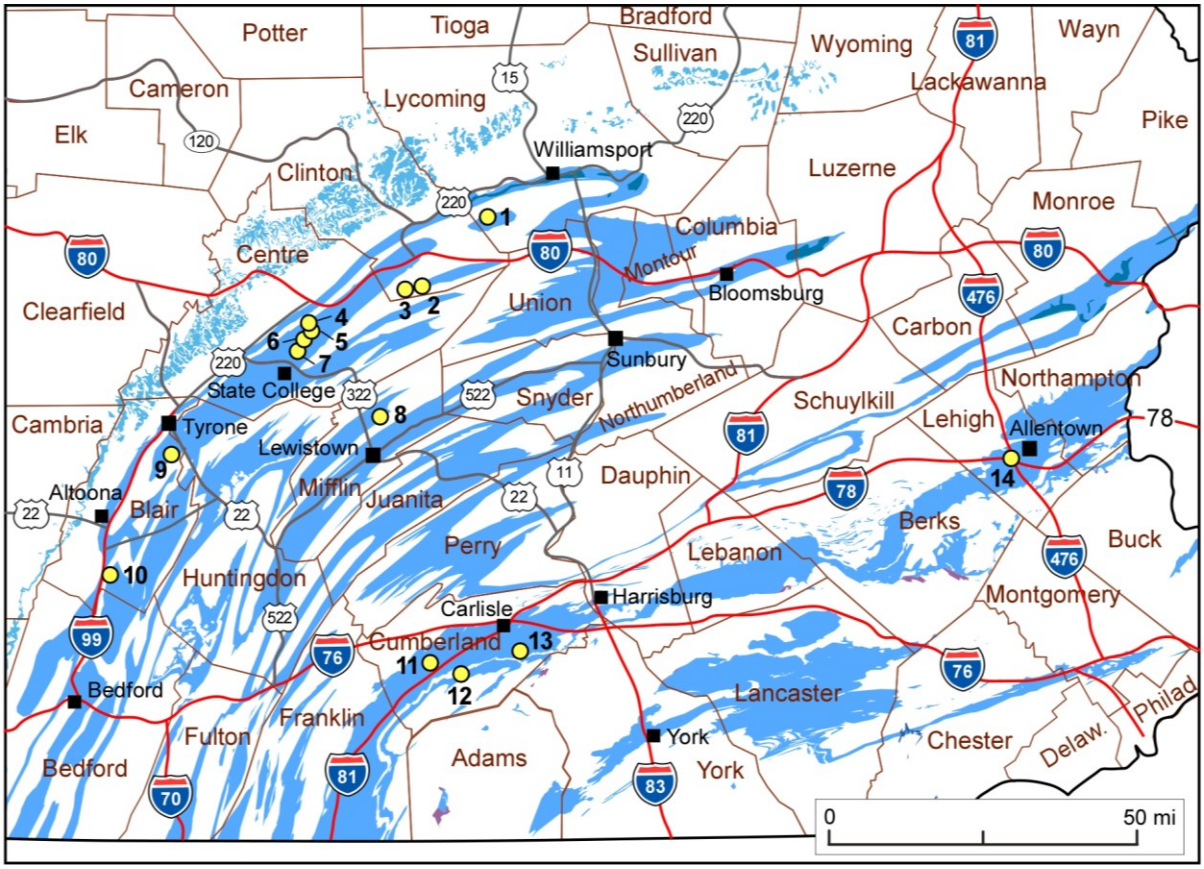


Figure 3.11.8 Locations of second magnitude (average discharge rate between 10 and 100 cfs; 10 cfs = 4,488 gpm), and other large karst springs in Pennsylvania, based on information presented in Flippo (1974), and Saad and Hippe (1990). Note that there are no updated, publicly available state-wide or county-wide reports that include information on mean, minimum, and maximum discharge rates of these or potentially other second-magnitude springs in the state. Karst (blue) areas from Weary, 2008. Spring names are provided in Table 3.11.1.

Table 3.11.1 Second magnitude and other notable large karst springs in Pennsylvania based on Flippo (1974), and Saad and Hippe (1990; denoted with *). Second magnitude springs have mean discharge rate between 10 and 100 cfs, or between 4,488 and 44,880 gpm.

No.	Spring Name	County	Aquifer Unit	Est. Mean (gpm)	No. of Measur.	Est. Min. (gpm)	Est. Max. (gpm)
1	Nippono Spring	Lycoming	Nealmont & Curtin Fm.	18,000	4	2,300	66,300*
2	Tylersville Spring	Clinton	Nealmont Formation	13,000	1	—	—
3	Ruhl and Seven Springs	Clinton	Nealmont Formation	14,000	1	4,000	26,000
4	Bellefonte (Big) Spring	Centre	Axemann & Bellefonte Fm.	8,000	3	6,000	14,000
5	Kelly Spring	Centre	Beekmantown Group	7,000	2	7,000	8,600
6	Forked (Paradise) Spring	Centre	Gatesburg Formation	13,160*	19*	2,580	18,400
7	Benner (Rock) Spring	Centre	Beekmantown Group	4,000	2	4,080	7,300
8	Mammoth Spring	Mifflin	Curtin & Loysburg Fm.	14,000	1	—	—
9	Arch Spring	Blair	Loysburg Formation	8,000	3	2,000	13,500
10	Roaring Spring	Blair	Nittany Formation	4,500	3	4,280	5,500
11	Big Spring	Cumberland	Beekmantown Group	12,500	9	6,000	15,000
12	Huntsdale Hatchery Sprs.	Cumberland	Tomstown Formation	12,000*	1-2	—	—
13	Boiling Springs	Cumberland	Elbrook Formation	11,500	7	10,800	18,300
14	Schantz Spring	Lehigh	Beekmantown Group	4,400	1	3,700	5,500

Since the publications of Flippo (1974), and Saad and Hippe (1990), there have been no updated state-wide reports on the characteristics of the state's springs including their discharge rates and water quality. In addition, it appears that there are no continuing discharge measurements, either by a state agency or USGS, at any of the large springs. Map in Fig. 3.11.8 and Table 3.11.1, which show all second-magnitude springs in Pennsylvania (there are no first-magnitude spring in the state), are a compilation of the current publicly available information and should therefore be viewed as a simple, preliminary assessment (estimate) of discharge rates of the largest karst springs in Pennsylvania.

Nippono (Enchanted) Spring, Lycoming County

Nippono Spring (in older geological records sometimes referred to as Nippenose Spring or Enchanted Spring) is situated in the Nipponese Valley in Lycoming County, near the village of Oriole in Limestone Township. The spring is privately owned, and it is currently protected by a registry agreement between the landowners and Northcentral Pennsylvania Conservancy. Access to the spring is restricted.

Nippono Spring is now widely accepted as the largest in Pennsylvania. There are total of four discharge rates for the spring available publicly, in the official reports by Government Agencies: (1) 18,000 gpm, which is a median rate first provided by Flippo in 1974 and then cited by Saad and Hippe in 1990; (2) One measurement of 20,000 gpm, performed on September 12, 1971 and provided by Flippo in 1974; (3) 2,300 gpm measured on October 01, 1932, also provided by Flippo (Table 2, p. 28); and (4) 66,300 gpm measured in March 1977 and reported by Lloyd

and Carswell (1981). Notably, Flippo (1974), based on only two actual measurements (20,000 gpm and 2,300 gpm), estimated that the median discharge rate is 18,000 gpm, and the minimum is 2,000 gpm; no maximum was estimated.

Lloyd and Carswell (1981; pp.18-19) estimate that the average discharge of Nippeno Spring (their name for Nippono Spring) is 52 Mgal/d (million gallons per day) or 36,000 gpm. This is based on an estimated average transmissivity of the carbonate rocks in the conduit-drainage system feeding the spring of about 11,500 ft^2d (square feet per day). This transmissivity was, in turn, estimated assuming average flow conditions and hydraulic gradients determined from a potentiometric surface map of the aquifer.

In summary, selecting an average discharge rate for Nippono Spring is somewhat subjective, to say the least. Nevertheless, the spring is officially considered as the largest in Pennsylvania and listed as such in more recent publications by the Pennsylvania Geological Survey (Kochanov, 2010).

The geologic conditions that contributed to the formation of the Commonwealth's largest spring are illustrated in Figs. 3.11.9 and 3.11.10.

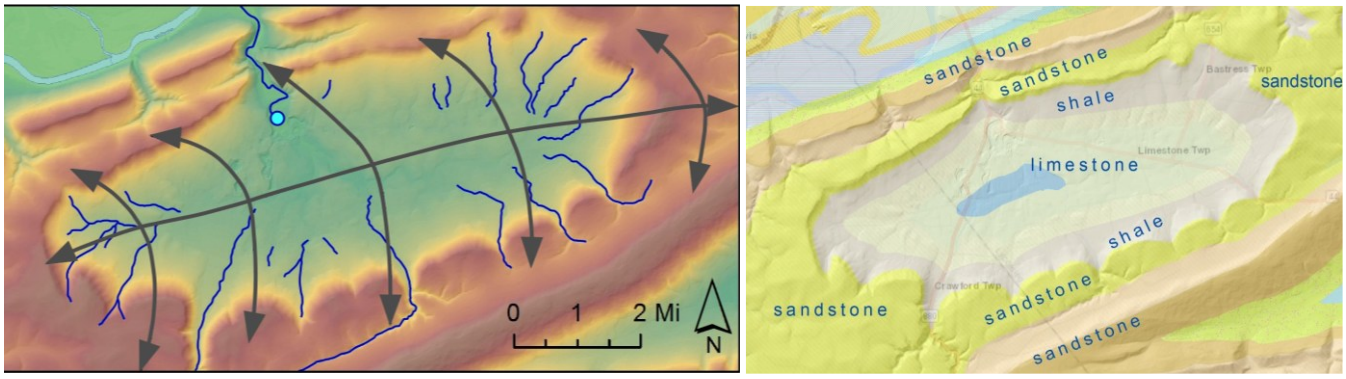


Figure 3.11.9 Nipponese Valley is formed in the eroded core of a doubly plunging anticline. The geology of the valley controls the groundwater flow. Streams flow down the rim, composed of Ordovician sandstones and shale and disappear into sinkholes at the perimeter of the valley. In the subsurface, water flows through connected fractures and larger voids in the Ordovician limestones before emerging as springs. This includes Nippono Spring (blue dot), Pennsylvania's largest. The spring is draining virtually the entire baseflow of the valley and serves as headwaters of the permanently flowing Antes Creek which continues north through a water gap to the West Branch Susquehanna River. From Reese, 2016.

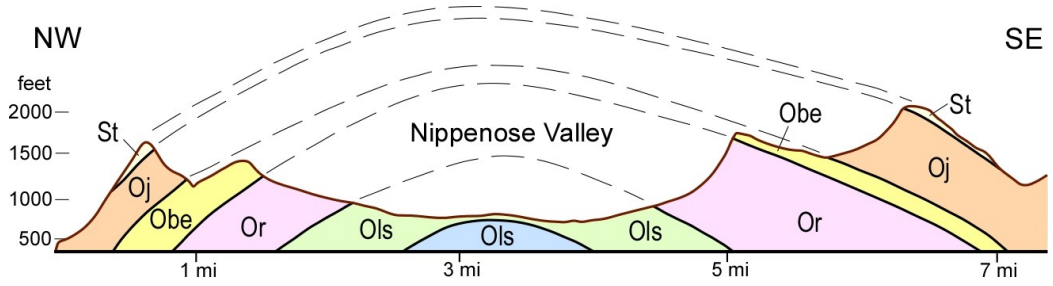


Figure 3.11.10 Cross section looking northeast through the breached anticline of the Nippenose Valley. Rock units include the Tuscarora (St), Juniata (Oj), Bald Eagle (Obe), and Reedsville (Or) Formations, and Ordovician limestones (Ols). Modified from Reese, 2016. According to Wells et al. (1977), the Ordovician limestones include, from oldest to youngest: Bellefonte Formation in partially eroded core of the anticline, Loysburg Formation, Hatter Formation, Snyder Formation, Linden Hall Formation, Rodman Formation, Salona Formation, and Coburn Formation. Antes Formation shales are deposited over limestones of Coburn Formation.



Figure 3.11.11 Nippono Spring (also called Enchanted Spring and locally known as Lochabar Spring) is a typical blue hole. It is the largest spring in Pennsylvania, with a median discharge rate of 18,000 gpm according to Flippo (1974). It is recognized as an Outstanding Scenic Geologic Feature of Pennsylvania (Geyer and Bolles, 1979). The spring is privately owned and access is restricted. Photograph taken with kind permission from Ms. Judith “Judee” Lyon.

Lochabar

"Lake where the deer shed their horns" is the literal translation of the romantic-sounding name—Lochabar. This farm stands on a portion of the fifteen hundred acres of land which, in 1700, was sold to William Penn by the king of the Susquehanna or Andastes Indians for "a parcel of English goods." This was King WiDaagh, son of King Nippenose, after whom the valley was named. The original grants of the Penn family listed the land as Sawmill Tract No. 1724.

The Nippenose Valley held a strange and compelling attraction for the Indians. Only in the deep forest of Lochabar could the secret order of the Immortals (known as the O.O.T.T.) be celebrated by the Andastes. Those who would undertake this "mystic rite and blood-curling initiation" won their places with the Immortals. The tests were beyond belief: the initiates had to grope their way through underground passages; grapple with serpents and demons; fight their way through fire and brimstone; be encumbered with insurmountable weights and put into the Giant's Pool—to emerge, at last, as Immortals.

The conditions at Lochabar were unique—for only there could be found wolf dens forty feet in diameter and eighty feet deep, with perpendicular walls, with subterranean streams and caverns leading from one wolf den to another. And the Giant's Pool, with its vertical walls of limestone and depth of three hundred feet, over which one had to leap at a single bound is not to be found elsewhere.

A great lake or a series of connected lakes are said to lie in subterranean limestone caverns beneath one thousand acres of the valley. This theory has not been disproven altogether because all surface waters have a tendency to disappear into the ground again the moment they reach the valley basin.

One immense spring bubbles up through a fissure in the rocks and it is the strange and beautiful emerald green pool formed by this spring that is called the Enchanted Spring. Steep, rocky banks covered with stately pine and hemlock trees surround this pool of mysterious beauty. The diameter of the pool measures about sixty feet. It was by the side of the Enchanted Spring that a sad and grieving King WiDaagh sat and meditated on his foolish transaction with Penn—the disposal of all this reasured land for a few wordly goods. As he sat and stared on the strange waters he often repeated this poem

"For who but learns in riper years
That man, when smoothest he appears,
Is most to be suspected."

It is said that the Enchanted Spring is haunted and this can be put to a test. If one stands on the south side of the pool and looks across the spring in a northeasterly direction at precisely three o'clock in the afternoon and gazes steadfastly at the face of the rocks which tower up from the water's edge, he will behold the gleaming eyes of the god of WiDaagh.

Williamsport Sun-Gazette, Williamsport, Pennsylvania, 04 Sep 1914, Friday, Page 7

Although Enchanted Spring is currently protected by a registry agreement between the landowners and Northcentral Pennsylvania Conservancy, it is entirely different question if it is protected from various external influences, the most obvious being massive limestone quarries, literally in the spring's backyard. It is unknown how both the historic and the ongoing operations in and around the quarries may have affected the spring. One reported impact is dramatic sedimentation and water turbidity after blasting at the quarries. Moreover, the spring sits only about 1,500 feet away from the Eiswert #1 cave which is the critical habitat for the incredibly rare Pennsylvania grotto sculpin, a cave-adapted fish found nowhere else on Earth.

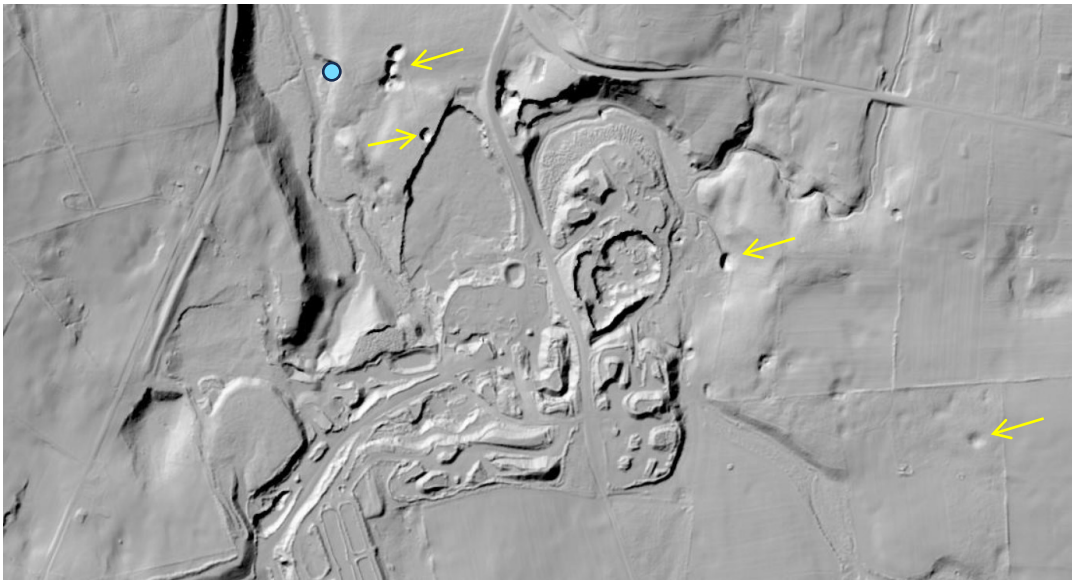
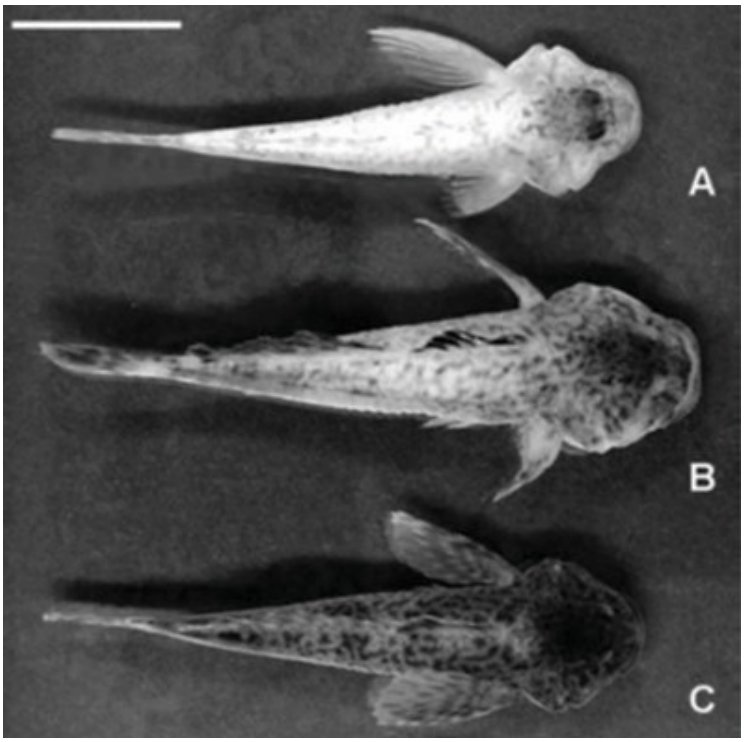


Figure 3.11.12 Massive limestone quarries scar the land surface in the immediate vicinity and upgradient of Nippono Spring (blue dot). Arrows point out some of the natural sinkholes. Image is about 1.2 miles across. Courtesy of USGS.

The following excerpts are from a scientific paper by Espinasa, Smith, and Lindquist (2021) and serve to illustrate the continuing threats to, and the needs to protect the exceptional karst environment of the Nippenose Valley.

The Pennsylvania grotto sculpin is known from just two caves of the Nippenose Valley in central Pennsylvania, USA. They exhibit emergent troglobitic morphological traits and are the second northernmost cave adapted fish in the world. (Note: the 2 caves are Eiswert #1, and Loose Tooth Cave, also within the Nippenose Valley, 2.13 km SSW of Eiswert #1).

The relevance of this study is not restricted to purely academic arenas. In 2002, two corporate hog farms intended to enter the Nippenose Valley. The proposed Concentrated Animal Feeding Operations (CAFOs) were to produce over 20,000 hogs along with 5 million gallons of antibiotic and steroid rich manure each year. This surface waste could easily enter and contaminate the underground network of groundwater through the honeycombed limestone, thereby contaminating the water supply for the inhabitants of the valley. Some residents quickly organized a group called the Concerned Citizens of Nippenose Valley (CCNV). CCNV invoked a local ordinance protecting their water supply to tie up the permit applications, while mounting a comprehensive public relations campaign to build broad-based community opposition to the CAFOs. While this was occurring, the troglomorphic sculpin was found in Eiswert #1 Cave and reported in the scientific literature (Espinasa and Jeffery 2003). In particular, Espinasa and Jeffery (2003) recommended that the U.S. Fish and Wildlife Service should consider the Pennsylvania grotto sculpin to be listed under the U.S. Endangered Species Act. Afterwards, the Williamsport Sun-Gazette ran an article titled "Fish Find May Nix Pig Farms." The CCNV's efforts culminated in a victory when both CAFO applications were withdrawn. Conservation risks persist for the Pennsylvania grotto sculpins. For example, a limestone quarry is just meters away from the cave and spring.



Nippenose Valley cave sculpins. From Espinasa et al., 2021. Related blind cave fish are protected in Missouri, are listed as *endangered* and *species of conservation concern,* and have the status of *federal endangered species.* https://mdc.mo.gov/discover-nature/field-guide/grotto-sculpin

Based on the result of their study, Espinasa, Smith, and Lindquist conclude that "*the Pennsylvania grotto sculpin deserves recognition as an independent species taxon from C. bairdii and C. cognatus. Recognition as an independent species will also help support current conservation efforts.*"

Perhaps the Enchanted Spring, the caves, and the Nipponese Valley will not share the sad destiny of many other exceptional karst features in the country, and that the State of Pennsylvania will not leave it all up to local citizen groups and others concerned.

Tylersville Spring, Clinton County

Tylersville Spring is situated near the head of Fishing Creek, about one-half mile northeast of the village of Tylersville, and approximately 600 feet east of Pa. Route 880. According to Flippo (1974), it is the fourth largest spring in Pennsylvania, having a median flow of 13,000 gallons per minute (in the Flippo's report it is listed as "Unnamed Spring"). The spring rises from fractures in the limestone of the Ordovician Nealmont Formation. It is recognized as an Outstanding Scenic Geologic Feature of Pennsylvania (Geyer and Bolles, 1979).



Figure 3.11.13 Tylersville Spring is one of the largest 2nd magnitude karst springs in Pennsylvania. Photo courtesy of Pennsylvania Geologic Survey. Originally published in Geyer and Bolles, 1979.

Ruhl and Seven Springs, Clinton County

Ruhl and Seven Sisters Springs constitute a spring pool utilized by the Pennsylvania Fish and Boat Commission's Tylersville Fish Culture Station on Fishing Creek in Loganton, two miles west of Tylersville. The Hatchery was originally constructed in 1963 by the United States Department of Interior, Fish and Wildlife Service (USFWS) and was closed in 1977. In 1984, the Commission entered into a lease agreement with the USFWS to maintain and operate the facility. The hatchery is located on approximately 40 developed acres (125 total acres) with 5,000 feet of concrete linear raceways.

The springs issue from enlarged fracture openings in the Nealmont Limestone of Ordovician age. They are officially recognized as an Outstanding Scenic Geologic Feature of Pennsylvania (Geyer and Bolles, 1979). They are also tracked closely within the Clinton County Natural Heritage Inventory.

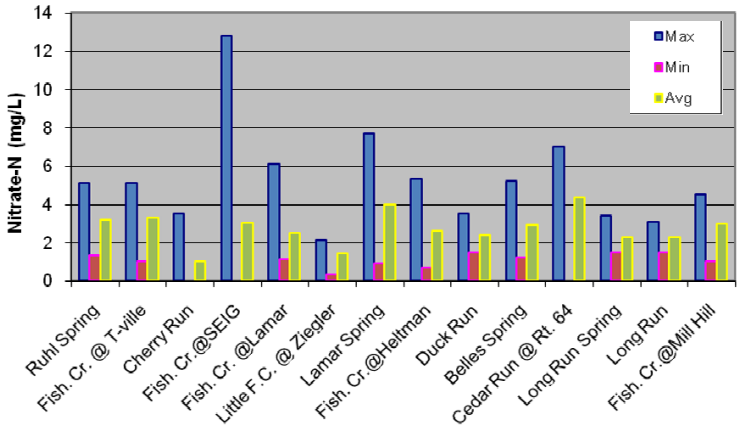


Figure 3.11.14 Ruhl Spring, which feeds the Tylersville State Fish Hatchery, had the highest average reactive phosphate concentration and the highest maximum value (3.0 mg/L) of 14 sites on the Fishing Creek Sites samples in 2008. This raised concern regarding the possibility of phosphates reaching Fishing Creek in large amounts at various times. Most of the creek's segments are designated as Class A Wild Trout Waters PAFBC, 2026). From *Coldwater Conservation Plan for the Fishing Creek/Cedar Run Watershed*, The Clinton County Conservation District, 2008.

Springs of Spring Creek, Centre County

As explained by Robert Carline in The Spring Creek Watershed Atlas (Carline, 2017), Spring Creek, a famous stream in the West Branch of the Susquehanna River watershed, is aptly named. Within this 146-square-mile watershed, there are at least seven springs that each produce more than 1 million gallons per day (Mgd) of clean, cold water. These springs have influenced settlement patterns in the watershed. The most famous is Big Spring around which the Borough of Bellefonte was founded in 1795.

In 1792, the flow from Thompson Spring was diverted to power the waterwheel at the Centre Iron Furnace in State College. Large springs in Pleasant Gap led to the establishment of the first trout hatchery in the watershed in 1903. A second hatchery was built in 1933 near large springs along Spring Creek in an area now known as Fisherman's Paradise. And, Benner Spring, a few miles downstream of State College, became the site of a third fish hatchery in 1951. The number of prolific springs in the watershed is tied to the geology of the area.

The watershed, which lies within the Ridge and Valley Physiographic Province, is bordered by long, high ridges on the north and south with a broad valley in between. The ridges are comprised primarily of sandstone and some shales, while the valley is underlain by thick layers of limestone and dolomite. Sinkholes, which are common in the valley floor, are connected to dissolution cracks and caverns in the bedrock. These dissolution cavities provide a substantial storage capacity for groundwater and are the source of many large springs.



Figure 3.11.15 Pleasant Gap Fish Hatchery on Logan Branch when it opened in 1903. Photo courtesy of Bob Wilberding, Hatchery Manager in 2003.

The nature of groundwater flow in the Spring Creek watershed was well understood already in the 1930s as attested with the following excerpts from Butts and Moore (1936):

The underground circulation in the limestone and dolomite areas is very extensive, and sinkholes are common. A striking example of subterranean drainage is afforded by Big Hollow, a distinct stream channel now usually dry. Its drainage probably issues in the large spring farther down the valley near a spot known as "Rock." (Benner Spring, author's note). *The stream issuing from McBride Gap plunges from view half a mile below and is supposed to reappear in the springs near Pleasant Gap Station. Buffalo Run apparently carries only part of the drainage from the southeast flank of Bald Eagle Mountain. The rest may issue from its underground course in the large spring at Bellefonte.*

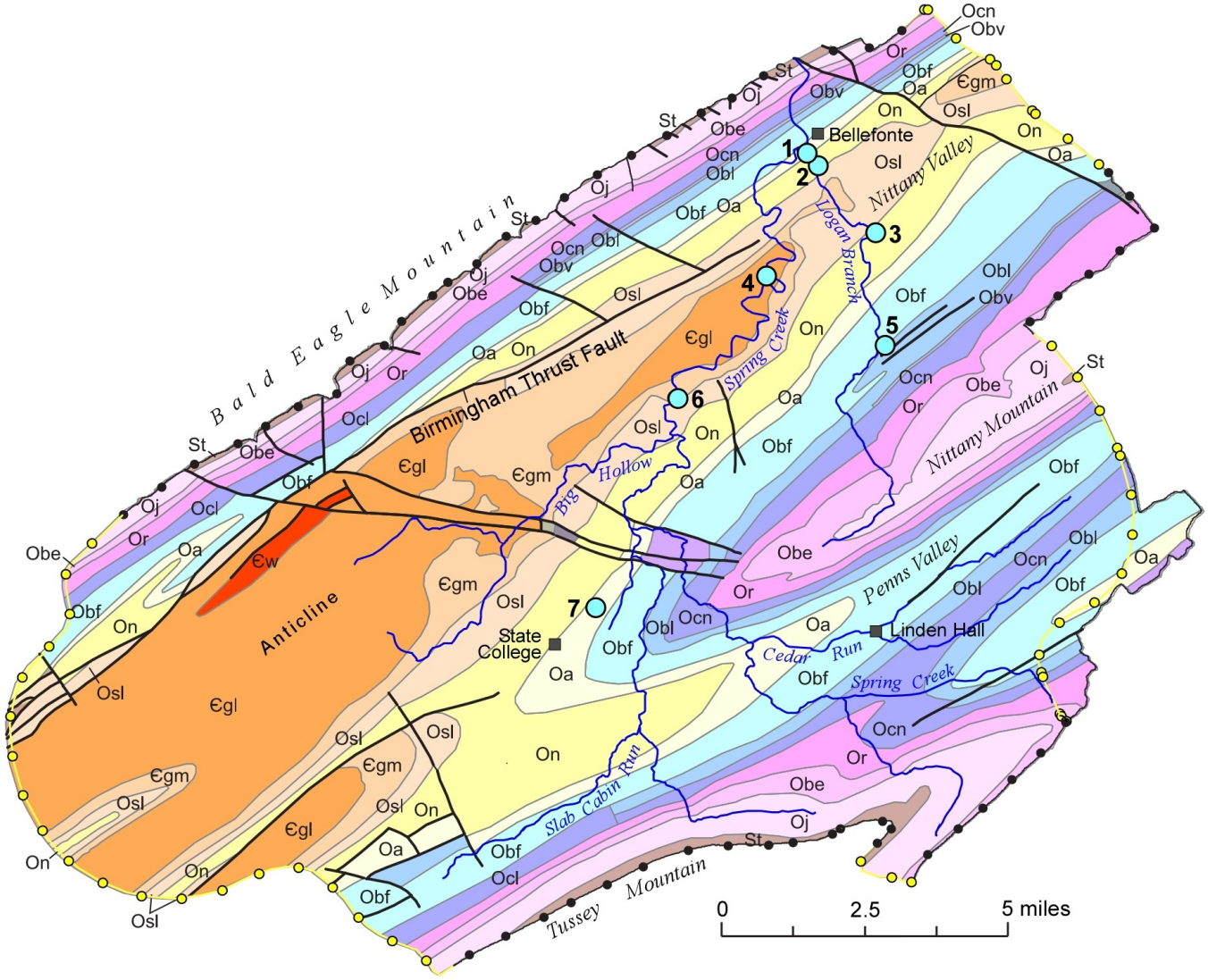
Most of the towns and villages in the quadrangle obtain their water supplies from springs. Bellefonte obtains water from a large spring within the town limits, which has a flow of 14,600 gallons a minute.

The abundant supply issuing from Thompson Spring, half a mile northeast of State College, has not been utilized because of the cost of pumping and the danger of contamination by sewage from the village above. Evidence of contamination is increasing is the greater percentage of nitrates found now than in former analyses. This spring flows during the summer about 2,625 gallons a minute. The apparent evidence of contamination of the water of Thompson Spring is an excellent example of conditions that generally exist where circulating ground water has produced open channels in limestone. The limestone is readily dissolved along joints and bedding planes by water containing carbon dioxide, and thus large and small cavities are produced through which the water flows as in a pipe that is, without any opportunity for self-purification by filtration as in sand or gravel. Consequently any polluting material that may enter the underground system in the vicinity of sink holes is likely to be carried rapidly through the limestone channels to the springs. Springs that by their large volume and low pressure indicate circulation in cavernous limestone should never be utilized as sources of water supply until careful tests have demonstrated the absence of immediate connection with sources of dangerous contamination. Such tests are usually made by introducing powerful dyes into the underground circulation at suspected points of pollution."



Figure 3.11.16 Thompson Spring in 2016. Photo by Robert K. Vierck. The spring, located just northeast of downtown State College, was historically know as "Great Falling Spring" or "Thompson Meadow Spring."
Restoration of Thompson Run - A Tribute to Joe Humphreys

The Spring Creek Basin is underlain by 6,000 to 8,000 ft of interbedded limestone, dolomite, and sandstone of Cambrian, Ordovician, Silurian, and Devonian age. The strata are folded into anticlines and synclines, and numerous normal, thrust, and strike-slip faults have offset the rocks in several places. The Birmingham Thrust Fault is the major fault extending through much of Nittany Valley. The geologic units and locations of major faults



EXPLANATION

SYSTEM	GROUP OR FORMATION	
SILURIAN	St - Tuscarora Formation	Siliciclastics
	Oj - Juniata Formation	
	Obe - Bald Eagle Formation	
	Or - Reedsville Formation	
ORDOVICIAN	Ocl - Coburn Formation through Loysburg Formation	CARBONATES
	Ocn - Coburn Formation through Nealmont Formation	
	Obl - Benner Formation through Loysburg Formation	
	Obv - Valentine Member of Benner Formation	
	Obf - Bellefonte Formation	
	Oa - Axemann Formation of Beekmantown Group	
	On - Nittany Formation of Beekmantown Group	
	Osl - Stonehenge/Larke Formation of Beekmantown Gr.	
CAMBRIAN	Ꞓgm - Mines Member of Gatesburg Formation	
	Ꞓgl - Lower members of Gatesburg Formation	
	Ꞓw - Warrior Formation	

Faults
Groundwater divide
Groundwater and surface water divide
Spring

1. Bellefonte (Big) Spring
2. Kelly Spring
3. Axemann Spring
4. Forked (Paradise) Spring
5. Pleasant Gap State Hatchery
6. Benner (Rock) Spring
7. Thompson Spring

Figure 3.11.17 Geologic map of the Spring Creek watershed. Modified from Fulton et al., 2005, and Berg et al.,1980.

as mapped by Berg et al. (1980) are shown on Fig. 3.11.17. The resistant quartzite of the Tuscarora Formation and the sandstone of the Bald Eagle Formation form the double ridges of Bald Eagle Mountain, and the less-resistant Juniata Formation underlies the small valleys between the double ridges. The Nittany and Penns Valleys formed on less resistant carbonate rocks of Cambrian and Ordovician age.

The rocks in the Spring Creek Basin have been fractured by many forces, principally those that formed the Appalachian Mountains. Fractures include cleavage, bedding-plane partings, joints, and faults. Some major fractures are expressed topographically and are referred to as fracture traces or lineaments. Fracture traces are natural linear features consisting of topo graphic, vegetation, or soil-tonal alignments that are visible primarily on aerial photographs, are greater than 1,000 ft in length, and are less than 1 mi in length. Maps of fracture traces in the State College area by Lattman and Parizek (1964) and Parizek and Drew (1966) suggest that fracture traces are abundant and tend to have north-south and east-west strikes, giving rise to large, irregular, rectangular blocks. Many fractures in the carbonate rocks beneath the valleys of Spring Creek Basin have been enlarged by dissolution. These enlarged fractures (vugs, solution cavities, sinkholes, and conduits) have a significant influence on the rate and direction of groundwater flow (Fulton et al., 2005).

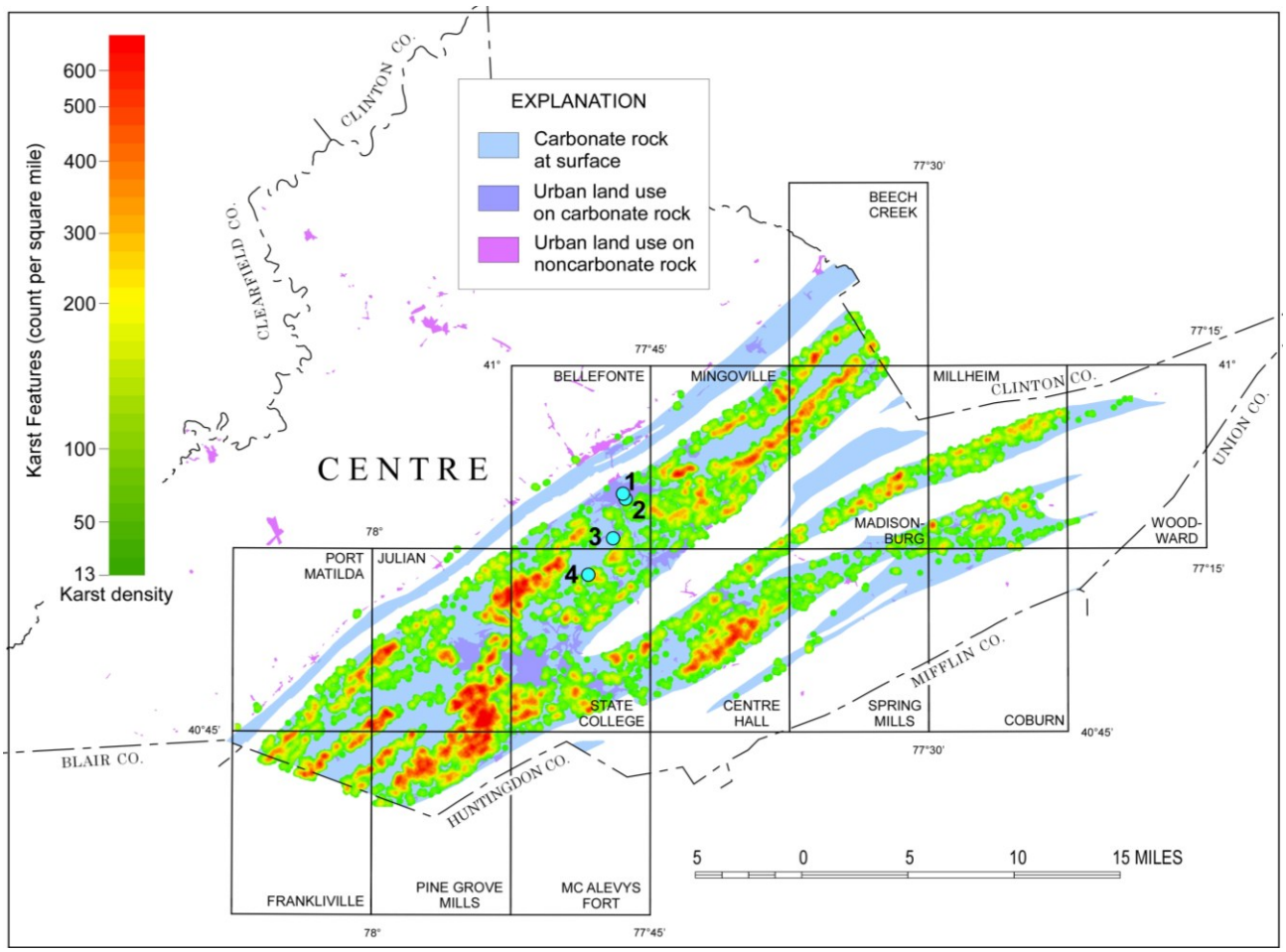


Figure 3.11.18 Density of mapped karst features in Centre County, Pennsylvania. Black quadrangles are USGS topographic quadrangles. Modified from Reese and Williams, 2005; Pennsylvania Bureau of Topographic and Geologic Survey. More maps are available at Sinkholes | Department of Conservation and Natural Resources| Commonwealth of Pennsylvania. Locations of four second-magnitude karst springs (blue dots) in Centre County are added. 1—Bellefonte (Big) Spring. 2—Kelly Spring. 3—Bellefonte Fish Hatchery Forked (Paradise) Spring. 4—Benner (Rock) Spring.

Bellefonte (Big) Spring, Centre County

The Bellefonte (Big) Spring issues at the contact between the Nittany Formation (blue, thick-bedded, coarsely crystalline dolomite) and the underlying Axeman Formation (blue thin-bedded limestone with some dolomite layers; Wood, 1980). The Nittany is one of the best carbonate aquifers in Centre County, and Pennsylvania as a whole. Reported yields of 23 nondomestic wells ranged from 0 to 2,200 gpm. Only three of these wells yield less than 100 gpm, and one half yield 500 gpm or more. A little less than half the high-capacity wells pump some sand, and a few collapse or fill in with sand. As pointed out by Wood (1980), although limestone is, in theory, more soluble than dolomite, the dolomites are generally the best aquifers. This is due largely to the coarseness of impurities in the rocks. Thus, clayey limestones or limestones containing shale or clay-rich beds, such as the Trenton Group, are poorly soluble, develop little secondary porosity, and have low yields. As the percentage of silt and sand increases, development of secondary porosity increases. Thus, the relatively sandy Nittany Formation is highly soluble, develops substantial secondary porosity, and have high yields.



Figure 3.11.19 Bellefonte Big Spring before it was covered in 1998. Courtesy of Pennsylvania Geological Survey.

Bellow excerpts are from article “What happens inside the pump house at Bellefonte’s Big Spring? Here’s a look” by Jacob Michael, published on April 10, 2025, in Centre Daily Times.

“*All water produced by the spring interacts with the pump house in some way, with four million gallons being distributed to five municipalities: Bellefonte and Milesburg boroughs, and Benner, College and Spring townships. The remaining 11 million gallons of produced water gets redirected around the building’s Talleyrand Park-facing*

side and discharged into Spring Creek. "We discharge a heck of a lot more water than we actually use, which is crazy considering how many different sources utilize this spring," Matt Auman, the borough's public works superintendent said during a recent tour of the pump house. "Rockview [state prison] uses a bit of it, and there are even a couple of bottling companies that come and use the spring too — even after all that usage, we still discharge so much. It's wild to think about." (Matt Auman, Bellefonte Borough public works superintendent).

Coca Cola once used the spring's water at its bottling plant in Milesburg before selling the plant in 2020 to Niagara Water, which also uses the spring as its water source. Weis Markets also bottles and distributes the water, and Big Spring Spirits uses it as a base for its liquors as well."



Figure 3.11.20 *Left*: Current view of the Bellefonte Big Spring and its pump house. The spring has remained covered since 1998 due to environmental standards mandated by the Pennsylvania Department of Environmental Protection. *Right*: The overflow from Bellefonte's Big Spring is pictured on Monday, March 31, 2025, by Abby Drey (*adrey@centredaily.com*)

Big Spring is the defining aspect of the City of Bellefonte. A story in John Blair Linn's *History of Centre and Clinton Counties* published in 1883 relates that the French statesman Charles Maurice de Talleyrand visited the Big Spring with Mrs. Ann Dunlop Harris (1765-1844). There he exclaimed "La belle font," leading her to suggest the name Bellefonte to her father Col. James Dunlop and her husband James Harris, who together laid out the town in 1795.

Talleyrand was in exile in America from the French Revolution, from March 1794 to June 1796. His principal residence during that time was a rented house in Philadelphia. On a visit to nearby Centre Furnace, he may have come to Bellefonte to visit James Harris and may have seen the spring. The story was relayed to Linn by Mary Orbison of Huntington County, who was the great-granddaughter of Ann Harris. A file at the Centre County Historical Library contains, however, letters from other descendants who did not believe the story to be true. In any case, until the city's Water Street was carved out of a steep bank, the spring did bubble out of the side of the bank and cascade down in a fountain-like manner (Bellefonte Historical and Cultural Association; https://bellefontearts.org/history-of-bellefonte-pa).

The spring has continually been the source of drinking water for the town's residents since 1807. Major William F. Reynolds gave Big Spring to the town on October 1, 1879, for the price of $1.00. The present pumphouse was built in 1926 and was restored in 2006. Historic images of the spring are available online at https://archive.bellefontearts.org/Smith_pages/Smith_spring.htm.

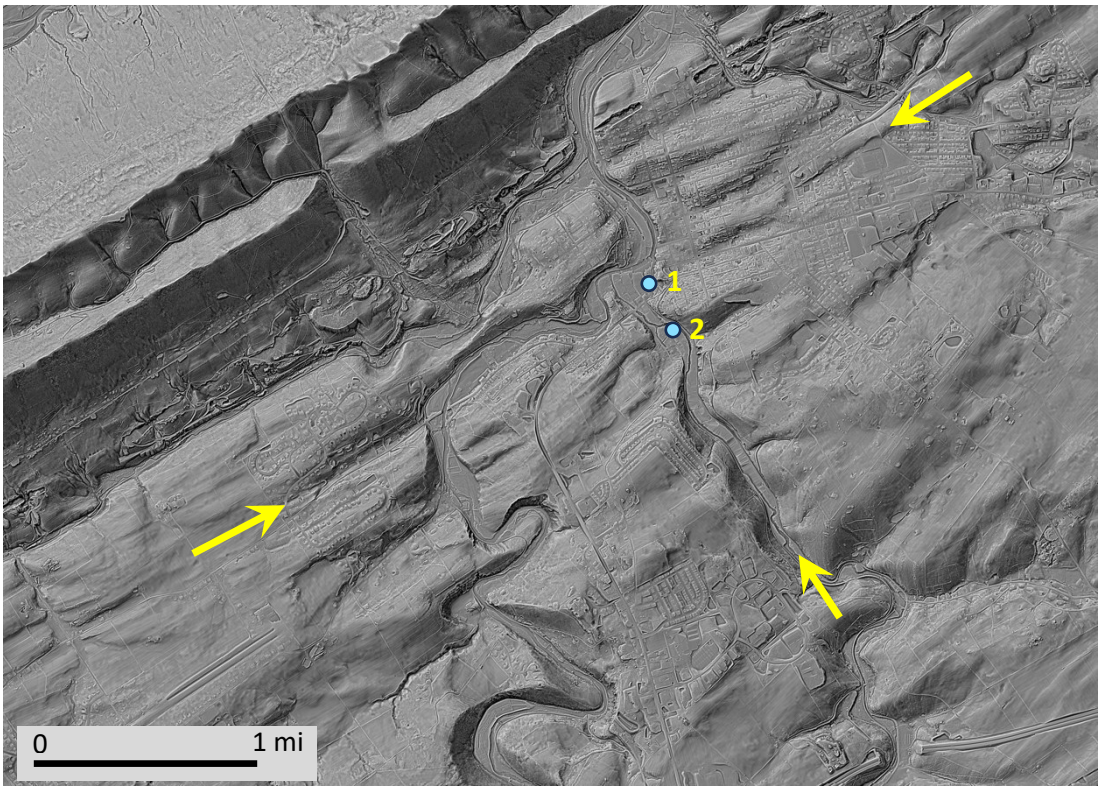


Figure 3.11.21 Part of enhanced terrain imagery of the State College 30 x 60 Minute Quadrangle from lidar-derived elevation models at 3-meter resolution. From Jackson and Doctor, 2023. Arrows indicate regional lineaments that may have played important roles in the emergence of Bellefonte (#1) and Kelly (#2) Springs. Note other lineaments with the same general directions.

Kelly Spring, Centre County

Kelly Spring (also spelled Kelley Spring) is situated at former Cerro Metal Products Company along the Logan Branch of Spring Creek, about 0.2 miles south of the Bellefonte corporate boundary. It rises from fractures in limestone of the Ordovician Beekmantown Group and was used as an industrial water source for decades. Kelly Spring is recognized as an Outstanding Scenic Geologic Feature in Pennsylvania (Geyer and Bolles, 1979).

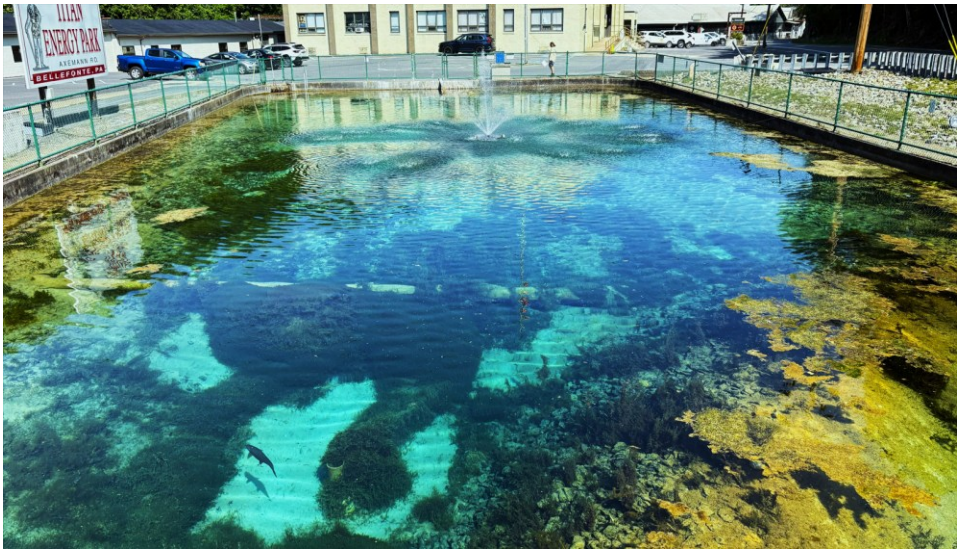


Figure 3.11.22 Kelly Spring, July 2026.

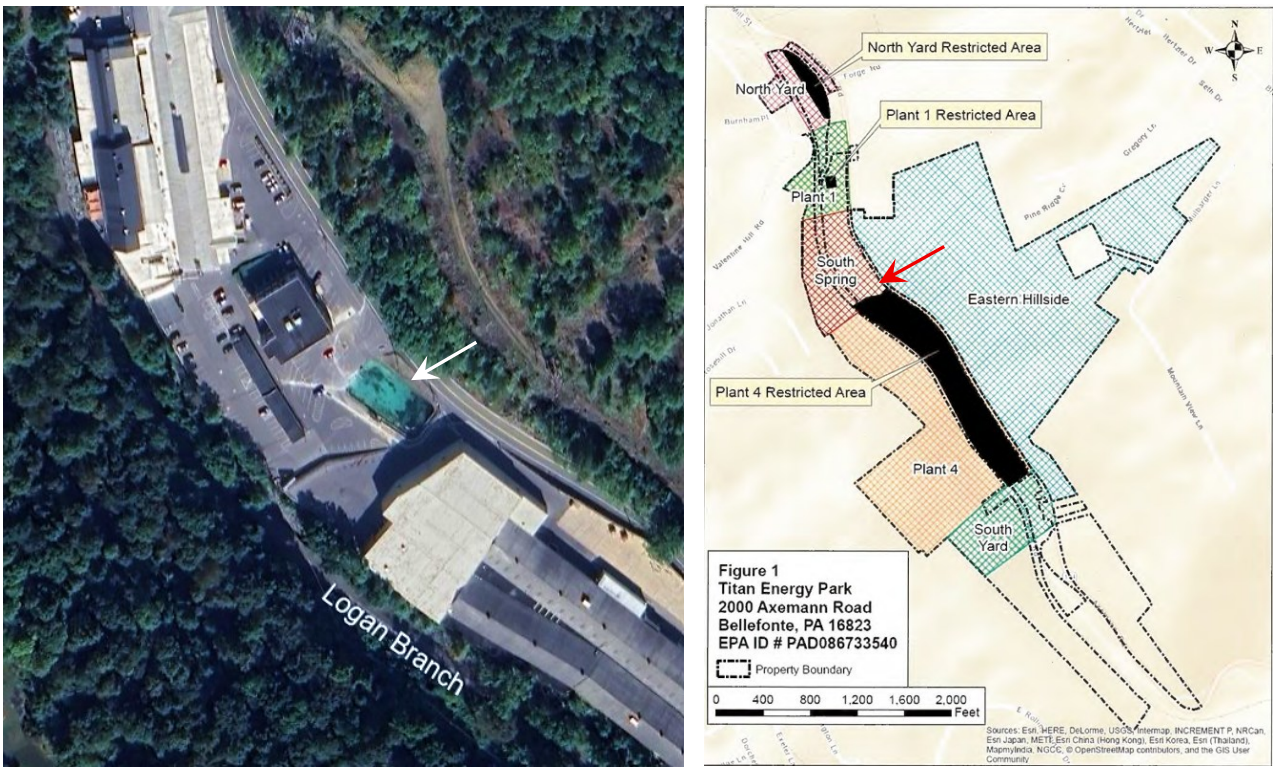


Figure 3.11.23 *Left*: Google Earth image (Sep. 15, 2024) of Kelly Spring (pointed out with white arrow) and parts of the Former Cerro Metals Products Plant RCRA Site (currently known as Titan Park). The site was operated between 1915 and 2008 when it was closed. *Right*: Map of the Site showing different areas of concern where soil and groundwater have been contaminated (from United States Environmental Protection Agency (USEPA), 2018). Red arrow points out the location of Kelly Spring. Interestingly, USEPA does not include any information on the spring or any possible impacts on its water quality from the historic industrial activities at the site. For all practical purposes, the spring did not and does not exist for the USEPA, or for the Office of Pennsylvania Remediation, Land and Chemical Division, which prepared the related "Statement of Basis" describing the Site and the cleanup of the significant soil and groundwater contamination.

Forked (Paradise) Spring, Centre County

In late 1932, the Pennsylvania Fish Commission purchased for $12,000 about 90 acres of land along Spring Creek 2.5 miles south of Bellefonte Borough. The tract, which included 1.12 miles of Spring Creek and a large spring (later named "Forked" or "Paradise" Spring), was labeled the Spring Creek Project with the dual purpose of fish cultural activities and demonstration of techniques to improve fish habitat. The spring is the main source of water for today's Bellefonte State Fish Hatchery.

Owing to the exceptional fishing, the project later became known as Fisherman's Paradise. C.A. French, Commissioner of Fisheries, noted that "During 1932 and 1933, a wave of enthusiasm for stream restoration work swept through the Commonwealth of Pennsylvania" and sportsmen "were clamoring for advice on methods of construction" (French 1938). In 1934, the Commission installed 46 structures that included dams, deflectors, and log covers.

Since 1962, this project has increased in reputation and popularity across the nation. There are often many out-of-state licenses on cars in the parking area. As the retired Executive Director of the Pennsylvania Fish and Boat

Commission John Arway said, “Fisherman’s Paradise is the golden jewel of fly fishing in Pennsylvania”. There have been several stream restoration projects in recent years including additional native plantings, improving and revitalizing various trout habitat structures, and reorienting the parking lots to divert rainwater away from the stream so that the water can be infiltrated (Carline et al., 2021).

In July 2026, the fishery was closed to public without much explanation. It is possible that contamination of the karst aquifer in the Spring Creek area with PFAS (“forever chemicals”), explained later in this chapter, was the reason.



Figure 3.11.24 Fisherman’s Paradise was famous for its large trout and heavy fishing pressure. From Carline et al., 2021. Photo courtesy of Pennsylvania Fish and Boat Commission (PFBC) archives.

Benner Spring, Centre County

Benner Spring in Benner Township is one of the water sources utilized by the Benner Spring State Fish Hatchery. Water supply to the facility is also from two production wells, and Spring Creek. Originally constructed in 1952, the hatchery is situated on 40 developed acres of land leased from the Rockview State Correctional Institution. It consists of exterior concrete raceways, production ponds, a warming pond, and a hatchery building that contains concrete and fiberglass interior raceways, Heath tray, jar, and Buchner jar incubators. Historically named the *Benner Spring Fish Research Station* due to its heavy focus on testing progressive vertical trout rearing, egg incubation techniques, and strain breeding, the site now also serves as headquarters for the Pennsylvania Fish and Boat Commission's Division of Production Services.

The spring sits along a broader 1,800-acre protected recreation area managed by local and state partners, including Benner Township and Penn State. The aggregate trail is highly popular for hiking, bicycling, and jogging. Visitors can access the spring via the Benner Spring trailhead on Rock Road. A short, scenic path leads directly to the spring which is an unsightly enclosure.

The spring and the township are named after General Philip Benner, an early ironmaster and Revolutionary War veteran who arrived from Chester County in 1793. Attracted by the area's high-quality iron ore, limestone, and water power, Benner brought 92 workers to build the Rock Ironworks along the creek. He established the industrial village of "Rock," named after the prominent rocky cliffs that can be seen along Spring Creek.

Groundwater and surface water contamination with PFAS (per- and polyfluoroalkyl substances, better known as “forever chemicals”), in the Spring Creek watershed was first officially discovered in 2019, during a statewide survey conducted by the U.S. Geological Survey (USGS) and the PA Department of Environmental Protection

(DEP). The Benner Spring Outfall and Hatchery Well No. 2 have shown groundwater concentrations exceeding DEP's cleanup criteria, while a number of other sampling location including Spring Creek itself and the "Paradise" Spring, the main source of water for the Bellefonte State Fish Hatchery, had elevated concentrations of PFAS.

Below are excerpts from a 2024 report entitled *PFAS Surface Water Survey, Spring Creek and Bald Eagle Creek, Centre County PA, 2022-2024* and authored by David Thomas Roberts, Sierra Club Moshannon Group, Pennsylvania, followed by excerpts from an article by Ellen Foreman, Member of Sierra Club, Moshannon Group, published on June 28, 2026.
https://www.sierraclub.org/pennsylvania/blog/2026/06/protecting-local-waterways-pfas-contamination



Figure 3.11.25 *Left*: Enclosure of Benner Spring. *Right*: spring overflow on July 24, 2026. The estimated flow rate was less than 1,500 gpm.

The presence of PFAS in Benner Spring shows that the Mines Member aquifer of the Gatesburg Formation is contaminated. Contaminated groundwater outflow from wells and springs along Spring Creek Canyon and contaminated stormwater from the Airport have formed a spreading plume of PFAS traveling down Spring Creek Canyon through Fisherman's Paradise to Bald Eagle Creek and beyond into the Susquehanna River Basin and the Chesapeake Bay.

There are several sources replenishing the PFAS in Spring Creek.

1. Discharge of stormwater from the State College Regional Airport is a source of PFAS contaminating Spring Creek. The use of aqueous film forming foam (AFFF) containing PFAS during decades of on-site Federal Aviation Agency fire train exercises at the Airport has created a toxic site and a spreading plume of PFAS.

2. The effluent from local wastewater treatment plants. PFAS enters the wastewater stream through residential use including clothes washing, disposal of products, and from small scale commercial use. The presence of PFAS in treated wastewater effluent indicates there is likely to be PFAS in the bio-solids produced by the wastewater treatment plants.

Application of contaminated bio-solids to agricultural fields has caused a major problem in Maine where more than 50 farms were found to be contaminated with PFAS. Bio-solids used for farm and consumer use must be tested to protect public and environmental health.

3. Other sources of PFAS entering Spring Creek include spring water flowing from the Gatesburg Mines Member aquifer at Benner Spring and contaminated well water from local trout hatcheries in Spring Creek Canyon. These sources are evidence of a PFAS plume in the aquifers of the Gatesburg Formation and the dolomite Mines Member which are major and essential water resources for homes, families, businesses, and agriculture in the State College, University Park, and Bellefonte areas.

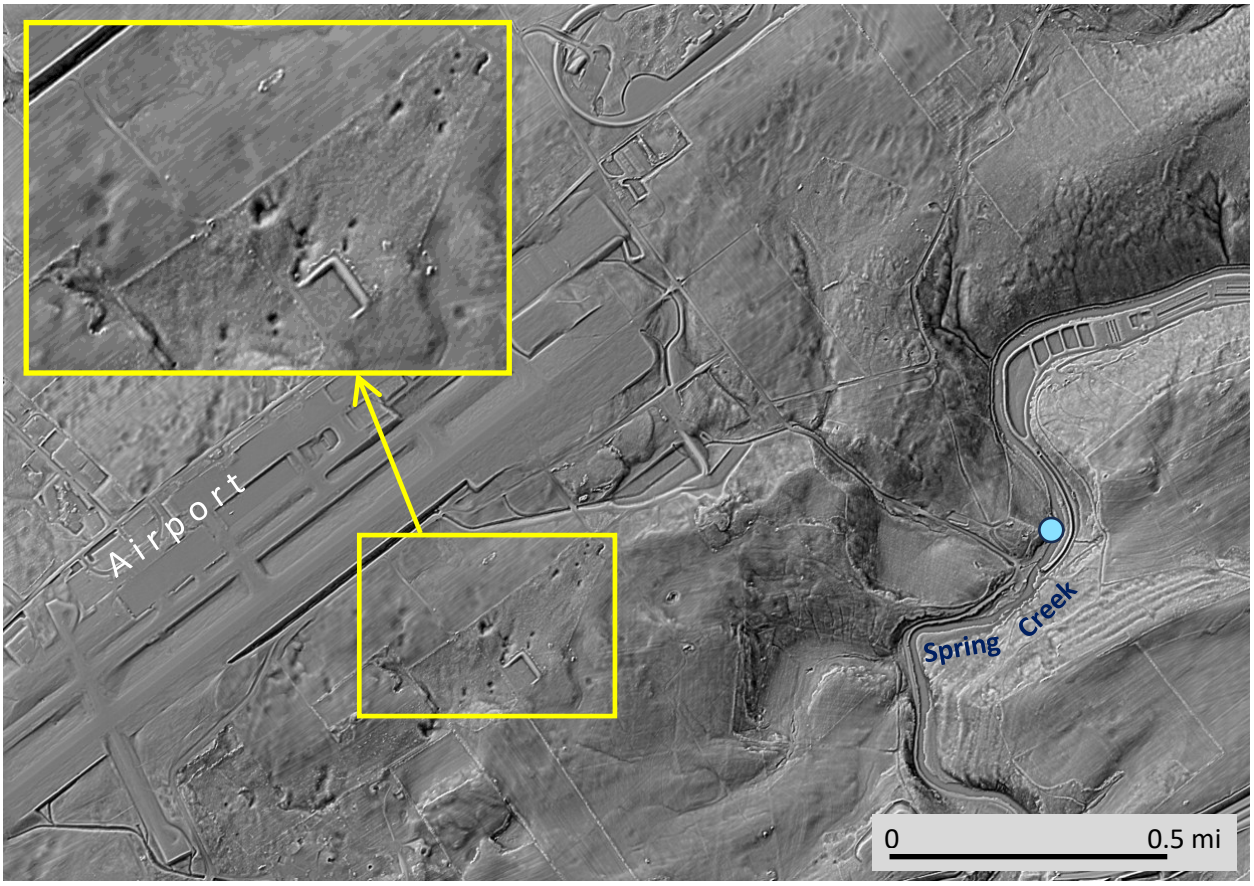


Figure 3.11.26 Part of enhanced terrain imagery of the State College 30 x 60 Minute Quadrangle from lidar-derived elevation models at 3-meter resolution. From Jackson and Doctor, 2023. Yellow box / inset points out the karstic nature of the area between Benner Springs (blue dot) and the State College Regional Airport including numerous sinkholes.

Airport is Largest Source

"The matter of where the chemicals are coming from is not in doubt, there is also no doubt as to who is responsible for the cleanup. The frustration is that nothing is happening and this situation continues to threaten both aquatic life as well as human health," Roberts said.

Penn State University (PSU) until recently owned the State College Airport. The use of firefighting foam on training exercises which leached into the soil has been identified as the primary source of the contamination. In late 2024, Penn State entered a Consent Order and Agreement with the Pennsylvania Department of Environmental Protection (DEP) under which the university agreed to remediate the contamination. PSU filed a suit against multiple manufacturers and producers of PFAS and the American Federation of Firefighters in June 2024.

While PSU has submitted a Remedial Investigation Workplan in November 2025, it does not address stormwater discharge from the Airport. Though the Moshannon Group supplied the water sample data to the DEP, the Agency noted that there is no Pennsylvania standard for PFAS in stormwater.

In addition to the direct effects on the stream, residential and business wells near the airport in Benner Township were found to contain PFAS levels exceeding state and federal drinking water standards.



Local Residents Suffer

A resident from the nearby Walnut Grove community, Rick Weyer, described the effects of the contamination. “We stopped drinking and cooking with our water until we were provided with a filtration system by Penn State which is extremely cumbersome. However, we have not been able to eat food from our gardens as our soil is contaminated with PFAS.” He added that medical authorities tested residents’ blood for PFAS and in his case the levels were in the 99th percentile.

Figure 3.11.27 Intensely fractured and karstified dolomite of the Mines Member of the Upper Cambrian Gatesburg Formation forms vertical cliffs of the Spring Creek canyon near Benner Spring (cliffs are the main reason for naming the spring “Rock Spring”).

While the health implications of ingesting food and water contaminated by PFAS continue to be the subject of multiple studies, a study cited by the CDC indicates that elevated levels of PFAS are associated with several health issues including altered immune and thyroid function, liver disease, lipid and insulin dysregulation, kidney disease, adverse reproductive and developmental outcomes, and cancer.”



Figure 3.11.28 Spring Creek in Bellefonte, after receiving water from all springs in the watershed including the largest, Big Spring, which is located in the town itself.

Mammoth Spring, Mifflin County

Mammoth Spring is situated about 2 miles southeast of Milroy, near the community of Shrader. It discharges from a cave opening in Ordovician Benner and Loysburg limestones and is considered Pennsylvania's third largest spring (Kochanov, 2010). This assessment is based on one reported discharge rate of 14,000 gpm (see Table 3.11.1).

The water cavern behind the spring was discovered by early settlers in the region, but it was not until 1926 that two boys discovered a dry cave about 400 yards upstream from the spring discharge point. Both the dry and wet caverns were open to the public in 1929 under the name of Alexander Caverns.

As described by Speece (1973), and Stone et al. (1932), by 1929, an additional artificial opening was created in the dry section of the cave to better allow commercialization. 115 stairs were created to allow people to enter the heavily decorated Cathedral Room. This magnificent room contained delicate pencils and films, stalactites, ribbons, domes, stumps, and columns. In order to allow visitors to see more of the cave, boat tours were added in 1930.

Where the dry cavern meets the wet cavern, a dock was constructed and visitors were taken by boat for nearly a quarter of a mile to daylight at Mammoth Spring. The wet part of the cave makes several nearly right-angled turns, developed along vertical joint planes in almost horizontal beds of limestone. Delicate cave formations, stalactites, and ribbons of dripstone hang down over the water. The greater width of the wet cavern, ranging from 40 to 100 feet, and the much greater height, up to 65 feet above the water, together with the fact that this part of the cave is only accessible by water, make this section extremely attractive. The temperature in the cave is reported to be 52 degrees (Geyer and Bolles, 1979; Stone et al., 1932).

The cave continued operating as a show cave until 1959, when the lease on the caverns expired and the landowners chose not to renew. Some years later, approximately in 1966, it was noted that the door at the artificial entrance to the cave had been removed. Upon investigation it was found that many of the beautiful natural sculptures had been vandalized. Today, Alexander Caverns is not a commercial cave. Its present owners have sealed the stairs to the cave and the water entrance to the caverns is forbidden.



Figure 3.11.29 Mammoth Spring flows from this large water cavern, which was a popular show cave between 1926 and 1959. Photo by Kevin Tarbert, former intern at the Pennsylvania Geological Survey, 2007. From Kochanov, 2010.



Figure 3.11.30 The flow from Mammoth Spring creates Honey Creek and a short, picturesque gorge. The Spring is designated as an Outstanding Geological Feature of Pennsylvania. Photograph originally published in Geyer and Bolles, 1979. Courtesy of Pennsylvania Geological Survey.

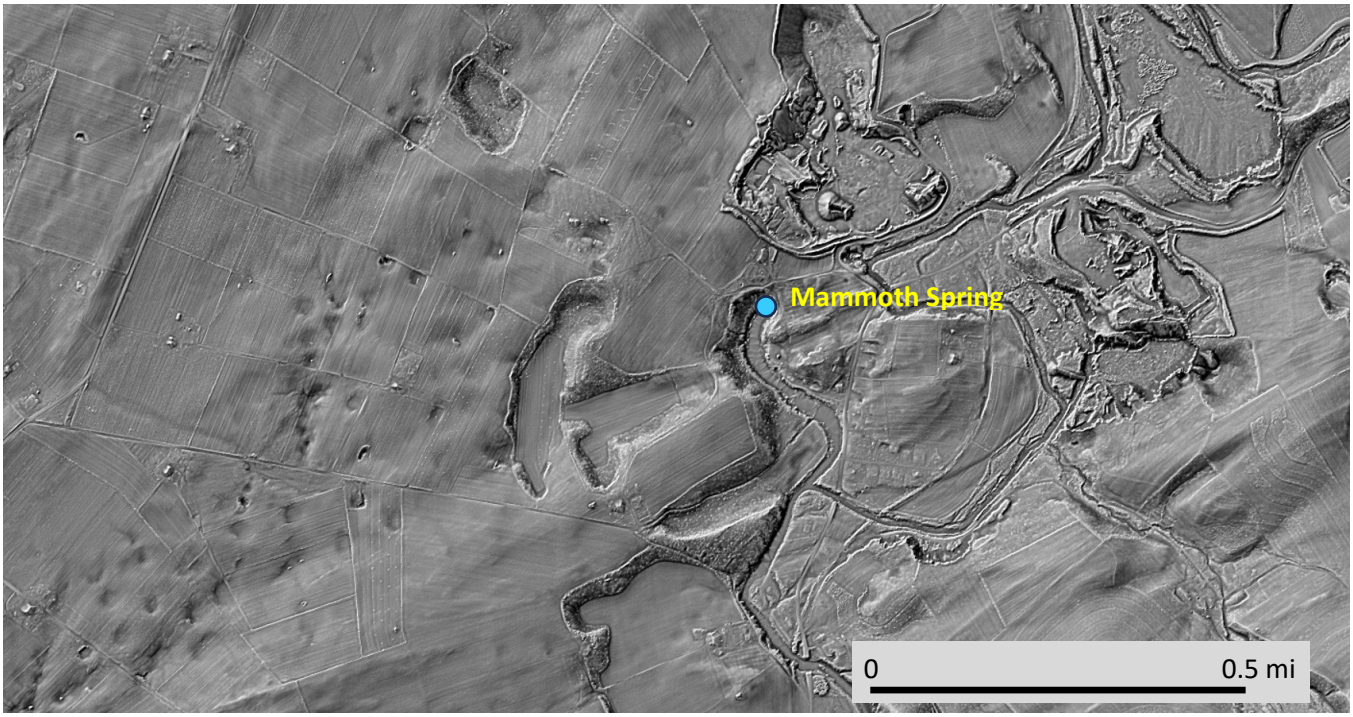


Figure 3.11.31 Part of enhanced terrain imagery of the State College 30 x 60 Minute Quadrangle from lidar-derived elevation models at 3-meter resolution. From Jackson and Doctor, 2023. Note numerous sinkholes and large closed depressions west of Mammoth Spring which are developed in Ordovician Loysburg Formation. Scars of former limestone quarries are visible east and north of the spring. The active Naginey Quarry in Armagh Township is located immediately north of the area shown. It is unknown if and how the historic and ongoing quarrying operations in the immediate vicinity of the spring may have impacted it. The last time a Pennsylvania agency characterized the spring was apparently decades ago, and no official record of its discharge rate is readily available since the last (and only) time it was measured, on November 11, 1971 (Flippo, 1974, p.28).

Arch Spring, Blair County

Arch Spring is located about 7 miles SE of Tyrone via Rt. 453 and Kettle Road in Sinking Valley. It discharges from the Ordovician Loysburg Formation, with a median flow rate of 8,000 gpm (Flippo, 1974). In an excellent narrative about the Tytoona Cave (see Fig. 3.11.6) and the Arch Spring, Garret Czmor, the Manager of Tytoona Cave Preserve which is owned by the National Speleological Society (NSS), provides many fascinating details about their history and natural wonders. Below are just a few excerpts (https://mar.caves.org/tytoona.htm.)

"Although several other caves exist in Sinking Valley, only Tytoona and the Arch Spring are of much interest. Arch Spring gave its name to a village that hardly exists today. The arch at Arch Spring resembles the famous Natural Bridge in Virginia but is much smaller. The limestone arch is 40 to 50 feet high, and the opening is 15 to 20 feet in diameter, with Sinking Run flowing through it.

Arch Spring, the source of this part of Sinking Run, is the eighth largest spring in the state, discharging from 2,000 to an estimated maximum of 30,000 gallons per minute. Upstream from the arch is a small pond in a large, steep-sided sinkhole. This is said to be a remnant of a large room that collapsed thousands of years ago. The sink is at least 100 feet long, 50 feet wide, and perhaps more than 30 feet deep. At the far side is an opening about 4 feet in diameter. This is Arch Spring, the resurgence of Tytoona Cave, over 4000 feet away in a straight line.



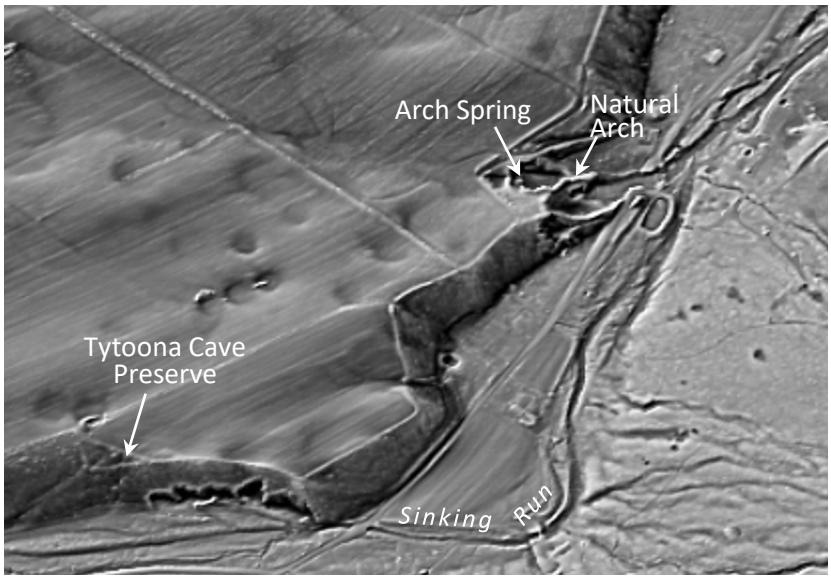
Figure 3.11.32 Arch Spring is recognized as an Outstanding Geological Feature in Pennsylvania.

The end of the system at Arch Spring has nothing to offer the dry caver, but it is a challenge for cave divers, although it is *privately* owned and diving is *not currently allowed*. It has many large, submerged rooms, one of which was described as being over 100 feet deep.

The entrance to Tytoona Cave is about a mile away from Arch Spring by road. It is in a large collapsed sink, another remnant of a large room, that is visible from the road during most of the year. The Tytoona Management Committee has improved the property with safer parking and a gravel trail. There are several signs and a kiosk display. The display and brochures educate the public about caving, the NSS, the property, and preserve policies.

The stream appears from under the far wall of the sink and flows for a short distance before entering the cave. The size of the stream fluctuates greatly. Sometimes it is even dry on the surface, but in the wet season it is about 25 feet across and 2 to 3 feet deep. In spring, it can be a raging torrent.

The first published account of the area appeared in an article by Emollit Mores in the *Columbian Magazine* in 1788. The *Columbian* mentions the spring, where "a rude arch of stone hanging over it, forms a passage for the water, which it throws out with some degree of violence, and in such plenty as to form a fine stream, which at length buries itself again in the bowels of the earth."



Tytoona Cave Preserve, located in limestone-rich Sinking Valley in Blair County, is the tenth cave property of the National Speleological Society. The Western Pennsylvania Conservancy sold the 6.8 acres to the NSS in December 23, 1997. Tytoona Cave is primarily used for recreational and educational purposes today."

Figure 3.11.33 Part of enhanced terrain imagery of the Tyrone 30 x 60 Minute Quadrangle from lidar-derived elevation models showing the Arch Spring area. From Jackson and Doctor, 2024a. The image is approximately 2.5 miles across.

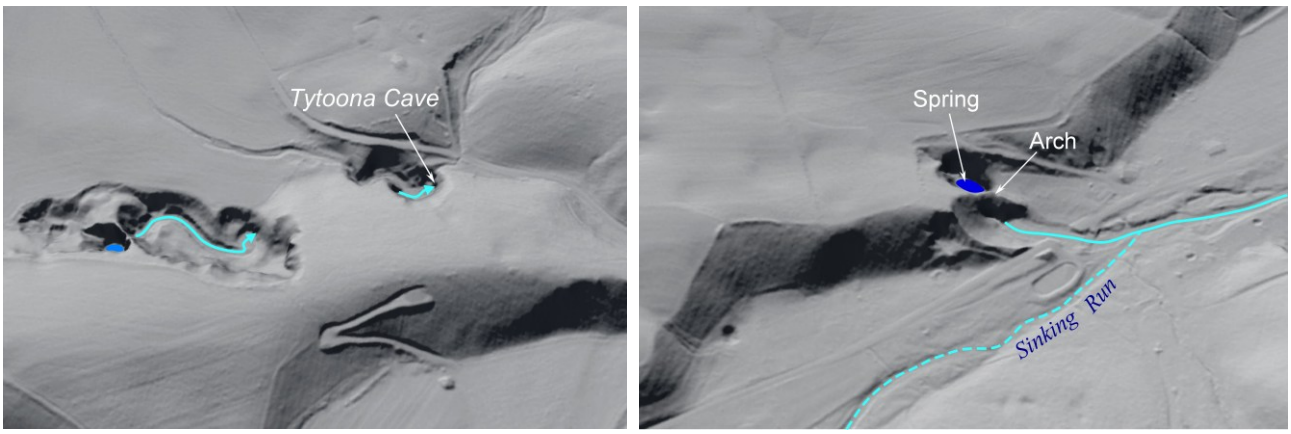


Figure 3.11.34 Oblique 3D views of karst windows in the Tytoona Cave and Arch Spring areas. From Lidar-based DEMs (digital elevation models) coverage by USGS. Available at USGS National Map Viewer.

Roaring Spring, Blair County

Roaring Spring is situated in the southwest corner of the Borough of Roaring Spring. It discharges from the Ordovician Nittany Formation limestones at a median rate of 4,500 gpm (Flippo, 1974) and is used for public water supply by the Roaring Spring Municipal Water Authority. The authority serves customers throughout Roaring Spring Borough and parts of Taylor Township. Roaring Spring Bottling Company (Roaring Spring Water) uses the spring as its primary source for regional residential and office bottled water delivery across Pennsylvania, Maryland, and West Virginia. The spring was named "Roaring Spring" because of the sound it made as it gushed out and flowed over a waterfall. The sound is said to have echoed through the valley. Now it is silent since much of the flow is diverted for water supply and the springs is dammed.



The spring's overflow, however, is still strong enough most of the time to fill a pond in the town's park and keep it an excellent habitat for trout and waterfowl. The spring water temperature is steady throughout the year, around 50 degrees, and the pond never freezes out in winter.

Figure 3.11.35 Roaring Spring, an Outstanding Scenic Geologic Feature of Pennsylvania.

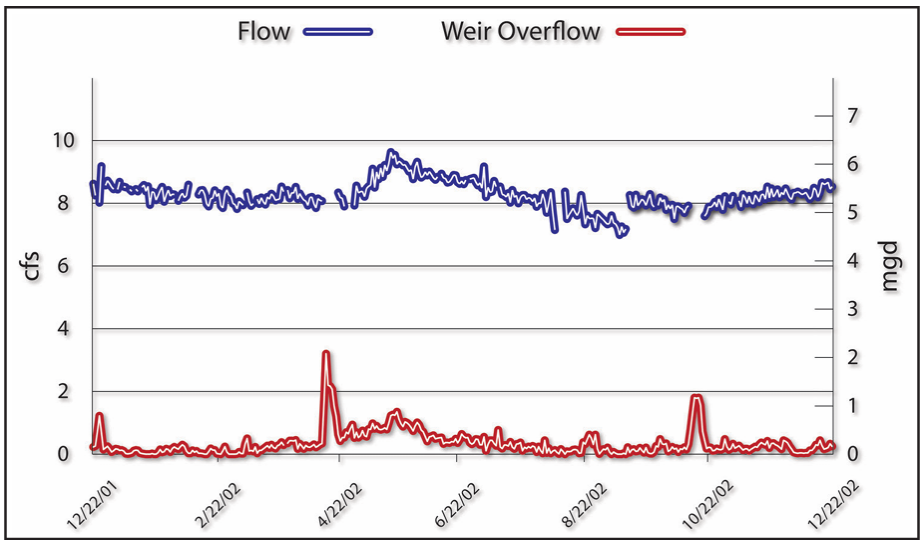


Figure 3.11.36 Hydrograph of spring flow and spring pool discharge for Roaring Spring during the 2001-2002 drought. The 'weir overflow' is the amount of water remaining after water user withdrawals. The amount of water withdrawn equaled the total spring flow on several occasions. From Susquehanna River Basin Commission, 2011.

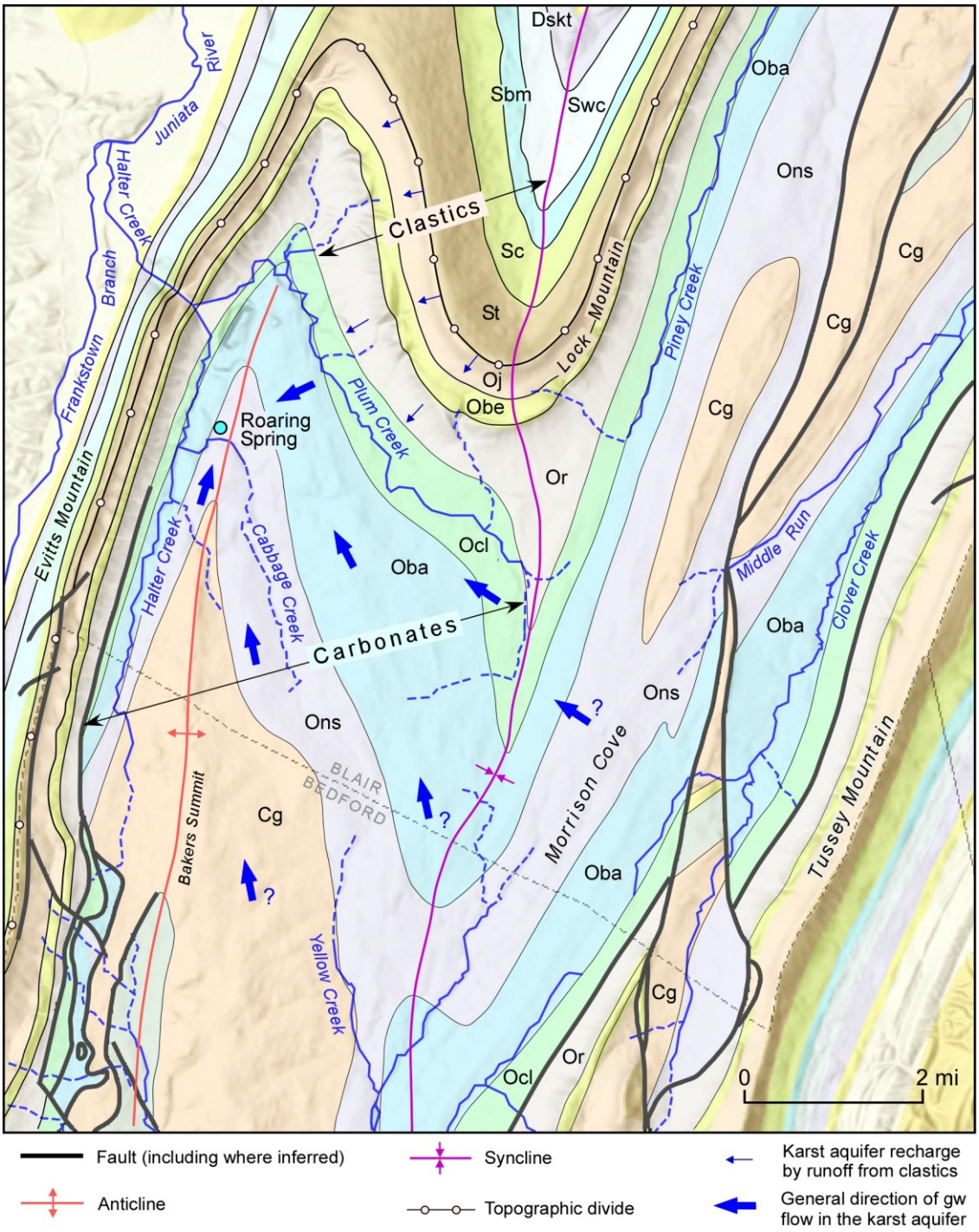


Figure 3.11.37 Geologic map of the Roaring Spring drainage area. Geologic units from PaGEODE—Pennsylvania GEOlogic Data Exploration, Bureau of Geological Survey (https://gis.dcnr.pa.gov/pageode/). From oldest to youngest: Cg—Cambrian Gatesburg Formation dolomite with sandstone interbeds. Ons—Ordovician Nittany Formation; mainly dolomite and sandy dolomite. Oba—Bellefonte and Axemann Formations carbonates, mainly limestone. Ocl—Coburn and Loysburg Formations carbonates, mainly limestone. Or—Reedsville Formation shale, siltstone, sandstone. Obe—Bold Eagle Formation shale, siltstone sandstone. Or—Reedsville Formation shale, siltstone, sandstone. Oj—Juniata Formation sandstone, siltstone, shale. St—Tuscarora Formation sandstone, minor shale, siltstone. Sc—Clinton Group sandstone, siltstone, shale. Sbm—Bloomsburg Formation shale and siltstone. Swc—Wills Creek Formation, shale, interbeds of limestone, dolomite, and sandstone. Dskt—Devonian and Silurian Keyser Formations, limestone, shaly limestone, interbeds of shale and siltstone.

In 2011, the Susquehanna River Basin Commission (SRBC) completed a study of Morrison Cove, an intermontane valley about 30 miles long and five to eight miles wide, part of which is drained by Roaring Spring which sustains the flow of Halter Creek. The objectives of the *Morrison Cove Water Resources Availability Study* (SRBC, 2011) were to assess existing water resources, establish an estimated sustainable yield from the constituent watersheds, inventory current water uses, and evaluate water quantity and quality issues in the study area. Morrison Cove includes an area identified by the SRBC as a "Potentially Stressed Area" and has a long history of agriculture-related water quality issues. A lack of flow data from U.S. Geological Survey gaging stations within Morrison Cove has precluded quantitative water resource assessment.

A detailed water availability analysis allowed SRBC to establish the amount of groundwater and surface water base flow currently available on a sustainable basis for use in each major watershed. For the purposes of this study, the sustainable limit of consumptive use is approximated by the 10-year base flow. The use of water utilization data representing the maximum approved or permitted daily use ensures a worst-case evaluation, and a conservative estimate of water availability.

The underlying bedrock in Morrison Cove is predominantly clastic sediments (sandstone and shale) in the ridges, and carbonates in the enclosed valley. The carbonates have solutionally enlarged fractures and conduits which substantially increase aquifer permeability. As a result, relatively high well yields are widely available within the valley portion of the study area for wells sited along major fractures and fracture traces.



Figure 3.11.38 Roaring Spring feeds the Spring Dam Pond in the historic center of town.

The study identified two highly permeable hydrogeologic terrains as Critical Aquifer Recharge Areas. The central portions of the study area are underlain by highly permeable dolomites, sandy dolomites, and sandstones of the Cambrian Gatesburg Formation, and the Ordovician Nittany Formation. These are overlain by a relatively thick mantle of weathering residuum composed largely of fine sand. The sandy residuum has a very high infiltration rate and correspondingly low runoff rate and is a nearly ideal medium for maximizing and storing recharge.

The second highly permeable terrain consists of a belt of highly soluble limestones—Ordovician Bellefonte and Axemann Formations, and Coburn and Loysburg Formations—situated along the toeslope of the surrounding

ridges and portions of the valley floors. The ridges provide relatively acidic, but otherwise high quality, groundwater and surface water runoff to the soluble limestones where extensive strike-oriented karst conduits have developed. These conduits convey most of the local and mountainside recharge to springs and seeps located in the downstream reaches of the local watersheds. They are largely responsible for the generally high-quality aquatic habitat available in the downstream reaches of the ridge-parallel streams (SRBC, 2011).

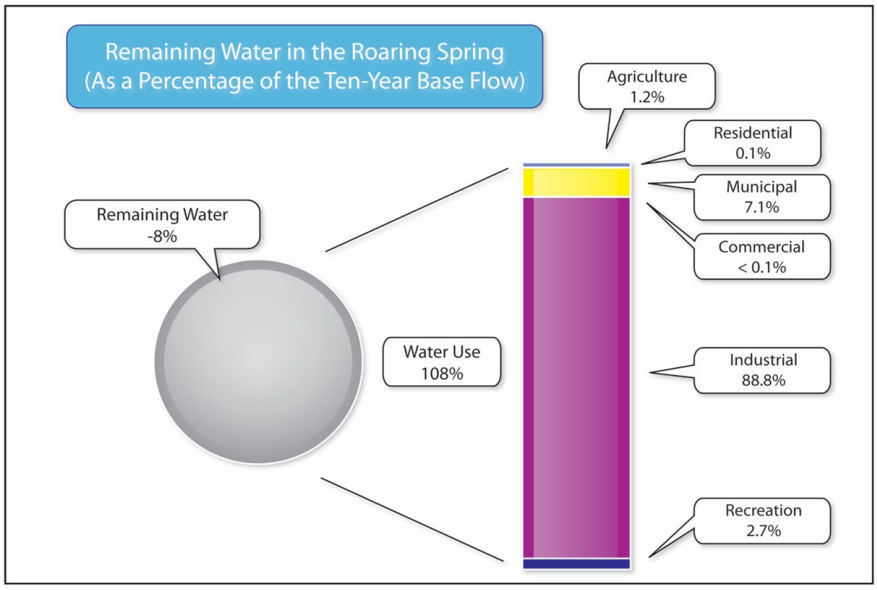


Figure 3.11.39 Remaining Water in the Roaring Spring. From Susquehanna River Basin Commission, 2011.

The study found that the amount of water currently withdrawn from the Roaring Spring exceeds the amount of water available on a sustainable basis. The amount of water currently consumptively withdrawn from the Halter Creek Watershed represents 87 percent of the 10-year base flow.

Considering the study findings, SRBC has developed the following recommendations to help secure adequate yields, ensure the protection of current uses and aquatic and riparian needs, and help prevent adverse impacts to the water resources and aquatic habitat of Morrison Cove.

- Manage withdrawals from the Roaring Spring to ensure their sustainability, and to maintain and protect aquatic habitat in Halter Creek.
- Focus groundwater development for municipal grade wells on the aquifers having both high quality water and sufficient permeability to allow high production rates (i.e., the Gatesburg Terrains).
- Locate municipal-grade surface water withdrawals at downstream locations where the maximum amount of water is available and where impacts to existing users and the environment would be minimized.
- Locate large groundwater withdrawals within watersheds in the downstream reaches to minimize the stream miles with reduced base flow and altered flow regime.
- Protect water quantity in the Gatesburg Terrain areas (north and south) through use of Stormwater and Development BMPs, to minimize impervious cover.
- Treat waters for nitrate levels that exceed federal Safe Drinking Water standard (10 mg/l), as is typical in the Interior Carbonates Terrain.
- Develop and implement methods to eliminate surplus manure.
- Encourage the restoration of riparian vegetation to increase the natural treatment of water and to improve aquatic habitat.
- Measure and record flow through the existing weirs on Plum and Halter Creeks, and on the Roaring Spring pool discharge on a daily basis.
- Continue and expand the collection of reported water use data.

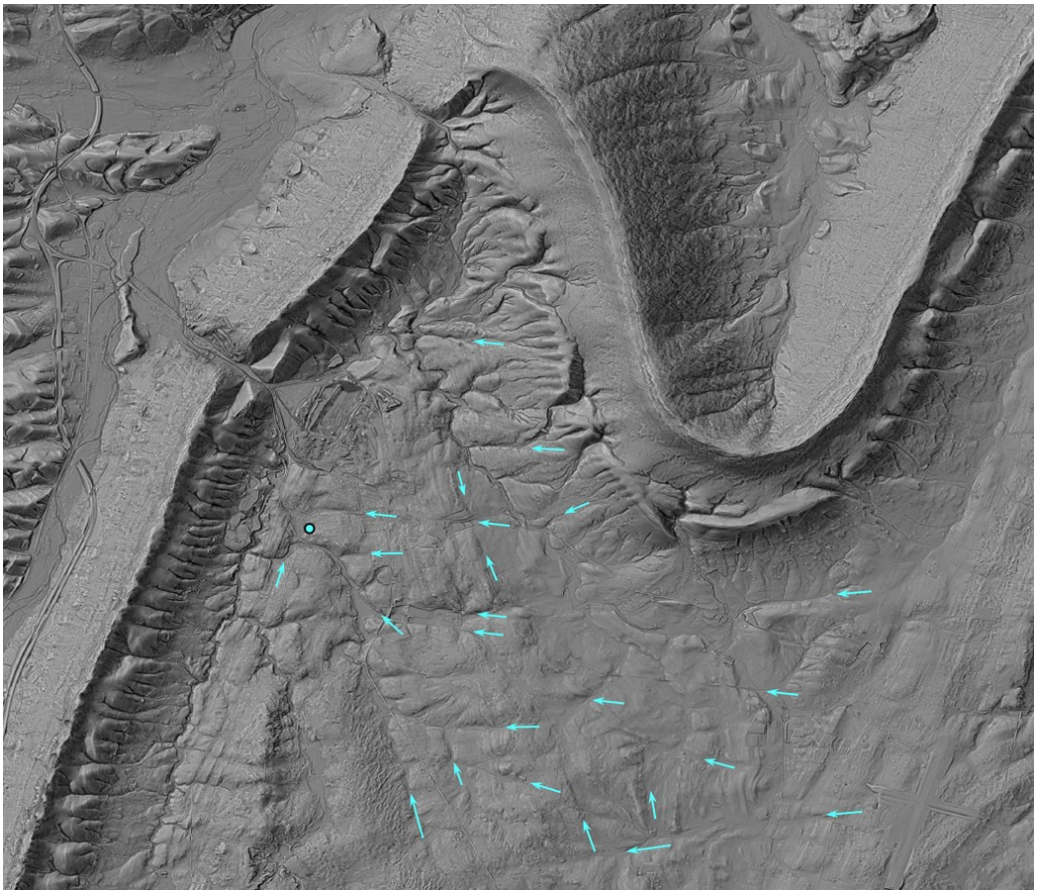


Figure 3.11.40 Part of enhanced terrain imagery of the Johnstown 30 x 60 Minute Quadrangle from lidar-derived elevation models at 3-meter resolution showing the Roaring Spring (denoted with blue dot) area. From Jackson and Doctor, 2024b. Arrows point out just some of the notable lineaments associated with the structural geologic fabric that is affecting groundwater flow in the underlying karst aquifer.

Cumberland Valley Springs, Cumberland County

More than 30 years ago, Becher and Root (1981) wrote that "Communities and industry west of Mechanicsburg are placing increasing dependence on groundwater supplies and will continue to do so in the future as streams are incapable of meeting increasing demands." This statement is as relevant today as it was when the authors published a definitive report on the groundwater resources of the Cumberland Valley in Cumberland County.

The northern half of the valley is underlain by shale and graywacke of the Martinsburg Formation. East of Carlisle these rocks are partly replaced by large masses of shale, graywacke, and carbonate rock that were transported from distant parts of the depositional basin (informally named transported Martinsburg). The southern half of the valley is underlain principally by a sequence of carbonate rocks about 15,000 feet thick, named the Cumberland Valley sequence. A thick wedge of colluvium masks the older rocks in this sequence on the north flank of South Mountain, in the southern part of the valley west of Mechanicsburg. A similar and correlative sequence of rocks named the Lebanon Valley sequence occurs in the extreme southeastern part of the area. Folds, faults, joints, and cleavage structures related to the South Mountain anticlinorium dominate the principal sequence but are truncated in the east by later structures of the Lebanon Valley sequence. Steep thrust faulting and overturned folds occur throughout the area but are most intensively developed in the east. The Conodoguinet and Yellow Breeches Creeks drain the area and flow eastward into the Susquehanna River. Most of the carbonate rocks and almost all of the shale are drained by Conodoguinet Creek. South Mountain and much of the eastern quarter are drained by the Yellow Breeches.

The median sustained yields of single wells in the carbonate rocks, in gallons per minute, calculated from specific-capacity data, are: Tomstown, 1,000; Waynesboro, 170; Elbrook, 220; Zullinger, 82; Shadygrove, 26; Stonehenge, 57; Rockdale Run, 400; St. Paul, 82; and Chambersburg, 11. Single wells may sustain maximum yields of 2,000 gallons per minute from the Tomstown and Elbrook; 1,000 gallons per minute from the Waynesboro, Zullinger, Rockdale Run, and St. Paul; and 200 gallons per minute from all others except the Chambersburg.

The hydrologic system is strongly influenced by the geology. Locations of streams and large springs and the yielding characteristics of rocks are largely dependent on the areal distribution of rock types and structure. The north-south-oriented diabase dike through Boiling Springs acts as a subsurface dam that separates eastern and western parts of the carbonate aquifer. Gains and losses of water in spring-fed streams in the carbonate aquifer are related to folds, faults, diabase dikes, and other geologic features. Joints, faults, and solution-enlarged openings are the most important yielding zones in the carbonate rocks, but cleavage probably provides most of the water-bearing openings in the Martinsburg Formation and in the shale zones of the Elbrook and Waynesboro Formations. Wells drilled on fracture traces or in topographically low positions have significantly greater yields than other sites (Becher and Root, 1981).

Information in this report can aid planning organizations, municipalities, rural communities, consulting geologists, engineers, well-drilling firms, and industry in their efforts to develop or manage the water and land resources of the valley. Individuals interested in drilling water wells for homes or farms can determine the chance of obtaining an adequate supply, select favorable well sites, predict optimum drilling depths, and anticipate development problems.

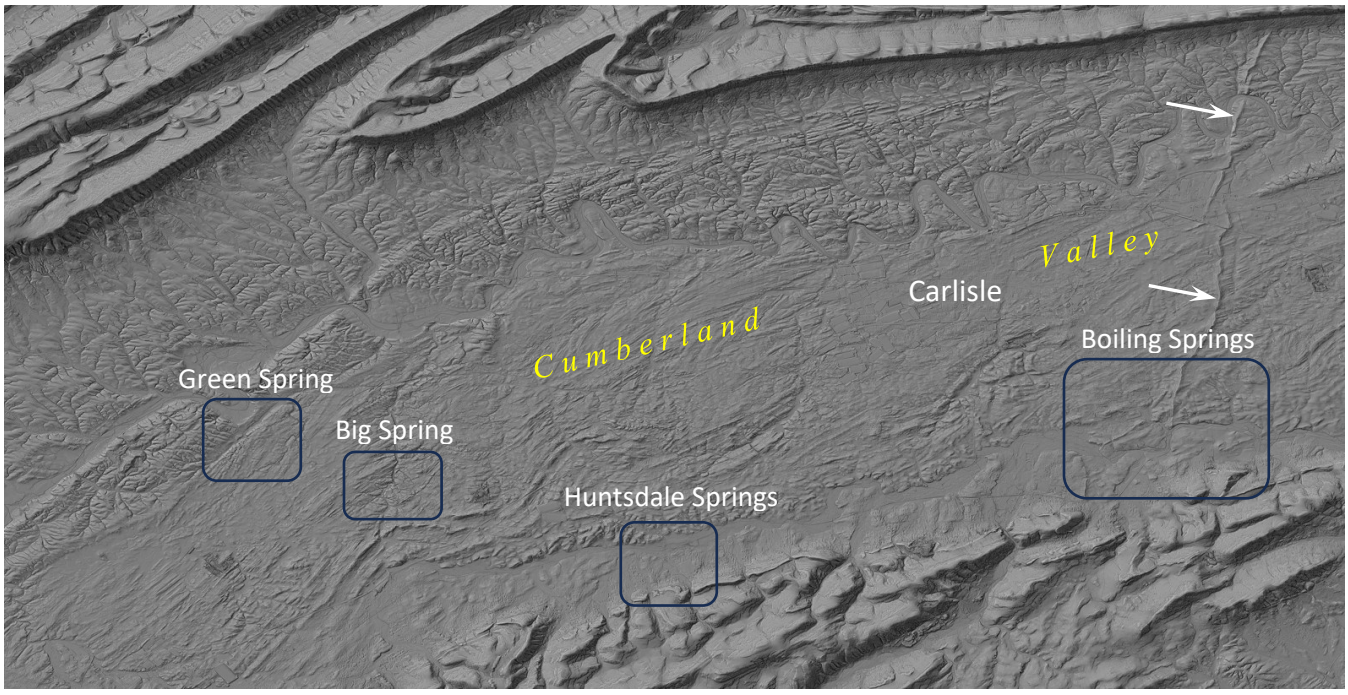


Figure 3.11.41 Part of the enhanced terrain imagery of the Carlisle 30 x 60 Minute Quadrangle from lidar-derived elevation models at 3-meter resolution. From Jackson and Doctor, 2024c. Image is about 20 miles across. Closeups and descriptions of outlined areas are provided further in this section. Arrows point out one of the geologically most striking features in the valley— diabase dike—that acts like a leaky dam and separates western and eastern parts of the carbonate aquifer.

Carlisle is a world-renowned destination for trout anglers, located right in the heart of the Cumberland Valley with its limestone-spring-fed, cold streams. The area offers outstanding fly-fishing opportunities for wild brown,

rainbow, and native brook trout. Letort Spring Run, which flows directly through Carlisle, is considered the birthplace of American spring creek fishing. Famous anglers like Ed Shenk and Vincent Marinaro made their names here. The wild brown trout in the "Letort" are notoriously selective and heavily pressured, offering a highly technical and rewarding challenge. The section upstream of Letort Park is designated as a catch-and-release, fly-fishing-only area (https://fishingflow.wordpress.com/2017/03/29/fly-fishing-cumberland-valley-letort-spring-run/).

Yellow Breeches is widely known for its stocked brown trout and has a popular mile-long catch-and-release section. Many choose to access this stream at Allenberry in Boiling Springs due to the parking and easily accessible waters. Big Spring Creek is another famous limestone creek that flows through woodland and farmland and includes a 1.5-mile catch-and-release-only fly-fishing area (6 Reasons Why Fly-Fishing Is Special to Cumberland Valley).

The Pennsylvania Fly Fishing Museum, located on the outskirts of downtown Carlisle, celebrates the rich fly-fishing heritage of Pennsylvania and Cumberland Valley and features exhibits for Charlie Fox, Vince Marinano, Lefty Kreh, Ed Jaworowski, Joe Humphreys, George Harvey, and others like them who have had a prominent influence on the sport and its resources. Admission to the museum is free.



Figure 3.11.42 Fly fishing on the Cumberland Valley's spring-fed, cold streams is an unforgettable experience. Photo courtesy of https://www.visitcumberlandvalley.com/





Figure 3.11.43 *Left*: Carlisle is home to prestigious Dickinson College, officially chartered in 1783. Historic photo of West College ("Old West") building built of local limestone and designed pro bono in 1803 by Benjamin Latrobe, architect of D.C.'s Capitol building. *Right*: Historic limestone houses dot Carlisle, reminding residents and visitors alike of the valley's rich karst heritage.

Green Spring, Cumberland County

Green Spring is situated on Hatchery Road in Newville, about 12 miles west of Carlisle via Route 641. The spring discharges from the highly karstified Chambersburg Formation carbonates at an estimated median rate of 1,300 gpm (Flippo, 1974, p.22).

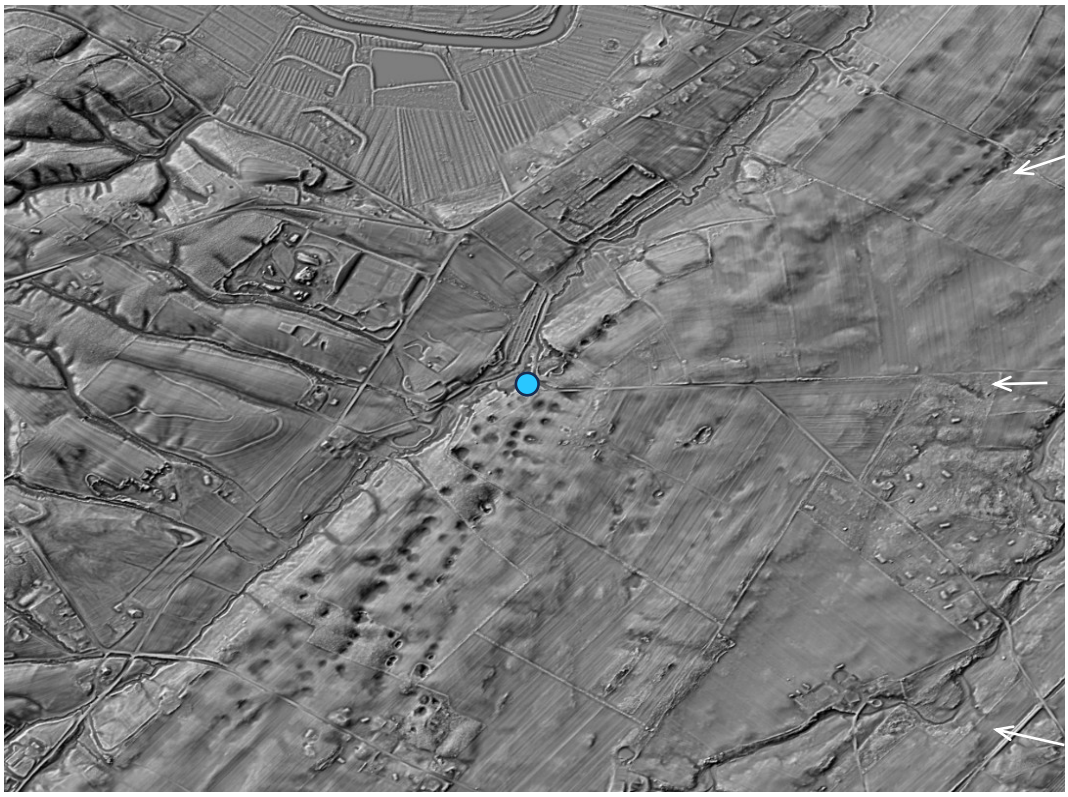


Figure 3.11.44 Part of enhanced terrain imagery of the Gren Spring area (the spring is denoted with the blue dot); Carlisle 30 x 60 Minute Quadrangle lidar-derived elevation models at 3-meter resolution. From Jackson and Doctor, 2024c. The lines of sinkholes, indicating preferential flowpaths in the karst aquifer, are in the Ordovician Chambersburg Formation limestone, and St. Paul Group limestone and dolomite. At the top of the image is the floodplain of Conodoguinet Creek in the village of Green Spring, non-carbonate sediments are on the left. Both are separated from the highly karstified carbonates (shown on the rest of the photo) by a large regional lineament, a likely fault, crossing the image diagonally. Note other lineaments crossing the terrain at an angle to the regional fault, some of which are pointed out with arrows (one of them conveniently served for tracing a local road, minimizing earthwork). Image is about 1 mile across.

Green Spring was utilized by a privately owned trout hatchery until the hatchery permanently closed, following a catastrophic fish kill and unrecoverable business loses. As reported in the local media (e.g., Penn Live Patriot News, and Susquehanna Valley Hearst Television), in March 2014, about 10,000 trout died at Green Spring Trout Farms in Newville, after the spring water feeding the tanks became muddy and smelled of manure. The Hatchery owner Doug Holt strongly believed that manure spread on nearby farms seeped into the underground spring system. He noted that the manure likely absorbed the oxygen in the water, suffocating the fish. The Pennsylvania Department of Environmental Protection (DEP) inspected the area. While they noted recent manure applications on surrounding fields, they stated that the farming was done within regulations. DEP never determined “a single, definitive cause” for the incident, the fishery eventually closed, and the manure is still being freely and indiscriminately spread on numerous farms in Pennsylvania and across the country, including on highly karstified terrains such as the one shown in Fig. 3.11.44.



Figure 3.11.45 Screenshot of a YouTube video describing catastrophic fish kill at Green Spring Hatchery. Available at YouTube channel of Susquehanna Valley Hearst Television, https://www.youtube.com/@WGAL

Big Spring, Cumberland County

According to Pennsylvania Geological Survey (Kochanov, 2010; Flippo, 1974), Big Spring is the fifth largest spring in Pennsylvania, having a median flow of 12,500 gallons per minute. As shown on a detailed geological map of the Big Spring area (Fig. 3.11.47), the spring rises from fractures in the Shadygrove Formation limestone of the Cambrian Conococheague Group. In contrast, Flippo (1974, p.21) states that the spring's aquifer is the Beekmantown Group of Ordovician age. Whatever the case may be, Big Springs drains a significant portion of the vast Cumberland Valley karst aquifer.



Figure 3.11.46 Main outlet of Big Spring in Cumberland County.

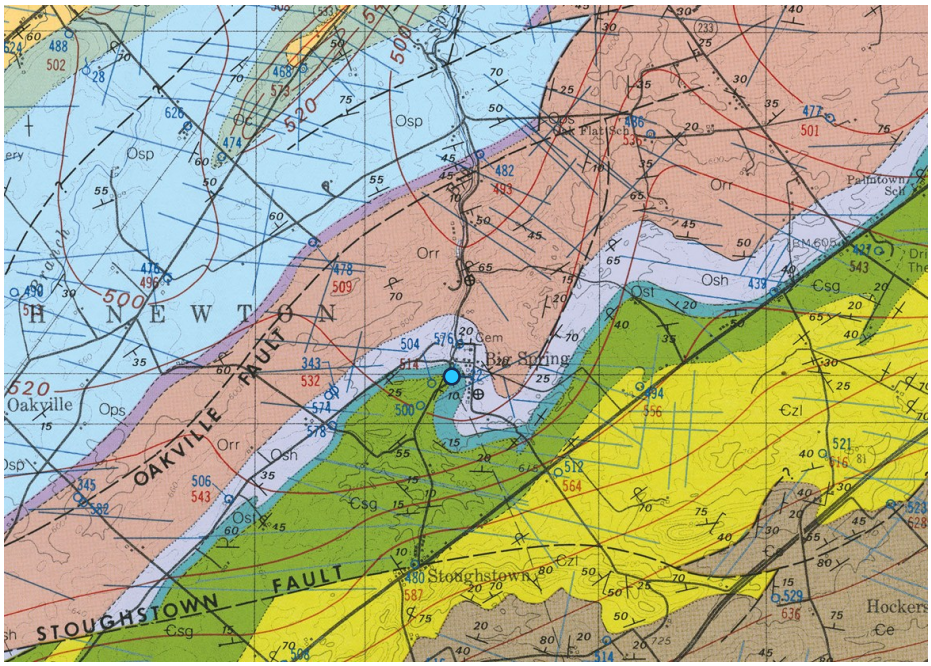


Figure 3.11.47 Geologic map of the Big Spring area (the spring is denoted with blue dot). Map is about 5 miles across. From Becher and Samuel, 1981, part of Plate 1. Geologic units from oldest to youngest: Ꞓe—Cambrian Elbrook Formation Limestone. Ꞓzl—Cambrian Zullinger Formation Limerstone. Cambrian Ꞓsg—Shadygrove Formation Limestone. Ost—Stoufferstown Formation Limestone with medium to thick beds of conglomerate, and abundant siliceous seems. Osh—Stonehenge Formation Limestone. Orr—Rockdale Run Formation Limestone. Ops—Pinesburg Station Formation Dolomite. Osp—St. Paul Group Limestone. Oc—Chambersburg Formation Limestone. Omac—Martinsburg Formation clastics (yellow small areas at the top of the map). Numerous blue lines are fracture traces obtained from aerial photographs; black lines (dashed where inferred) are faults.

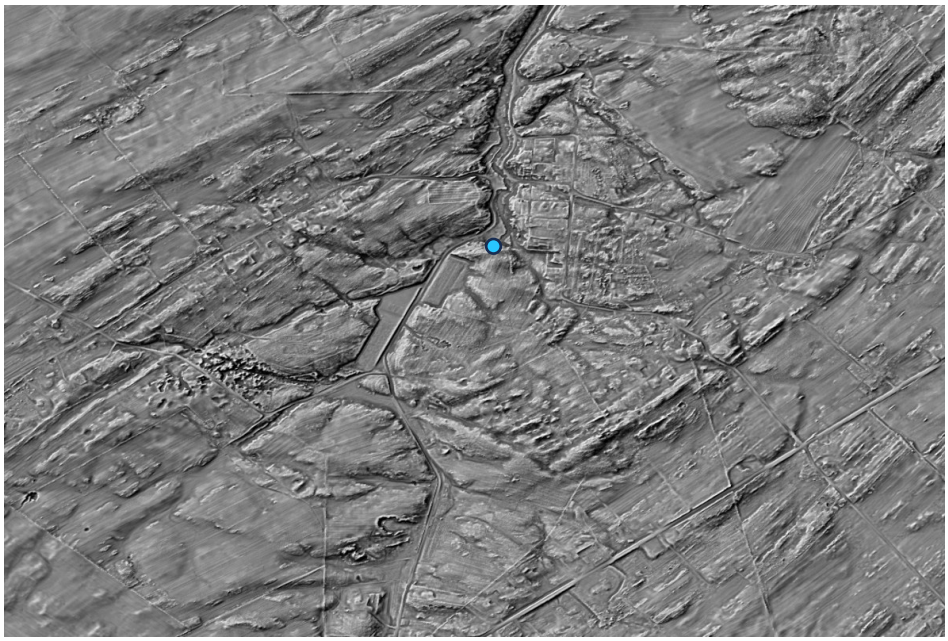


Figure 3.11.48 Part of enhanced terrain imagery of the Big Spring area (the spring is denoted with the blue dot); Carlisle 30 x 60 Minute Quadrangle lidar-derived elevation models at 3-meter resolution. From Jackson and Doctor, 2024c. Visible are numerous lineaments which crisscross the general SW-NE trend of folded geologic units. Image is about 1 mile across.

Big Spring is the head of Big Spring Creek (the creek is commonly referred to simply as Big Spring, often causing confusion) in the village of Big Spring, approximately 3 miles south of the Borough of Newville. The Pennsylvania Fish and Boat Commission (PFBC) designates segments of the creek as Class A wild trout waters for brook trout and rainbow trout from its headwaters downstream to Nealy Road (catch-and-release, fly fishing only), while downstream sections through Newville are stocked with trout each spring. Below Laughlin Dam in Newville to where the creek enters Conodoguinet Creek, the creek is designated as a Class A wild brown trout fishery.

A state hatchery built at the spring by the PFBC became operational in 1972. Shortly thereafter, the native wild brook trout population in Big Spring Creek dramatically declined. A study conducted by Dr. Jack Black and Gene Macri, titled "An Ecological Survey of Big Spring with Emphasis on the Effects of Fish Hatchery Effluent," began in 1995 and was released to the public and the Pennsylvania Department of Environmental Protection (DEP) in 1997. It revealed that the hatchery's effluent had negatively affected the stream. This study, along with the subsequent reports from the DEP and advocacy from local citizen groups, prompted the closure of the hatchery in 2001. Following this closure, the stream made a remarkable comeback, now hosting over 350 pounds of brook trout per acre in the upper section, making it the most productive brook trout stream in the nation (Big Spring Preservation Association – Saving The Big Spring Creek).

With year-round flows of steady 46–51°-degree water (no winter freeze) Big Spring Creek served as an ideal site for water-powered mills since the 1760s, with two mills established prior to the Revolutionary War. Historically, six mills have operated on the creek. They were critical for farmers between Chambersburg and Harrisburg who needed grains processed into flower, corn meal, or livestock feed. The establishment of the Cumberland Valley Railroad (CVRR) in 1837 was a great benefit for farmers shipping mills products to distant markets. Laughlin's Mill, the last mill structure remaining on the creek, is located in Newville.



Figure 3.11.49 Old concrete walls and control gates are parts of the water control system at the former fish hatchery that utilized water of Big Spring. The hatchery closed in 2001 after findings that its effluent had negatively affected the stream.

Based on dye tracing results, Hurd et al. (2010) estimated that the drainage area of Big Spring is approximately 29 square miles, whereas the surface watershed area is only 3.4 square miles. They have documented fast, regional conduit flow along strike (approximately 1.9 mi/day based on first arrival time) and vulnerability to intensive land use for an exceptional-value spring-fed Big Spring Creek.

As explained by Hurd (2012), delineation of the contributing areas of Big Spring and surrounding springs using dye tracing was, in part, conducted due to construction of a permitted quarry. The Pennsylvania Department of Environmental Protection, Bureau of Mining, did not require a fluorescent dye trace in order to approve the quarry permit, citing adequacy of a flow model that indicated slow (meters per day) localized northward groundwater flow and concerns about coloration of water that might result from the dye. Hurd notes that the quarry's consultants did point out, however, that some of the Cambrian Zullinger Formation that underlies most of the property is fractured. Moreover, the newly constructed detention pond never filled, due to rapid drainage into an associated sink indicating rapid groundwater flow to unknown receptors (Hurd, 2012).



Figure 3.11.50 A failing detention basin draining runoff from impervious surface directly into the aquifer via a sinkhole. Dye from this site, far outside the surface watershed, traveled 5.5 miles to Big Spring within 3.5 days. From Hurd et al., 2010; photo by T.M. Hurd.

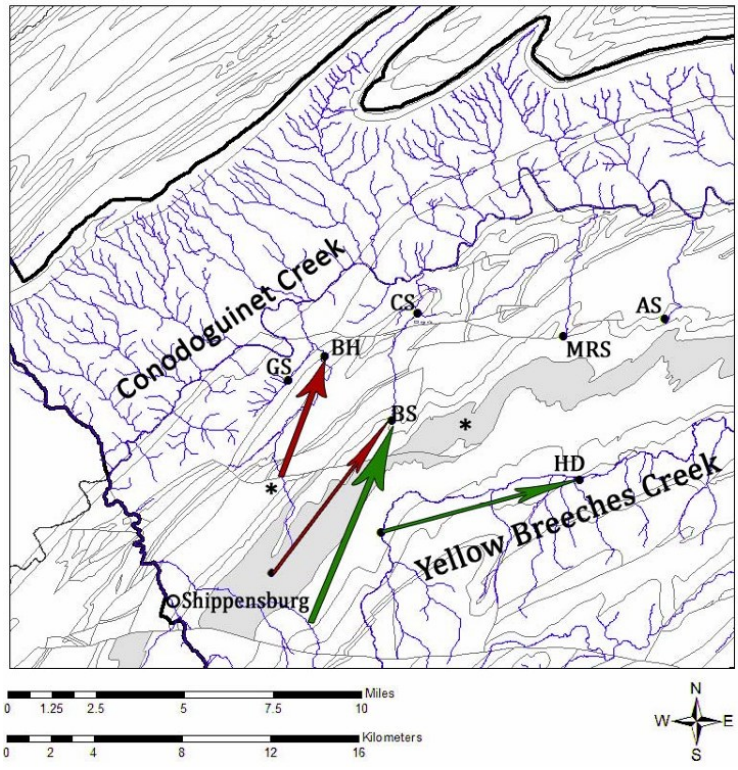


Figure 3.11.51 Groundwater flow in western Cumberland County as determined by fluorescent dye tracing. Thin arrows show groundwater flow determined by Hurd et al. (2010); bold arrows show groundwater flow direction determined in 2009. Uranine was used to trace interbasin flow from upper Burd Run/Middle Spring to Big Spring and flow from the upper Yellow Breeches to Hunstdale Springs. Sulforhodamine B was used along with sodium naphthionate to trace flow in the Bullshead Branch system and from a sinkhole in the Zullinger Formation near the Interstate Route 81 and State Route 174 interchange. The Zullinger Formation is shown in light gray, and the asterisks show locations of limestone quarries in the region. Springs sampled were Big Spring (BS), Green Spring (GS), Bullshead Branch (BH), Cool Spring, Newville's municipal supply (CS), Mount Rock Spring (MRS), Alexander Spring (AS), and Huntsdale Springs (HD). Burd Run of Middle Spring was also sampled but there was no definitive detection of uranine, suggesting a different source water than that sinking higher in the watershed. From Hurd, 2012.

Huntsdale Hatchery Springs, Cumberland County

Huntsdale Fish Culture Station, built in 1932 and owned by the Pennsylvania Fish and Boat Commission (PFBC), is one of the largest hatcheries in Pennsylvania. Cold water is supplied directly from 9 natural karst springs, whereas warmer water for alternative species is from the Yellow Breeches Creek. The springs discharge from the Early Cambrian Waynesboro and Tomstown Formation carbonate, at a combined mean rate of over 10,000 gpm (Becher and Root, 1981). Spring known as #6 is the largest, providing on average about 1/2 to 2/3 of the water supply (2,500 gpm was pumped on July 23, 2006).



Huntsdale Fish Hatchery produces roughly 370,000 pounds of trout annually. This amounts to over 900,000 to 1 million individual fish reared each year. It primarily focuses on coldwater culture. This includes brook, brown, rainbow, and vibrant golden rainbow trout. The indoor display pond houses rare blue trout, a natural genetic mutation found in some rainbow and brown trout. The hatchery also utilizes pond rearing for cool and warmwater species. This includes hybrid striped bass introduced to stock Pennsylvania's lakes.



Figure 3.11.52 Spring #6, the largest of the nine springs tapped by the Huntsdale Fish Cultural Station, is easily accessible for observation. As explained by the hatchery's manager Andrew Wagner (pictured on the top photo), its water is cyclically pumped to different parts of the operation (the pump assembly is shown on the lower photo). Huntsdale Hatchery Springs are recognized as an Outstanding Scenic Geologic Feature of Pennsylvania (Geyer and Bolles, 1979).

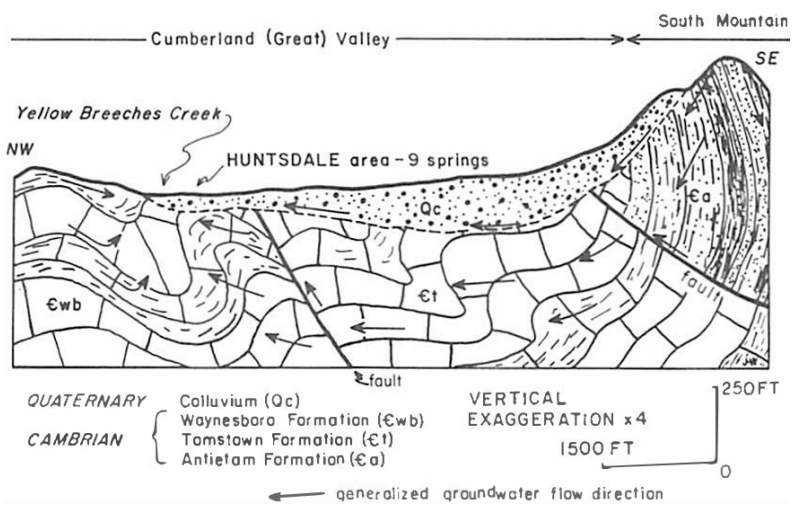


Figure 3.11.53 Geologic setting for the springs in the Huntsdale Fish Hatchery area. Cross section is drawn across the Cumberland Valley and South Mountain. From Way, 1986.



Figure 3.11.54 McManus (left) and Butcher (right) Springs used by the Huntsdale State Fish Hatchery.



Figure 3.11.55 Knaub Spring (*left*) usually provides water to the part of the Hatchery shown on the *right*.

Boiling Springs, Cumberland County

Boiling Springs are in the village of Boiling Springs, located in South Middleton Township, approximately 8 miles south of Carlisle and 22 miles southwest of Harrisburg, the state capital. The village was named after large karst artesian springs that now bubble up into serene Children's Lake, in the beautiful historic district which was listed on the National Register of Historic Places in 1984.

Children's Lake was formed in the early 1740's when the springs were dammed for the grist mill which still stands on the lake's southeast shore. By 1760, the village consisted of the mill, "miller's house," a blacksmith shop, two store dwellings and several nearby farms. In 1872, a stone wall was constructed around the lake by the owner, Carey W. Ahl. The village grew along the banks of Yellow Breeches Creek, a renowned limestone trout stream that attracts fly fishermen from around the country.

As described by Geyer and Bolles (1979), Boiling Springs, which have a combined median flow of 11,500 gallons per minute, are the most picturesque springs in the Cumberland Valley. Their origin is unique: the folded Cambrian limestones and dolomites of the Elbrook Formation have been injected by a near-vertical, thin diabase dike. This diabase is almost impervious and acts as a hydraulic barrier. At Boiling Springs, the dike splits into two segments, so that the village is located in the interior apex of a "V" formed by the dikes. The direction of groundwater flow is to the north and east from the higher elevations on South Mountain. Groundwater becomes progressively confined between the two dikes until it "boils" forth mainly from two springs near the apex.

There are other boils and bubbles over the bottom of the lake which can be plainly seen because of the crystal-clear water. The water temperature varies little from a normal 53 degrees Fahrenheit, so the lake constantly cools the atmosphere, but never freezes.



Figure 3.11.56 A spring boil in Children's Lake. Boiling Springs are recognized as an Outstanding Scenic Geologic Feature of Pennsylvania.

Moser et al. (2014) propose that the water discharged at Boiling Springs is being recharged from the northeastern face of South Mountain, just south of the Boiling Springs watershed. There, the bedrock is mainly quartzite of the Weverton Formation, which has high primary and secondary porosity and permeability. The water could then move deep underground through the karst aquifer before being discharged at Boiling Springs. The authors also emphasize that the groundwater flow at the springs is anomalous in two ways. First, the amount of water discharged at this location is roughly 16 million gallons per day. This discharge is four times larger than expected from the 3 mi^2 recharge area of the Boiling Springs watershed. This implies that a significant amount of water discharged from Boiling Springs is coming from sources outside the local watershed. Second, the water temperature cycle at Boiling Springs lags four to six months behind that of regional air temperature, suggesting a long groundwater flow path.

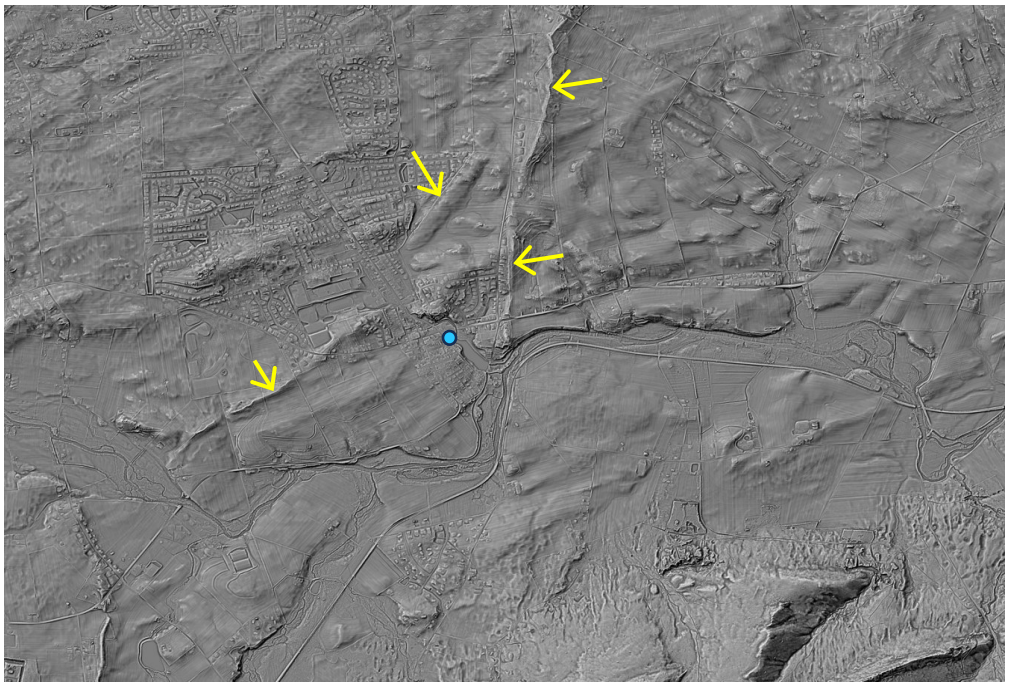


Figure 3.11.57 Part of enhanced terrain imagery of the Boiling Springs area (the main discharge point is denoted with the blue dot); Carlisle 30 x 60 Minute Quadrangle lidar derived elevation models at 3-meter resolution. From Jackson and Doctor, 2024c. Arrows point out the diabase dikes, thought to be the main reason for the emergence of the strong artesian springs.. Image is about 2.7 miles across.



Figure 3.11.58 The power of Boiling Springs is best appreciated at the two outfalls from the Children's Lake.

Schantz Spring, Lehigh County

Schantz Spring, which forms the headwaters of Cedar Creek, is located about five miles west of Allentown in Lehigh County. It is a vital groundwater source supplying roughly half of the region's drinking water. The spring is named after Jacob Schantz, who acquired the property in 1792. In 1888, David Koch purchased the spring. In 1894 he leased it to his son, who ran it for four years until the spring was sold to the city. It has served the city's water needs ever since.

Owned by the City of Allentown and managed by the Lehigh County Authority, this massive karst spring requires minimal filtration. Due to its high quality, the water only needs to be treated with chlorine for disinfection before flowing directly to thousands of properties (https://www.lehighcountyauthority.org/drinking-water/water-supply-updates/)

As mused by the local media entertaining their readers (e.g., Morning Call - Lehigh Valley & Allentown PA News, Sports, Weather, Business & Things to Do) "The exact underground source of the spring has been heavily debated for decades. In the early 1900s, some engineers theorized the spring was fed by subterranean streams connected to Seneca Lake in New York or even Lake Erie. However, United States Geological Survey studies in the 1970s concluded the spring's true source is a deep, extensive underground aquifer located in northwestern Lehigh County."

A detailed scientific explanation about the origin of the spring is provided by Sloto et al. (1991): "Schantz Spring is located near the contact between the Allentown Dolomite and the Epler Formation of the Beekmantown Group at an elevation of 340 ft. The contact is interpreted to be a shallow thrust fault that dips about 15° southeast and brings the Allentown Dolomite up over the Epler Formation. The size of the Schantz Spring ground-water basin, in part, controls the discharge of Schantz Spring. The size of the ground-water basin changes when the groundwater divides that delineate it shift because of changes in recharge or withdrawals. Wood et al. (1972, p. 21 and pl. 1) determined that the ground-water basin that drains to Schantz Spring is an elongated area of approximately 10.4 mi^2 that extends northwestward from the spring to the headwaters of Iron Run. They estimated that 8.25 mi^2 of this basin underlies the surface-water basin for Iron Run, a tributary to Little Lehigh Creek above gaging station 01451500, and that 2.15 mi^2 underlies the surface-water basin for Cedar Creek. The average daily discharge from Schantz Spring ranged from 5.2 million gallons per day (Mgal/d) in 1966 to 8.3 Mgal/d in 1975; the average daily discharge for 1956-84 (29 years) was 6.9 Mgal/d. Note that, in gallons per minute, these numbers are 3,600; 5,760; and 4,790 respectively.



Figure 3.11.59 Historic postcard of Schantz Spring before it was capped.

3.12 New Jersey, and New York

3.12.1 New Jersey

Soluble rocks in New Jersey, such as limestone, dolomite, marble and limestone-clast conglomerate cover about 350 square miles in the Valley and Ridge, Highlands and Piedmont provinces. In the Coastal Plain, the Vincentown Formation underlies about 100 square miles, and consists locally of soluble lime sand and thin limestone layers. The limestone layers are more common from western Monmouth County southwestward to the Delaware River. Also, a few thin cemented shell beds occur locally in other Coastal Plain formations (Dalton, 2014).

The largest springs in New Jersey are formed in karst limestone and dolomite formations which crop out in the northwestern part of the state along the regional, northeast-southwest Appalachian structural trend (Fig. 3.12.1). The Wisconsinan Terminal Moraine bisects the outcrop belt into a northern glaciated sector and a southern unglaciated sector. The rocks range in age from Middle Proterozoic to Middle Paleozoic (Monteverde and Dalton, 2002; Pallis et al., 2022).

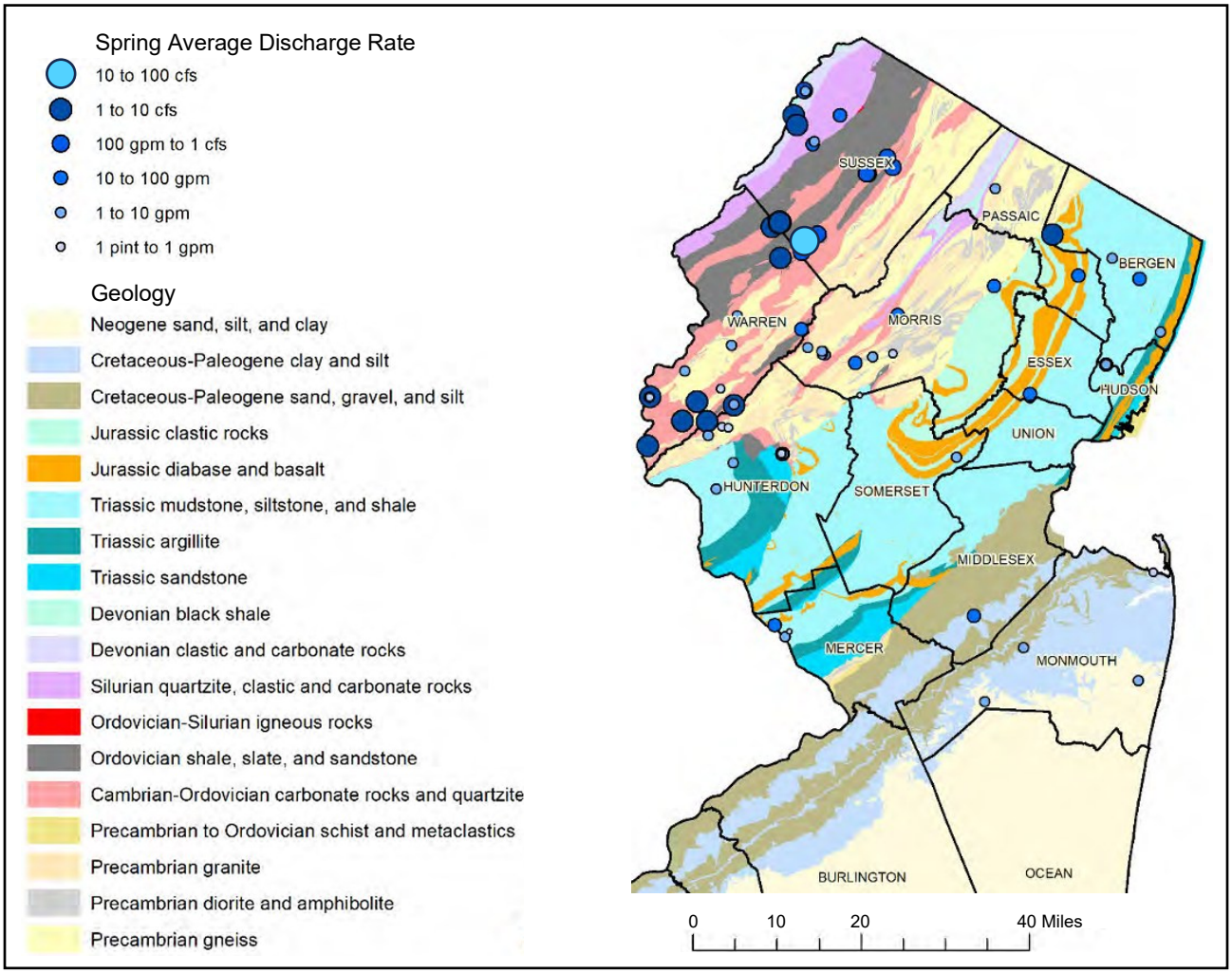


Figure 3.12.1 Map of springs by average discharge rate for selected springs in New Jersey where a discharge rate has been recorded. Brook Spring near Stillwater in Sussex County is recognized as New Jersey's only 2nd magnitude spring (largest blue dot; average discharge rate 10 to 100 cfs). Modified from Pallis et al., 2022.

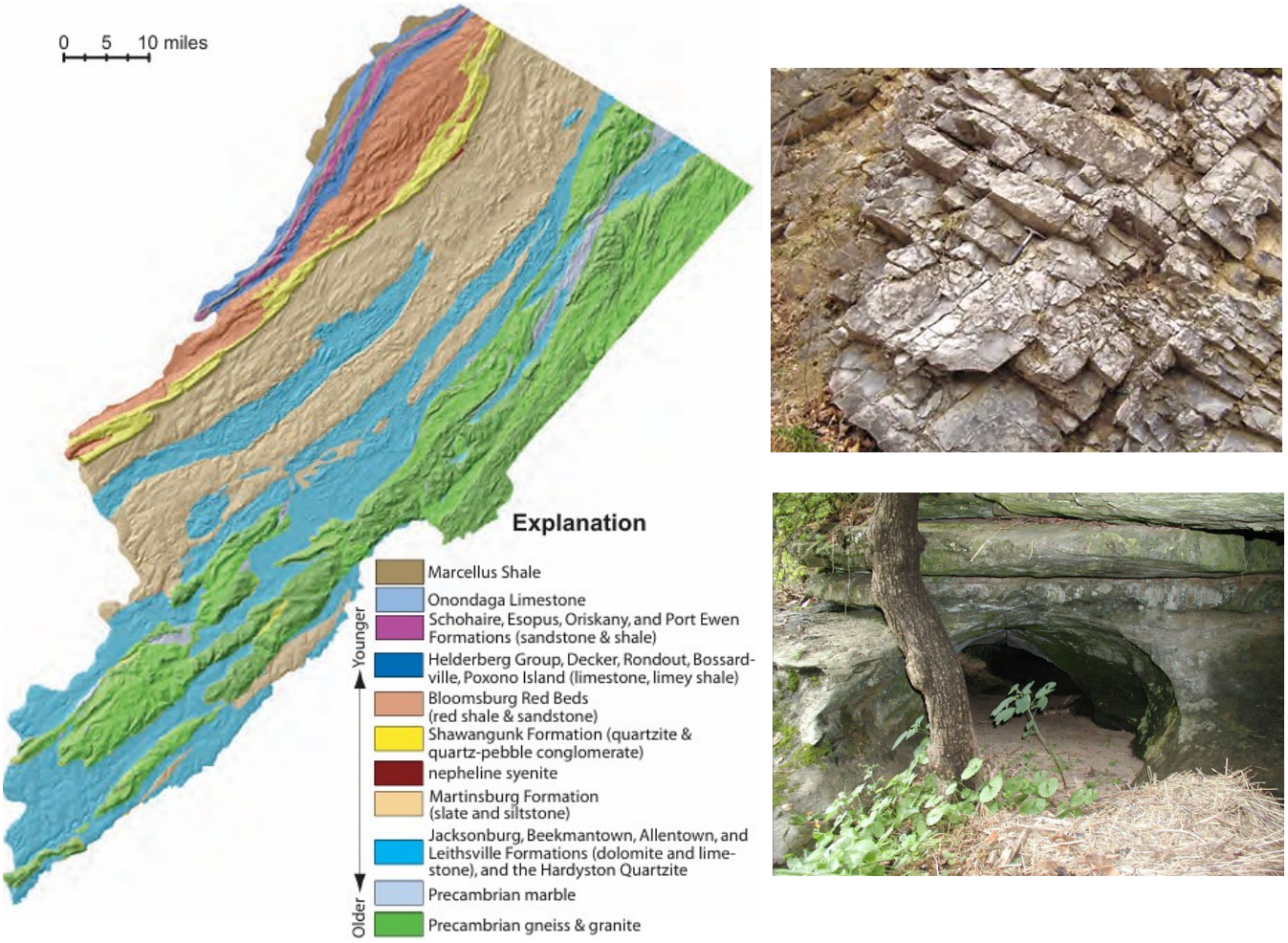


Figure 3.12.2 *Left*: Bedrock geology of New Jersey's Valley and Ridge Physiographic Province. From Witte and Monteverde, 2012. *Top right*: Highly jointed Allentown Dolomite in Kittatinny Valley near Newton. Bedding dips to the left whereas closely-spaced joints dip in the opposite direction. Joints typically exhibit preferred orientations and many are orthogonal to bedding. Joints, fractures, and faults formed during the Taconic and Alleghenian Orogenies when the Lower Paleozoic Formations were tectonically compressed. From Witte and Monteverde, 2012. *Bottom Right*: Vulture Cave in the Onondaga Limestone, Delaware Water Gap National Recreation Area, Montague, New Jersey. The cave opening is about 4 feet (1.2 m) in diameter. Photo by R. Witte. From Monteverde and Witte, 2021.



Figure 3.12.3 Eastward flowing stream crosses the approximate location of the contact between the Martinsburg Formation slates and siltstones, and the Ordovician Beekmantown Group's Jacksonburg Limestone. Here the stream completely disappears into a swallow hole. To the right of the swallow hole is a sinkhole that developed adjacent to the stream. Similar small streams sink across this Martinsburg-carbonate elsewhere in the Newton area. From Monteverde and Witte, 2021.

Table 3.12.1 The ten largest springs in New Jersey all issue from Paleozoic karst aquifers in the Valley and Ridge physiographic province, in Warren and Sussex Counties. Bonnie Brook Spring near Stillwater is recognized as New Jersey's only 2nd magnitude spring. Note that 1 cubic foot per second (cfs) equals 449 gallons per minute (gpm). From Pallis et al., 2022.

Rank	Spring	Magnitude	Details	County	Notes
1	Bonnie Brook Spring	2n^{d} <100 to >10cfs	900 gpm in 1947 and 5,000 gpm in 1967 per USGS.	Sussex	Estimate
2	Schuster Pond/Mountainwood Spring Water Co.	3rd 1 to 10 cfs	4,000 gpm in 1934. 3.7 cfs (1,630 gpm) 1966.	Warren	Reported in 1934. Measured with Stream-flow meter in 1966.
3	Stanley Spring/Troutdale Spring, Muskey Trout Hatchery	3rd 1 to 10 cfs	2,160 gpm in 1948 per USGS. 1,200 gpm per owner, 2012.	Warren	Weir measurement 1948.
4	Shoemaker Spring, Pequest Fish Hatchery	3rd 1 to 10 cfs	1,347 gpm, June 16, 1973.	Warren	Weir measurement.
5	Hatchery Pool Spring, Pequest Fish Hatchery	3rd 1 to 10 cfs	1,222 gpm, June 16, 1973.	Warren	Weir measurement.
6	Shurts Road Spring	3rd 1 to 10 cfs	1,000 gpm, with 35 gpm from adjacent spring house.	Warren	Verified during visit.
7	State Fish Hatchery at Hackettsown Spring	3rd 1 to 10 cfs	833 gpm. NY Sun, 1917.	Warren	Verified during visit.
8	Brau Kettle Spring	3rd 1 to 10 cfs	500-100 gpm. With a peak of 3,500 gpm.	Sussex	Weir measurement.
9	Kennedy Mill-Stewartsville Spring	3rd 1 to 10 cfs	2.23 cfs. At least 4 discrete springs at base of cliff.	Warren	Verified during visit.
10	Marble Mountain Spring	3rd 1 to 10 cfs	1,000 gpm, June 29, 1948.	Warren	Verified during visit.

Bonnie Brook Spring, Sussex County, and Shuster Spring, Warren County

One of the largest documented karst drainage systems in New Jersey discharges from the Upper Cambrian Allentown Dolomite at Bonnie Brook and Shuster Springs (Fig. 3.12.4). As part of a 1968 New Jersey Department of Health investigation to identify the source of bacterial contamination in the Bonnie Brook Spring, the New Jersey Geological Survey recommended placing dye in the swallow-hole-outlet of Schuster Pond, located more than 4,000 feet away from the spring, along the strike of the local bedrock. The dye appeared in the spring in less than two hours. The 1968 Schuster Pond dye test showed a connection between the Schuster Pond and the spring (Pallis et al., 2022).

Canace et al. (1996) state that the Schuster Pond area exhibits disappearing streams, springs and groundwater flow characteristics typical of a karst conduit-influenced flow system. They measured an instantaneous discharge

of Shuster Spring of 3.7 cfs (1,630 gpm) using a stream-flow meter. The record of spring discharge as measured by the owner of the spring shows significant variation over the course of a year, including changes exceeding an order of magnitude within time spans of one month. Such extreme variations in discharge from a major spring is an indication that the spring at Schuster Pond is partially fed by a conduit system (Canace et al., 1996).

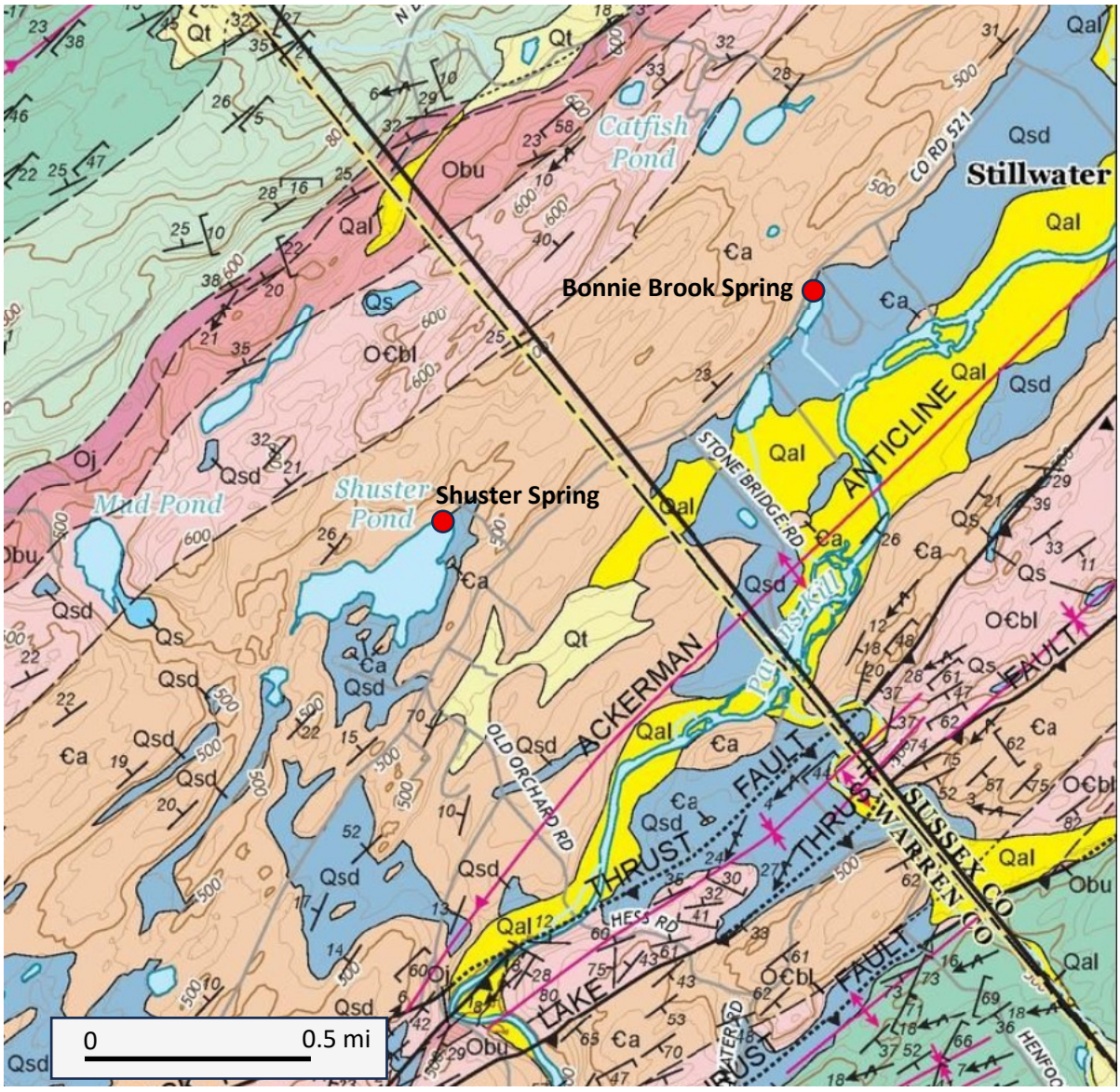


Figure 3.12.4 Part of the Geologic Map of the Flatbrookville Quadrangle Sussex and Warren Counties, New Jersey, and Monroe County, Pennsylvania (Monteverde et al., 2021), showing the area around Bonnie Brook and Shuster Springs. Geologic units, from oldest to youngest: €a—Allentown Dolomite (Upper Cambrian; regionally 1,800 ft thick). O€bl—Beekmantown Group Dolomite, lower part (Lower Ordovician to Upper Cambrian; 600 ft thick). Obu— Beekmantown Group Dolomite, upper part (Lower Ordovician; 100 to 300 ft thick). Oj—Jacksonburg Limestone (Upper Ordovician; 200 ft thick). Omb—Bushkill Member of Martinsburg Formation (Upper Ordovician; 1,400 ft thick): slate with siltstone. Omr—Ramseyburg Member of Martinsburg Formation (Upper Ordovician; 4,000 ft thick): slate, sandstone, and siltstone. Qsd—Meltwater deposits (late Wisconsian; up to 150 ft thick): boulder-cobble to pebble gravel, pebbly sand and minor silt; in places includes minor clay and very fine sand. Qt—Till (late Wisconsian; less than 20 ft thick): very poorly sorted matrix of sand, silt, and clay and containing 5 to 35 per cent pebbles, cobbles, and boulders. Qs—Swamp and bog deposits (Holocene and late Wisconsinan; up to 25 ft thick). Qal—Stream alluvial deposits (Holocene and late Wisconsinan; up to 40 ft thick).

Bonnie Brook Spring has the largest discharge rate of any spring ever measured in the state: 5,000 gpm (11.1 cfs) recorded by the U.S. Geological Survey on May 22, 1967 (Kasabach et. al., 1967). On September 10, 1947, flow from Bonnie Brook Spring was estimated by Mr. William Stanley of Roselle to be around 900 gpm (Herpers, 1947). Even though these two measurements are the only ones publicly available, New Jersey Geological Survey officially recognizes Bonnie Brook Spring as the largest in the state (Table 3.12.1).



Figure 3.12.5 Bonnie Brook Spring springhouse. Photo by Z. Allen Lafayette; from Pallis et al., 2022.

The Bonnie Brook Spring and its associated springhouse are historic fixtures on the Bonnie Brook Farm in Stillwater Township. The spring itself, historically documented as "Big Spring," has long been a defining natural feature of the property. Today, Bonnie Brook Farm remains a privately owned historic property that celebrates its deep roots in Sussex County history. Vintage postcards from as early as 1907 showcase the "Big Spring" as a scenic highlight of the estate. The current owners occasionally open portions of the farm for community events, giving locals a glimpse of the pastoral, waterfall-lined landscape.

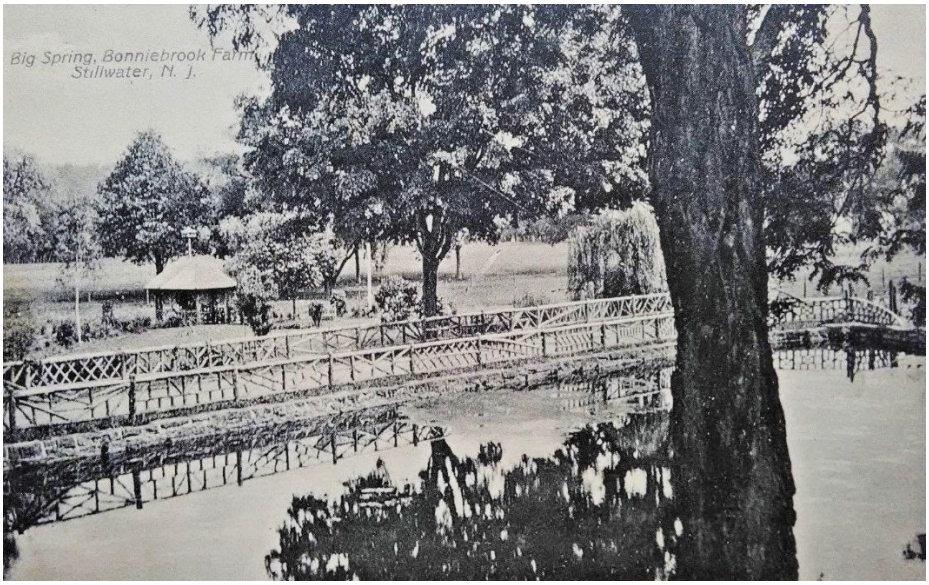


Figure 3.12.6 Historic postcard of “Big Spring” (now Bonnie Brook Spring) on Bonnie Brook Farm in Stillwater, New Jersey.

Shuster Pond Preserve is a conservation easement on privately-owned land. Public access is provided via a hiking trail that can be accessed from Mallard Pond Road. Visitors must stay on the trail to avoid trespassing on private property.

This 92-acre preserve is part of the state-designated Shuster Pond Natural Heritage Priority Site. It is a prime example of an intact limestone forest. The unique ecosystem hosts a variety of rare and endangered plants associated with limestone, plus abundant wildlife that thrives within the dense interior forest, and in and around Shuster Pond. The spring that feeds the pond is the second most prolific in the Ridge and Valley Region, flowing at an average of 5 million gallons per day, and ultimately helps maintain the water quality of the Paulins Kill River.



Shuster Pond Preserve is part of a large, open-space greenway of preserved land that includes several other Ridge and Valley Conservancy (RVC) preserves, as well as lands owned by The Nature Conservancy and the State of New Jersey.

Figure 3.12.7 View across Shuster Pond towards Shuster Spring in far distance. The pond outlet is in lower center-right. Courtesy of Ridge and Valley Conservancy.

https://www.ridgeandvalleyconservancy.org

Brau Kettle, Sussex County

One of the most interesting New Jersey karst features is the Brau Kettle, located 125 feet south of the intersection of Old Mine Road and Jager Road, four miles northeast of the Dingman's Ferry bridge in Sandyston Township, Sussex County. References to the kettle go back to the early French and Dutch settlers and the name likely derives from the Dutch name for a "brewing" or "boiling kettle" which describes how water suddenly bubbles up from the ground (Dalton, 1976). This site is mentioned in early French Jesuit and Dutch colonial manuscripts as a landmark near which colonial traders exchanged goods with the Munsee and other local Native American tribes.

The hydrogeologic setting and characteristics of Brau Kettle are described in detail by Monteverde and Witte in a field trip guidebook prepared for the 37th Annual Meeting of the Geological Association of New Jersey, October 16 & 16, 2021 (Hozik, M.J., editor, 2021).

The kettle is a conically-shaped depression approximately 10 feet deep by 20 feet wide with its floor located in glacial till. The sloping walls of the kettle are in thin wind-blown sand and till. The depth to rock is unknown, but given the kettle's geometry and discharge history, it is assumed that the Onondaga Limestone is very near the

kettle's floor. Brau Kettle can be classified as an intermittent spring that varies from dry, to partially filled, to spilling, with highly variable fill and spill periods. A hydrogeologic investigation of Brau Kettle and its relationship to the Onondaga Limestone commenced in 2008 by the New Jersey Geological and Water Survey under a research permit granted by the National Park Service. This investigation consisted of measured hourly water level data using an ADR logger from the kettle and a nearby domestic well, precipitation data, and kettle discharge measurements.

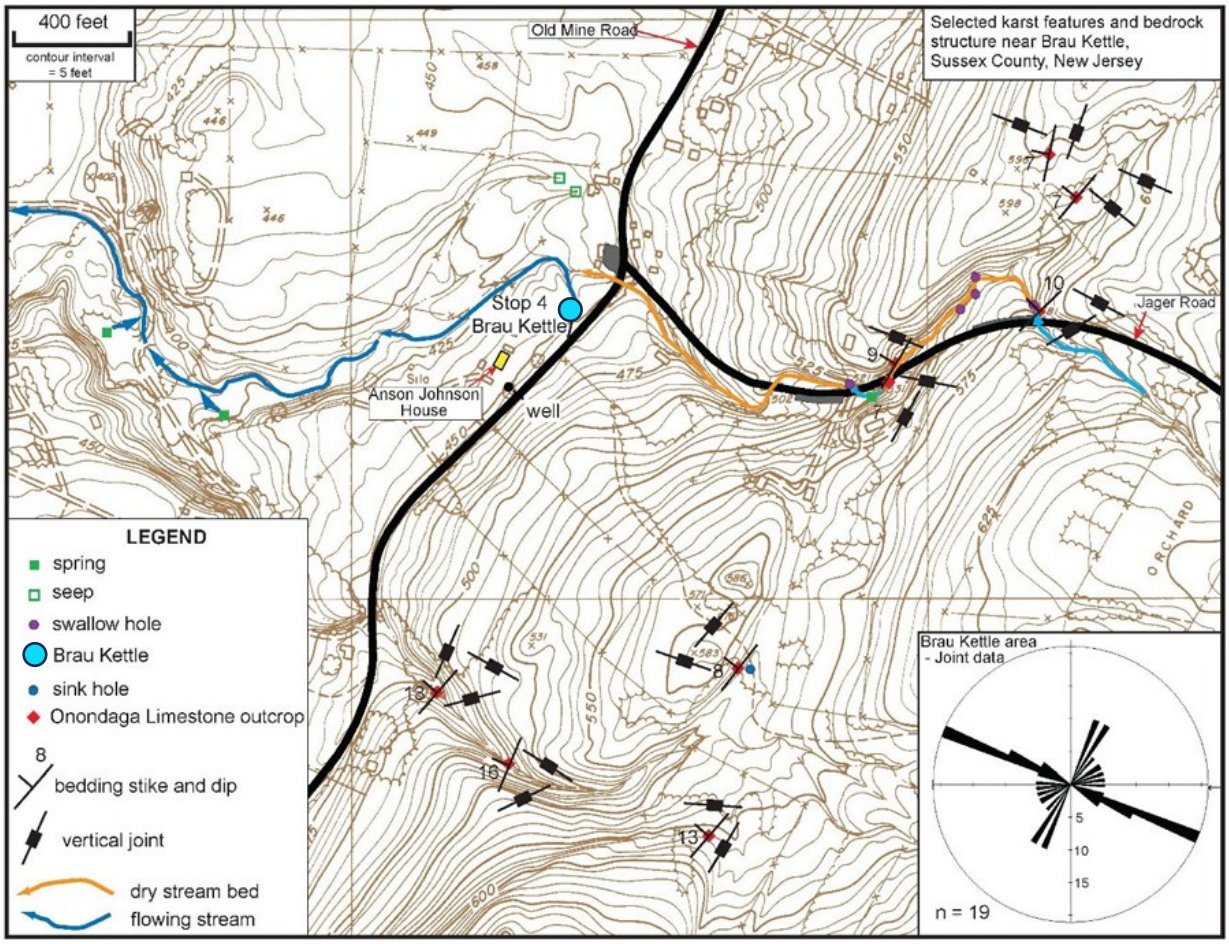


Figure 3.12.8 Map of the Brau Kettle Area. From Monteverde and Witte, 2021.

It is hypothesized that the kettle was formed when a near-surface solution feature (joint or joint intersection) in the Onondaga Limestone enlarged to the point where the overlying surficial materials collapsed creating a sinkhole. Over time the flowing groundwater removed most of the finer materials leaving a boulder lag on the kettle's floor. Because the kettle is well above the Delaware River near the base of Wallpack Ridge and the small unnamed dry stream, groundwater only rises in the kettle during wet recharge periods. Farther downstream (closer to the Delaware River) is a series of perennial springs which discharge (in a boil-like fashion) through glacial outwash and postglacial alluvium. The lower elevation springs can be thought of as the perennial "base-line" discharge points and the kettle can be thought of as the overflow or relief valve when groundwater levels are elevated and discharge is high through the local joint controlled hydrogeologic system.

The period when a square notched weir was installed on the Brau Kettle outlet channel and used to measure discharge is shown on Fig. 3.12.9. Calibration of the manual and data recorder measurements was poor with an R-squared error of 0.79 and seepage around the edges of the weir was observed after several months of operation.

The discharge estimates should be assumed approximate at best. The kettle and domestic well water level elevation can be seen rising and falling in response to recharge events Discharge is observed to have occurred in the wetter winter months when evapotranspiration is low and recharge rates and water levels are typically highest. Discharge also periodically occurs during the summer and fall for short durations when heavy rains cause significant but temporary increases in water levels. Discharge rates hover in the 500 to 1000 gpm range and peak as high as 3,500 gallons per minute (gpm). This would make the kettle a 3rd order spring and fairly large for what is typically observed in New Jersey. Also of interest is that a nearby stream channel (located approximately 100 feet to the north and lower in elevation than the base of the kettle) is typically dry when the kettle is actively discharging. This suggests that groundwater flow is highly constrained along joint-controlled flow paths (Monteverde and Witte, 2021).

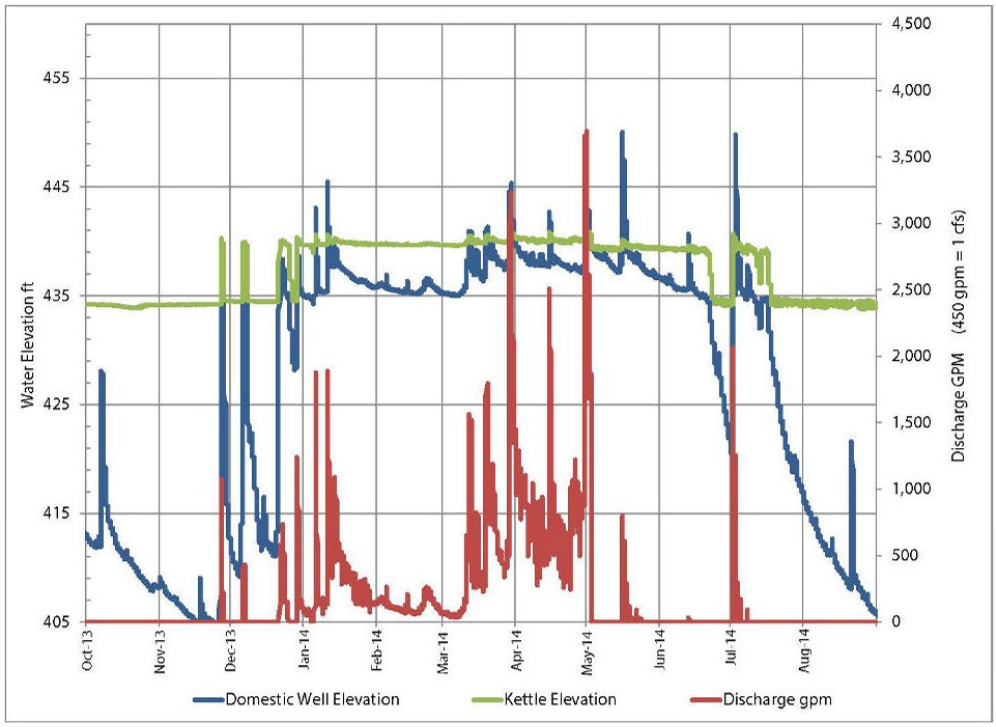


Figure 3.12.9 Water levels at the Anson Johnson House domestic well and Brau Kettle, and Brau Kettle discharge rate from October 2013 to August 2014. From Monteverde and Witte, 2021.



Figure 3.12.10 Seasonal views of Brau Kettle. Photo A shows the kettle flowing during the late winter, typically a period of high groundwater levels in the Onondaga Limestone. Photo B shows the kettle partially filled, either filling or draining in response to summer thunderstorms. Photos by R. Witte. From Monteverde and Witte, 2021.

3.12.2 New York

New York does not have any 1st or 2nd magnitude springs because the extent of the individual karst aquifers is very limited—they are highly compartmentalized due to faulting, folding and the nature of depositional environments in which various non-carbonate sediments were frequently interbedded with the carbonates. Nevertheless, when it came to promoting their springs around the world, the City of Saratoga Springs was in a league of its own, unrivaled by any other place on earth at the time. In addition to the "miraculous springs that cure many diseases", it did not (and still does not) hurt that the New Yorkers sought summer refuge in the cooler parts of the state up north, bringing along their money and entrepreneurial spirit.

Dozens of pretty spring houses (e.g., see Figs. 3.12.11 and 3.12.13), hotels, and entertainment establishments sprouted in the nineteenth century throughout the city. As demand grew, wells were drilled and they were quickly touted as *Wonderful Mineral Fountains.* The springs were immortalized in various publications, on postcards, and with novel stereophotographs that lured in many visitors. Those seeking a cure and those that just wanted to escape the big hot city to the south to socialize, to be entertained, to be seen, and to attend horse races in one of the most famous racetracks in the country, all found what they were seeking at Saratoga.





Figure 3.12.11 *Left*: Hathorn Spring, shown in the center, is also known as the "hangover cure" water. Located on the corner of Putnam and Spring Street, this spring is considered one of most effective digestive waters. The elaborate pavilion, benches and landscaping add to its allure. Photo taken in 1904 by Detroit Publishing Company, courtesy of Library of Congress *Right*: High Rock Spring is located across Maple Avenue from The Olde Bryan Inn. At its base, High Rock Spring is distinguished by a cone of hardened mineral deposits. It is considered an excellent source of natural spring water. Address: High Rock Park, 112 High Rock Avenue. Photo taken between 1900 and 1906 by Detroit Publishing Company, courtesy of Library of Congress.

In 2023, Arthur Palmer and Margaret Palmer from Oneonta, New York, nominated Saratoga Springs for inclusion in the list of Nationally Important Karst Aquifer Springs (NIKAS) assembled by the Karst Commission (KC) of the International Association of Hydrogeologists (Palmer and Palmer, 2023). The following description of the hydrogeologic characteristics of the springs summarizes this nomination, courtesy of KC, and Arthur and Margaret Palmer.

The principal aquifer feeding the Springs is the Cambrian-Ordovician dolomite and limestone of the Beekmantown Group, which is overlain by a shale cap-rock. The original springs are located where the Saratoga normal fault cuts across the units. During the 20th century, wells drilled through the shale have encountered the carbon dioxide (CO_2)-rich water, releasing additional groundwater under pressure.



Figure 3.12.13 Stereophotograph of Congress Spring. Discovered in 1792 by a congressman from New Hampshire, Congress Spring became the centerpiece of Congress Park and the village that grew up around it. Bottled and sold around the world, Congress water was the most famous of the Saratoga mineral waters. Address: Congress Park, 268 Broadway. Photo published by George Stacy in 1865, courtesy of Library of Congress.

Besides high content of CO_2, the water has a high saline content and thousands of milligrams per liter concentrations of total dissolved solids. The springs lie along the north-south trace of the Saratoga normal Fault. Inorganic carbon and helium isotope ratios indicate a mantle or magmatic origin for the CO_2. The stable isotopic content of the spring water and strontium (Sr) isotopic composition (dissolved Sr) define mixing lines between modern local meteoric waters and a probable Canadian Shield-type brine under the Adirondack Mountains (Siegel, 2005). The springs are saturated with respect to calcite and spring mounds and precipitates have formed indicating solution of carbonate rocks at depth; therefore, the springs represent the surface expression of suspected hypogenic karst (Palmer et al., 2017).

Native Mohawk and Iroquois Tribes knew about the springs and believed in their medicinal properties. In the 19th century the area became popular as a spa. Bottled water was sold but the pumping depleted the wells. Laws were passed to limit use and in 1962 the springs were named a state park and declared a National Historic landmark. Today there are 17 springs in the park and a network of scenic paths that lead to the spring mounds and fountains. The water now is coming from wells, as the springs are plugged, over time and naturally, with carbonate precipitation (Palmer and Palmer, 2023). Additional references are Hollocher et al. (2002), and Young (1978).



Figure 3.12.14 "Island Spouter" – mound of travertine formed around a drill-hole which releases pressure and has highly variable flow. Photo courtesy of Arthur Palmer.



Figure 3.12.15 Travertine deposits at a paleo spring (old inactive spring) in Saratoga Springs. All original Saratoga Springs were naturally plugged over time with carbonate precipitation and water now is coming from wells.

"For generations, visitors have traveled to Saratoga County to enjoy our natural mineral springs, which have long been regarded for their restorative properties. In fact, for generations, local doctors have even prescribed these waters as part of restorative treatments—a legacy of wellness that continues today!

Saratoga Springs Mineral Water Benefits

Since their discovery, Saratoga's naturally carbonated springs have been linked to health and wellness. Each spring has a distinct mineral profile, which contributes to its flavor and therapeutic qualities.

Below is a quick overview of the potential benefits tied to these local springs and the minerals they contain:

***Calcium**: Contributes to bone health and can help regulate heart rhythm and muscle function.*

***Magnesium**: Supports muscle recovery, reduces cramping, and can promote relaxation.*

***Iron**: Supports red blood cell production and can help with fatigue caused by low iron levels.*

***Silica**: Thought to support skin, hair, and nail health by promoting collagen production.*

***Bicarbonates**: Help ease digestion problems by neutralizing stomach acids.*

***Sodium and potassium**: Both play a role in replenishing electrolytes, especially after exercise.*

The precise mix of these minerals varies from spring to spring, which is part of what makes Saratoga's waters so unique! Locals often have favorites, which they visit regularly for specific effects or simply because they enjoy the taste.

Wellness tourism has shaped Saratoga County for generations, with the springs continuing to play a central role in how visitors experience the area today. Come and discover the restorative power that flows just beneath the surface of Saratoga County."

https://www.discoversaratoga.org/things-to-do/attractions/mineral-springs/

References and Select Readings

Adolphson, D.G., Ruhl, J.F., and Wolf, R.J., 1981. Designation of principal water-supply aquifers in Minnesota: U.S. Geological Survey Water-Resources Investigations Report 81-51, iii, 19 p., https://doi.org/10.3133/wri8151.

Alexander, C.E. Jr., Green, J.A., Alexander, S.C., and Spong, R.C., 1995. Springsheds. County Atlas Series, Atlas C-8, Part B, Plate 9-Springsheds. Minnesota Department of Natural Resources, Division of Waters.

Aley, T., 1975. A predictive hydrologic model for evaluating the effects of land use and management on the quantity and quality of water from Ozark springs: Protem, Mo., Ozark Underground Laboratory, 236 p. with appendices.

Aley, T., 1976. Identification and preliminary evaluation of areas hazardous to the water quality of Alley, Round, and Pulltite Springs, Ozark National Scenic Riverways, Missouri: Protem, Mo., Ozark Underground Laboratory, 117 p. with appendix.

Aley, T., 1978. Hydrologic studies of springs, Ozark National Scenic Riverways: Protem, Mo., Ozark Underground Laboratory, 93 p. with appendix.

Aley, T., and Aley, C., 1982. Hydrologic studies of springs draining areas east of the Current River in Missouri: Protem, Mo., Ozark Underground Laboratory, 91 p. with appendices.

Aley, T., and Aley, C., 1987. Groundwater study, Ozark National Scenic Riverways: Protem, Mo., Ozark Underground Laboratory, National Park Service contract CX6000-4-0083, 222 p.

Aley, T., and Aley, C., 1998. Groundwater tracing and recharge area delineation study for two karst study areas in Monroe County, Illinois. Protem, Missouri, The Ozark Underground Laboratory, unpublished report to the Mississippi Karst Resource Planning Committee, Waterloo, Illinois, 66 p.

Alpine, A.E., ed., 2010. Hydrological, geological, and biological site characterization of breccia pipe uranium deposits in northern Arizona. U.S. Geological Survey Scientific Investigations Report 2010–5025, 353 p., 1 pl., scale 1:375,000.

Anaya, R., 2004. Conceptual model for the Edwards-Trinity (Plateau) aquifer system, Texas: in Mace, R.E., Angle, E.S., and Mullican, W.F., III, eds., Aquifers of the Edwards Plateau: Texas Water Development Board Report 360, p. 345–366.

Anaya, R., and Jones, I.C., 2004. Groundwater availability model for the Edwards-Trinity (Plateau) and Cenozoic Pecos Alluvium aquifer systems, Texas: Texas Water Development Board GAM report, 208 p. Anaya, R., and Jones, I.C., 2009, Groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifer systems, Texas: Texas Water Development Board GAM report, 103 p.

Anderson, C., 1993. Index and short description to the geologic terms used by the Georgia Speleological Survey. In: Blackburn, R., editor, 1993 Georgia Speleological Survey Bulletin.

Anderson, M.T., Driscoll, D.G., and Williamson, J.E., 1999. Interactions along Rapid Creek near Rapid City, South Dakota. U.S. Geological Survey Water-Resources Investigations Report 98-4214, Rapid City, South Dakota, 99 p.

Andreychouk, V., Dublyansky, Y., Yezhov, Y., and Lysenin. G., 2009. Karst in Earth's Crust: Distribution and the Main Types. University of Silesia and Ukrainian Institute of Speleology and Karstology, Sosnowiec— Simferopol, 72 p.

Anthony, D. and Granger, D., 2004. A Late Tertiary origin for multilevel caves along the western escarpment of the Cumberland Plateau, Tennessee and Kentucky, established by cosmogenic ^{26}Al and ^{10}Be. Journal of Cave and Karst Studies, v. 66, no. 2, p. 46–55.

Arthur, D.A., Upchurch, S., Skiles, W., Kincaid, T., Davis, H., and McGurk, B., 2004. Panel II. Delineation of springshed boundaries. Workshop to develop blue prints for the management and protection of Florida's springs, May 8–9, 2002, Ocala, Florida. Florida Geological Survey Special Publication No. 51

Ashley, G.H., and Kindle, E.M., 1903. The geology of the Lower Carboniferous area of southern Indiana : Indiana Dept. Geology and Nat. Resources, Ann. Rept. 27, pp. 49-122.

Atkinson, T.C., 1977. Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain), Jour. Hydrology, v. 35, pp. 93-110.

Back, W., Hanshaw, B.B., Plummer, L.N., Rahn, P.H., Rightmire, C.T., and Rubin, M., 1983. Process and rate of dedolomitization: Mass transfer and ^{14}C dating in a regional carbonate aquifer. Geological Society of America Bulletin, 94(12), pp. 1415–1429

Baker, V.R., 1976. Hydrogeology of a cavernous limestone terrain and the hydrochemical mechanisms of its formation, Mohawk River basin, New York: Empire State Geogram, v. 12, no. 2, pp. 2–65.

Baker, E.T., Jr., Slade, R.M., Jr., Dorsey, M.E., Ruiz, L.M., and Duffin, G.L., 1986, Geohydrology of the Edwards Aquifer in the Austin area, Texas: Texas Water Development Board Report 293, 217 p.

Barlow, P.M., 2003. Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast. U.S. Geological Survey Circular 1262, 113 p.

Barrett, J.K., and Pearl, R.H., 1975. Hydrogeological Data of Thermal Springs and Wells in Colorado. Information Series 6, Colorado Geological Survey, Department of Natural Resources, Denver, Colorado, 124 p.

Bargar, K.E., 1978. Geology and thermal history of Mammoth Hot Springs, Yellowstone National Park, Wyoming. U.S. Geological Survey Bulletin 1444, 55 p., 1 pl. https://pubs.er.usgs.gov/publication/b1444.

Barrios, K., and Chelette, A., 2004. Econfina Creek Spring Inventory: Washington and Bay Counties, FL. Northwest Florida Water Management District. Water Resources Special Report 04-02.

Barker, R.A., and Ardis, A.F., 1996, Hydrogeologic framework of the Edwards-Trinity aquifer system, west-central Texas: U.S. Geological Survey Professional Paper 1421–B, 61 p.

Bass, N.W., and Northrop, S.A., 1963. Geology of Glenwood Springs quadrangle and vicinity, northwestern Colorado: U.S. Geological Survey Bulletin 1142-J, 74 p

Bauman, J., 2023. Big Spring (Kitch-iti-kipi), Schoolcraft County, T42N/R17W/S25. Michigan Department of Natural Resources, Status of Fishery Resource Report No. 2023-352, 6 p. + Tables

Beck, D.A., Ryan, R., Veley, R.J., Harper, D.P., and Tanko, D.J., 2006. Water-surface elevations, discharge, and water-quality data for selected sites in the Warm Springs area near Moapa, Nevada. U.S. Geological Survey Open-File Report 1311, 230 p.

Beckman, H., and Hinchey, 1944. The large springs of Missouri. Missouri Geological Survey and Water Resources, v. XXIX, 2nd series, 164 p.

Becher, A.E., and Root, S.I., 1981. Groundwater and geology of the Cumberland Valley, Cumberland County, Pennsylvania. Pennsylvania Geological Survey, 4th ser., Water Resource Report 50, 95 p. + Plates

Bennison, A. P., 1989. Geologic Highway Map of the Mid Atlantic Region. Tulsa, OK, American Association of Petroleum Geologists.

Berg, T.M., Edmunds, W.E., Geyer, A.R., Glover, A.D., Hoskins, D.M., MacLachlan, D.B., Root, S.I., Sevon, W.D., and Socolow, A.A., compilers, 1980. Geologic map of Pennsylvania (2nd ed.): Pennsylvania Geological Survey, 4th ser., Map 1, 3 sheets, scale 1:250,000

Bernstein, L.M., 1992. A revised lithostratigraphy of the Lower-Middle Ordovician Beekmantown Group, St. Lawrence Lowlands, Quebec and Ontario: Canadian Journal of Earth Sciences, v. 29, no. 12, pp. 2677–2694,

Beus, S.S., 1989. Devonian and Mississippian geology of Arizona. In Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona. Arizona Geological Society Digest, v. 17, p. 287–312.

Bickley, G.W.L., 1852. History of the Settlement and Indian Wars of Tazewell County, Virginia. Morgan & Co., Cincinnati, 267 p. http://www.kinyon.com/virginia/tazewell1852/2chapter06.htm

Biddanda, B.A., Coleman, D.F., Johengen, T.H., Ruberg, S.A., Meadows, G.A., Van Sumeren, H.W., Rediske, R.R., and Kendall, S.T., 2006. Exploration of a submerged sinkhole ecosystem in Lake Huron. Ecosystems 9:828-842.

Biggs, E.V., and Hoy, N.C., 2017. Water-powered mills of the Cowpasture River valley. 5 p. Berriedale Farms Website Essay No. 7 -- Water-powered Mills of the Cowpasture Valley.pdf

Billingsley, G.H., 2000. Geologic map of the Grand Canyon 30́x 60́ quadrangle, Coconino and Mohave Counties, northwestern Arizona: U.S. Geological Survey Geologic Investigations Series I–2688, version 1.0, scale 1:100,000, 15 p.

Billingsley, G.H., Goodwin, G., Nagorsen, S.E., Erdman, M.E., and Sherba, J.T., 2019. Geologic and related photographs of the Grand Canyon region (1967–2010). U.S. Geological Survey data release, accessed at https://www.sciencebase.gov/catalog/folder/5a9751d5e4b06990606c5197

Bills, D.J., Truini, M., Flynn, M.E., Pierce, H.E., Catchings, R.D., and Rymer, M.J., 2000, Hydrogeology of the regional aquifer near Flagstaff, Arizona: U.S. Geological Survey Water-Resources Investigations Report 00–4122, 143 p., 4 plates.

Bills, D. J., and M. E. Flynn. 2002. Hydrogeologic Data for the Coconino Plateau and adjacent areas, Coconino and Yavapai Counties, Arizona. Open-File Report 02—265. USGS, Reston, Virginia.

Bills, D.J., Flynn, M.E., and Monroe, S.A., 2007, Hydrogeology of the Coconino Plateau and adjacent areas, Coconino and Yavapai Counties, Arizona (ver. 1.1, March 2016): U.S. Geological Survey Scientific Investigations Report 2005–5222, 101 p., 4 plates, http://dx.doi.org/10.3133/sir20055222

Bills, D.J., Tillman, F.D., Anning, D.W., Antweiler, R.C., and Kraemer, T.F., 2010. Chapter C, Historical and 2009 Water Chemistry of Wells, Perennial and Intermittent Streams, and Springs in Northern Arizona. pp. 141-200. In: Alpine, A.E., ed. 2010. Hydrological, geological, and biological site characterization of breccia pipe uranium deposits in northern Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5025, 354 p., 1 pl., scale 1:375,000.

BIO-WEST, 2026. Comal River System: Critical Period and Species-specific Sampling Events. Memorandum to Chad Furl and Kristy Kollaus, Edwards Aquifer Authority, from Christa Kunkel, BIO-WEST, 13 p.

Blair, R.J., Marbert, B.S., and Goodman, P.T., 2012. Integrated Surface Water and Groundwater Assessment of Large Springs in the Green River Basin (BMU4, Round 2). Kentucky Division of Water, Frankfort, KY, 91 p.

Bowers, W.E., 1972. The Canaan Peak, Pine Hollow, and Wasatch Formations in the Table Cliff Region, Garfield County, Utah. U.S. Geological Survey Bulletin 1331-B, B1-B39.

Bowles, C.G., and Braddock, W.A., 1963. Solution breccias of the Minnelusa Formation in the Black Hills, South Dakota and Wyoming, in Short papers in geology and hydrology, Articles 60-121, U.S. Geological Survey Professional Paper 47S-C, p. C91-C95.

Bradfield, A., 1992. Hydrology of the Cave Spring Area Near Chattanooga, Hamilton County, Tennessee. U.S. Geological Survey Water-Investigations Report 92-4018, 28 p.

Brahana, J.V., and Bradley, M.W., 1985a. Preliminary delineation and description of the regional aquifers of Tennessee—The Central Basin aquifer system. U.S. Geological Survey Water-Resources Investigations Report 82–4002, 35 p., https://pubs.usgs.gov/wri/wrir82-4002/

Brahana, J.V., and Bradley, M.W., 1985b. Delineation and description of the regional aquifers of Tennessee—The Knox aquifer in central and west Tennessee. U.S. Geological Survey Water-Resources Investigations Report 83–4012, 32 p., https://pubs.usgs.gov/wri/wri834012/

Brahana, J.V., and Bradley, M.W., 1986. Preliminary delineation and description of the regional aquifers of Tennessee—Highland Rim aquifer system: U.S. Geological Survey Water-Resources Investigations Report 82–4054, 38 p., https://pubs.usgs.gov/wri/wri824054/

Brahana, J.V., Mulderink, D., Macy, Jo Ann, and Bradley, M.W, 1986. Preliminary delineation and description of the regional aquifers of Tennessee—The East Tennessee aquifer system: U.S. Geological Survey Water-Resources Investigations Report 82–4091, 30 p., https://pubs.usgs.gov/wri/wri824091/

Brahana, J.V., Tennyson, R., Terry, J., Hays, P.D., and Pollock, E.D., 2009, Reactivated basement faulting as a hydrogeologic control of hypogene speleogenesis in the southern Ozarks of Arkansas, USA, *in* Stafford, K., ed., Advances in hypogene studies: National Cave and Karst Research Institute Symposium 1—National Cave and Karst Research Institute, pp. 99–110

Brannon, J.C., Podosek, F.A., and Cole, S.C., 1996, Radiometric dating of Mississippi Valley-type ore deposits—Carbonate hosted lead-zinc deposits: Society of Economic Geologists, Special Publication 4, p. 536–545, accessed September 25, 2015.

Brezinski, D.K., 2004. Stratigraphy of the Frederick Valley and its relationship to karst development. Maryland Geological Survey Report of Investigations, no. 75, 101 p.

Brezinski, D.K., 2009. Geologic Map of Keedysville and parts of Shepherdstown, Harpers Ferry and Charles Town Quadrangles, Washington and Frederick Counties, Maryland. Maryland Geological Survey, Version: K_SHCGEO2009.1

Brezinski, D.K., 2018. Geology and karst development of the Hagerstown Valley (Great Valley) of Maryland. Maryland Geological Survey, DNR Publication No. 12-053118-73, 102 p. + Geologic and karst map of the Hagerstown Valley.

Brezinski, D.K., and Bell, S.K. 2009. Geologic Map of the Funkstown Quadrangle, Washington County, Maryland. Maryland Geological Survey Digital Geologic Map, scale 1:24,000.

Brezinski, D.K., Fauth, J.L. 2009. Geologic Map of the Myersville and Smithsburg Quadrangles, Frederick and Washington Counties, Maryland. Maryland Geological Survey Digital Geologic Map, scale 1:24,000.

Brezinski, D.K., and Conkwright, R., 2013. Geologic Map of Garrett, Allegany, and western Washington Counties, Maryland. Maryland Geological Survey. https://www.mgs.md.gov/

Brezinski, D.K., and Glaser, J.D., 2014. Geologic and Karst Features Map of the Maryland Portions of the Clear Spring and Hedgesville Quadrangles, Washington County, Maryland. Maryland Department of Natural Resources, Maryland Geological Survey.

Brezinski, D.K., Gemperline, J.M., Adams, R.K., and Bolton, D.W., 2018. Factors Affecting Karst Spring Turbidity in Eastern Washington County, Maryland (Poster Presentation). Maryland Geological Survey, Baltimore, Maryland. https://www.mgs.md.gov/news/karst_2018.html

Brezinski, D.K., Vincett, W.K. III, and Adams, R.K., 2025. Bedrock and Surficial Geologic Map of Garrett and Allegany Counties, Maryland. Maryland Geological Survey, MD DNR Publication No. DNR 12-120125-1

Bright, J., 2009. Isotope and major-ion chemistry of groundwater in Bear Lake Valley, Utah and Idaho, with emphasis on the Bear River Range, in Rosenbaum, J.G., and Kaufman, D.S., eds., Paleoenvironments of Bear Lake, Utah and Idaho, and its catchment: Geological Society of America Special Paper 450, p. 105–132, doi: 10.1130/2009.2450(04).

Bright, J., Kaufman, D.S., Forester, R.M., and Dean, W.E., 2006. A continuous 250,000 yr record of oxygen and carbon isotopes in ostracode and bulk sediment carbonate from Bear Lake, Utah-Idaho. Quaternary Science Reviews, v. 25, pp. 2258–2270, doi: 10.1016/j.quascirev.2005.12.011.

Brooks, H.K., 1967. Rate of Solution of Limestone in the Karst Terrane of Florida. Florida Water Resources Research Center, Publication No. 6, University of Florida, Gainesville, FL., 16 p.

Broun, A.S., D.A. Wierman, L. Llado, A.H. Backus, 2008, Cypress Creek/Jacob's Well Hydrogeologic Report: Hays Trinity Groundwater Conservation District report, 43p. + tables + appendices

Brown, T.A., Dunning, C., and Sharpe, J.B., 2000. Altitude, depth, and thickness of the Galena-Platteville Bedrock Unit in the subcrop area of Illinois and Wisconsin. U.S. Geological Survey Water-Resources Investigations Report 97-4054, 4 Plates: 34.00 x 47.77 inches smaller, https://doi.org/10.3133/wri974054C.

Brune, G., 1975. Major and Historical Springs of Texas. Texas Water Development Board Report 189, 95 p. Austin.

Brune, G., 1981. Springs of Texas: Branch-Smith, Inc., Fort Worth, v. 1, 565 p.

Bureau of Land Management, 2011. Northern Arizona proposed withdrawal—Final environmental impact statement, Volumes 1 and 2: U.S. Department of the Interior, Bureau of Land Management, BLM/AZ/PL-11/002, https://permanent.fdlp.gov/gpo26632/Complete.pdf.

Bureau of Land Management, 2012. Public Land Order No. 37787; Withdrawal of public and national forest system lands in the Grand Canyon watershed; Arizona: Federal Register, v. 77, no. 11, p. 2563–2566 https://www.federalregister.gov/documents/2012/01/18/2012-849/public-land-order-no-7787-withdrawal-of-public-and-national-forest-system-lands-in-the-grand-canyon

Burnham, T., Luffman, I., Whitelaw, M., and Gao, Y., 2016. Assessing structural control on groundwater flow in the Morrell Cave springshed, Sullivan County, Tennessee. In: Feinberg, J.M., Gao, Y., and Alexander, E.C., eds., Caves and Karst Across Time, GSA Special Papers, Geological Society of America, Volume 516, Doi: https://doi.org/10.1130/2015.2516(13)

Butts, C., and Moore, E.S., 1936. Geology and Mineral Resources of the Bellefonte Quadrangle, Pennsylvania. U.S. Geological Survey Bulletin 855, 111 p. + 2 plates

Callahan, J.T., 1964. The yield of sedimentary aquifers of the Coastal Plain, Southeast River Basins. U.S. Geological Survey Water-Supply Paper 1669-W, 56 p.

Castañeda CE. 1936. Our Catholic heritage in Texas, 1519-1936: Austin (TX): Von-Boeckmann-Jones.

Couch, H.E. 1978. Study of the lower Cretaceous and associated aquifers in the Balmorhea district of Trans-Pecos, Texas. Department of Water Resources Report, 61 p.

Cady, R.C., 1938. Ground-water resources of northern Virginia: Virginia Geological Survey, Bulletin 50, 200 p.

Calvin, A.E. Jr., 1996. The Underground Rivers of Mystery Cave. Retrieved from the University Digital Conservancy, https://hdl.handle.net/11299/185397.

Canace, R., Monteverde, D., and Serfes, M., 1996. Karst Hydrogeology of the Shuster Pond Area, Hardwick Township, Warren County, New Jersey. New Jersey Geological Survey, Karst Geology of New Jersey and Vicinity, Thirteenth Annual Meeting of the Geological Association of New Jersey, October 11-12, 1996.

Carline, R., 2017. Aquatic Resources of Spring Creek: A Historical Perspective. The Spring Creek Watershed Atlas. Aquatic Resources of Spring Creek: A Historical Perspective

Fisherman's Paradise – An Historic Reach of Spring Creek, Robert Carline, Jun 9, 2021, 4 min read, Updated: Aug 20, 2021, *Robert F. Carline, Rebecca L. Dunlap, Jason E. Detar, and Bruce A. Hollender*

Carline, R.F., Dunlap, R.L., Detar, J.E., and B. A. Hollender. 2021. Fisherman's Paradise – An Historic Reach of Spring Creek; updated Aug 20, 2021. The Spring Creek Watershed Atlas; available at https://www.springcreekwatershedatlas.org/post/fisherman-s-paradise-an-historic-reach-of-spring-creek

Carter, J.M., Driscoll, D.G., and Williamson, J.E., 2002. The Black Hills Hydrology Study. U.S. Geological Survey Fact Sheet FS-046–02.

Campbell, B.G., and Coes, A.L., eds., 2010. Groundwater availability in the Atlantic Coastal Plain of North and South Carolina. U.S. Geological Survey Professional Paper 1773, 241 p., 7 pls.

Campbell, J.W., Delong, B.E., Carey, V., and Ray, C., 2012. Survey of Terrestrial Invertebrate Species from Byers Cave; Dade County, Georgia. Georgia Journal of Science, Vol. 70, Numbers 3-4, pp. 172-178

Ceryak, R., 1977. Hydrogeology of a river basin in karst terrain, Alapaha River, Hamilton County, Florida. Suwannee River Water Management District Information Circular 5, Suwannee River Water Management District.

Chandler, R.V. and Moore, J.D., 1987. Springs of Alabama: Geological Survey of Alabama Circular 134, Tuscaloosa, Alabama, 95 p.

Chapman, J.S., Perkins, J.W., Johnson, R.J., Nugent, B.L., Britton, J.Q., and Daft, G.W. Jr., 2016. Bedrock Geologic Map of the Bowden 7.5' Quadrangle, West Virginia. West Virginia Geological and Economic Survey, Publication OF-1502.

Chaudhary, A., Haack, S.K., Duris, J.W., and Marsh, T.L., 2009. Bacterial and Archaeal Phylogenetic Diversity of a Cold Sulfur-Rich Spring on the Shoreline of Lake Erie, Michigan. Appl Environ Microbiol; 2009 Jun 19;75(15):5025–5036. doi: 10.1128/AEM.00112-09

City of Ada, 2017. WaterSMART: Development of a Feasibility Study under the Title XVI Water Reclamation and Reuse Program for Fiscal Year 2017. Ada, Oklahoma, 38 p.

Clark, W. E., Chisholm, J. L., and Frye, P. M., 1976. Water resources of the upper New River basin, West Virginia: West Virginia Geol. and Econ. Survey and West Virginia Dept. Nat. Resources, Div. Water Resources, River Basin Bull. 4.

Cloos, Ernst, 1951. The physical features of Washington County, Maryland. Maryland Geological Survey County Report, no. 14, pp. 41-43.

Cohen, S., 1981. Historic Springs of The Virginias; A Pictorial History. Quarrier Press, Charleston, West Virginia, 210 p.

Collins, W.D., Foster, M.D., Reeves, F., and Meacham, R.P., 1930. Springs of Virginia; A report on the discharge, temperature and chemical character of Springs in the southern part of the Great Valley. Commonwealth of Virginia, State Commission on Conservation and Development, Division of Water Resources and Power, Bulletin No. 1, Richmond, 55 p. + map

Cooley, M.E., 1963. Hydrology of the Plateau uplands province, in Annual report on the ground water in Arizona, spring 1962 to spring 1963, by Natalie D. White, R.S. Stulik, E.K. Morse, and others: Arizona State Land Dept. Water-Resources Report 15, p. 27–37.

Cooley, M.E, 1976. Spring flow from pre-Pennsylvanian rocks in the southwestern part of the Navajo Indian Reservation, Arizona: U.S. Geological Survey Professional Paper 521-F, 14 p.

Cooley, M.E., Harshbarger, J.W., Akers, J.P., and Hardt, W.F., 1969. Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, with a section on Vegetation by O.N. Hicks. U.S. Geological Survey Professional Paper 521–A, 61 p.

Cooper, M.P., and Mylroie, J.E., 2015. Glaciation and speleogenesis—Interpretations from the northeastern United States. New York, Springer International Publishing, 142 p.

Cooper, M.P., and Mylroie, J.E., 2015a. Caves and Karst of New England and Eastern New York. In: Glaciation and speleogenesis—Interpretations from the northeastern United States. New York, Springer International Publishing, pp. 121-130. DOI:10.1007/978-3-319-16534-9_8

Copeland, R.E., 2003. Florida Spring Classification System and Spring Glossary. Special Publication No. 52 [with revisions by Florida Springs Nomenclature Committee (FSNC); December, 2005]. Florida Geological Survey, Tallahassee, 18 p.

Costain, J. K., Keller, G. V., and Crewdson, R. A., 1976. Geological and geophysical study of the origin of the warm springs in Bath County, Virginia. U.S. Department of Energy, TID-28271, 184 p.

Crawford, N.C., 1984. Karst landform development along the Cumberland Plateau escarpment of Tennessee. In LeFleur, R.G., ed., Groundwater as a geomorphic agent: Boston, Allen and Unwin, Inc., pp. 294-338.

Crawford, N.C., 1987. The karst hydrogeology of the Cumberland Plateau Escarpment of Tennessee: Subterranean stream invasion, conduit cavern development, and slope retreat in the Lost Creek Cove area, White County, Tennessee: Tennessee Department of Environment and Conservation, Division of Geology Report of Investigations no. 44, pt. 1, 43 p.

Cressler, C.W., Franklin, M.A., and Hester, W.G., 1976. Availability of Water Supplies in Northwest Georgia. State of Georgia Department of Natural Resources, The Geologic and Water Resources Division, Atlanta, Georgia, 140 p.

Crossey, L.J., Karlstrom, K.E., Curry, B., McGibbon, C., Reed, Wilgus, J., C.J. Whyte, C.J., and T. Darrah, T., 2024. Hydrotectonics of Grand Canyon Groundwater. Annual Review of Earth and Planetary Sciences, Vol. 52. https://doi.org/10.1146/annurev-earth-080723-083513

Crossey, L.J., Fischer, T.P., Patchett, P.J., Karlstrom, K.E., Hilton, D.R., Newell, D.L., Huntoon, P., Reynolds, A.C., and de Leeuw, G.A.M., 2006. Dissected hydrologic system at the Grand Canyon: interaction between deeply derived fluids and plateau aquifer waters in modern springs and travertine. Geology 34(1):25–28.

Currens, J. C., 1999. A sampling plan for conduit flow karst spring. Minimizing sampling cost and maximizing statistical utility. Eng Geol, 52(1-2): 121–128.

Currens, J.C., 2002. Kentucky is Karst Country. What You Should Know About Sinkholes and Springs. Information Circular 4, Serries XII, Kentucky Geological Survey, 29 p.

Currens, J.C., 1999. Mass flux of agricultural nonpoint-source pollutants in a conduit-flow-dominated karst aquifer, Logan County, Kentucky. Report of Investigations 1, Series XII, Kentucky Geological Survey, University of Kentucky, Lexington, Kentucky, 151 p. + 2 plates.

Curry, B.H., Crossey, L.J., and Karlstrom, K.E., 2023. The Grand Canyon National Park (USA) water corridor: water supply, water quality, and recharge along the Bright Angel Fault. Hydrogeology Journal, 31(8), 1773–1790

Cvijić, J., 1895. Karst; Geografska Monografija (Karst; A Geographic Monograph; in Serbian). Beograd, Stamparija Kraljevine Srbije, 176 p.

Cvijić, J., 1918. Hydrographie souterraine et évolution morphologique du karst. Recueil des Travaux de l'Institut de Géographie alpine, Grenoble, t. VI, fasc. 4, pp. 1-56

Cvijić, J., 1926. Geomorfologija (Morphologie Terrestre). Knjiga druga (Tome Second). Beograd, 506 p.

Dalton, R., 1976. Caves of New Jersey. New Jersey Department of Environmental Protection, New Jersey Geological Survey, Bulletin 70, 51 p.

Dalton, R., 2014. Karst Features of New Jersey. New Jersey Geological and Water Survey Information Circular, 4 p.

Darr, M.J., Rattray, G.W., McCoy, K.J., and Durall, R.A., 2014. Hydrogeology, water resources, and water budget of the upper Rio Hondo Basin, Lincoln County, New Mexico, 2010. U.S. Geological Survey Scientific Investigations Report 2014–5153, 72 p., http://dx.doi.org/10.3133/sir20145153.

Darton, N.H, 1901. Preliminary description of the geology and water resources of the southern half of the Black Hills and adjoining regions in South Dakota and Wyoming: U.S. Geological Survey 21st Annual Report, pt. 4b, pp. 489-599.

Dasher, G., 2012. The caves and karst of West Virginia. West Virginia Speological Survey Bulletin No. 19, 263 p.

Davies, W.E., 1950. The Caves of Maryland. Maryland Department of Geology, Mines, and Water Resources, Bulletin 7, 76 p.

Davies, W.E., 1958. Caverns of West Virginia. State of West Virginia, Geological and Economic Survey, v. XIX(A), 330p.

Davies, W.E., 1965. Caverns of West Virginia (Supplement). State of West Virginia, Geological and Economic Survey, Supplement to v. XIX(A), 72 p.

Davies, W.E., Simpson, J.H., Ohlmacher, G.C., Kirk, W.S., and Newton, E.G., 1984. Engineering aspects of karst. U.S. Geological Survey, National Atlas, scale 1:7,500,000.

Davis, B.L., 1959. Petrology and petrography of the igneous rocks of the Stansbury Mountains, Tooele County, Utah. Brigham Young University Research Studies Geology Series, v. 6, no. 2, 56 p.

Davis, J.H., and B.G. Katz. 2007. Hydrogeologic investigation, water chemistry analysis, and model delineation of contributing areas for City of Tallahassee public-supply wells, Tallahassee, Florida. U.S. Geological Survey Scientific Investigations Report 2007-5070, 67 p.

Davis, P., Wilcox, R., and Gross, G.W., 1979. Spring characteristics of the western Roswell Artesian Basin. Partial Technical Completion Report, New Mexico Water Resources Institute, Las Cruces, NM, 93 p.

Davis, N.W., and Hess, J.W., 1982. Hydrogeology of the Drainage System, Burnsville Cove, Virginia. In: White, W.B. (Guest Editor), Burnsville Cove Symposium. National Speleological Society Bulletin, 44:3, pp. 78-83

Dean, S.L., Kulander, B.R., McColloch, G.H., McColloch, J.S., Sites, R.S., and Kulander, C.S., 2001. Bedrock geology of the Petersburg East quadrangle, Hardy County, West Virginia (revised 2002; draft, subject to review). Geologic Quadrangle Maps of West Virginia OF-0203. West Virginia Geological and Economic Survey.

De Buchananne, G.D., and Richardson, R.M., 1956. Ground-water resources of East Tennessee. Tennessee Division of Geology Bulletin 58, pt. 1, 393 p.

Dennison, J. M. and Johnson, R. W., Jr., 1971. Tertiary intrusions and associated phenomena near the Thirty Eighth parallel fracture zone in Virginia and West Virginia: Geol. Soc. Am. Bull., v. 82, pp. 501-508.

Dettinger, M.D., 1989. Distribution of carbonate-rock aquifers in southern Nevada and the potential for their development, summary of findings, 1985-88. Program for the Study and Testing of Carbonate-Rock Aquifers in Eastern and Southern Nevada, Summary Report No. 1, Carson City, Nevada, 37 p.

Dettinger, M.D., Harrill, J.R., Schmidt, D.L., and Hess, J.W., 1995. Distribution of Carbonate-Rock Aquifers and the Potential for Their Development, Southern Nevada and Adjacent Parts of California, Arizona, and Utah. U.S. Geological Survey Water-Resources Investigations Report 91-4146, 99 p.

Diaz, V.D., McNeill, D.F., Goodin, R.C., and Klaus, J.S., 2019. Porosity Distribution and Evolution in Pleistocene Reef Limestone: Implications for Scale-Dependent Fluid Flow. Journal of Sedimentary Research, Vol. 18(2), pp. 252-267.

Doctor, D.H., Orndorff, W., Maynard, J., Heller, M.J., and Casile, G.C., 2014. Karst geomorphology and hydrology of the Shenandoah Valley near Harrisonburg, Virginia. Geological Society of America Filed Guides 2014; 35; pp.161-213. doi: 10.1130/2014.0035(06)

Doctor, D.H., and Alexander, E.C., 2021. Karst geology of the Upper Midwest, USA. Chapter in *Caves and Karst of the Upper Midwest, USA*, 21 p., https://doi.org/10.1007/978-3-030-54633-5_1.

Dover, J.H., 1995. Geologic map of the Logan 30′ × 60′ quadrangle, Cache and Rich counties, Utah, and Lincoln and Uinta counties, Wyoming: Denver, Colorado, U.S. Geological Survey Miscellaneous Investigations Series Map I-2210, scale, 1:100,000.

Dover, J.H., 1987. Geologic map of the Mount Naomi Roadless Area, Cache County, Utah, and Franklin County, Idaho. U.S. Geological Survey Miscellaneous Field Studies Map MF-1566-B.

Downey, J.S., 1984. Geohydrology of the Madison and Associated Aquifers in Parts of Montana, North Dakota, South Dakota, and Wyoming. U.S. Geological Survey Professional Paper 1273–G, 47 p.

Driscoll, D.G., Carter, J.M., Williamson, J.E., and Putnam, L.D., 2002. Hydrology of the Black Hills area, South Dakota. U.S. Geological Survey Water- Resources Investigations Report 02-4094, 150 p.

Dudley, W.W., and Larson, J.D., 1976. Effect of irrigation pumping on desert pupfish habitat in Ash Meadows, Nye County, Nevada. U.S. Geological Survey Professional Paper 927, 52 p.

Duigon, M.T., 2001. Karst hydrogeology of the Hagerstown Valley, Maryland. Maryland Geological Survey, Report of Investigations No. 73, 128 p.

Duigon, M.T., 2007. Preliminary assessment of the contributing area of the spring supplying the A.M. Powell State Fish Hatchery, Washington County, Maryland: Maryland Geological Survey, 39 p.

Duigon MT. 2009. Phase 2 study of the area contributing groundwater to the spring supplying the A.M. Powell State Fish Hatchery, Washington County, Maryland. Maryland Geological Survey Open-File Report No. 2008-02-18, 32 p.

Dunning, C.P., Feinstein, D.T., Buchwald, C.A., Hunt, R.J., and Haserodt, M.J., 2017. Estimation of the groundwater resources of the bedrock aquifers at the Kettle Moraine Springs State Fish Hatchery, Sheboygan County, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2017–5074, 104 p., https://doi.org/10.3133/sir20175074.

Eakin, T.E., and Moore, D.O., 1964. Uniformity of Discharge of Muddy River Springs, Southeastern Nevada, and Relation to Interbasin Movement of Ground Water. U.S. Geological Survey Professional paper 501-D, pp. D171-D176

Eakin, T.E., 1964. Ground-water appraisal of Coyote Spring and Kane Spring Valleys and Muddy River Springs area, Lincoln and Clark Counties, Nevada. Nevada Department of Conservation and Natural Resources, Ground-Water Resources Reconnaissance Series, Report 25, 40 p.

Eakin, T.E., 1966. A regional interbasin groundwater system in the White River area, southeastern Nevada: Water Resources Research, v. 2, p 251–271.

Ebersole, S.E., Guthrie, G.M., and VanDervoort, D.S., 2019. An update to the physiographic districts of Alabama. Geological Survey of Alabama Open-File Report 1901, 20 p., 1 plate.

Eckhardt, G., 2010. Case Study: Protection of Edwards Aquifer Springs, the United States. In: Kresic, N., and Stevanovic, Z., eds, Groundwater Hydrology of Springs, Engineering, Theory, Management, and Sustainability. Elsevier Butterworth-Heinemann, Amsterdam, New York, pp. 526-542.

Edwards Aquifer Authority (EAA), 2021. 2021 Groundwater Discharge and Usage. Available at https://www.edwardsaquifer.org/hydrologic_data_post/2021-discharge/

Edwards Aquifer Authority (EAA), 2024. Habitats Conservation Plan, Edwards Aquifer. Available at https://www.edwardsaquifer.org/habitat-conservation-plan/

Edwards, R.J., Marsh, E., and Hubs, C., 1980. The Status of the San Marcos Gambusia, Gambusia georgei. Department of Zoology, The University of Texas at Austin, Austin, Texas, 34 p.

Ellins, K.K.; Kincaid, T.R.; Hisert, R.A.; Johnson, N.A.; Davison, C.A.; and Wanninkohf, R.H., 1991. Using 222Rn and SF6 to Determine Groundwater Gains and Stream Flow Losses in the Santa Fe River: Hydrogeology of the Western Santa Fe River Basin, Field Trip Guidebook No. 32., Southeastern Geological Society.

Ells, G.D., 1963. Information on Michigan Silurian Oil and Gas Pools. Michigan Department of Conservation, Geological Survey Division 14 p.

Enomoto, C.B., Coleman, J.L., Jr., Haynes, J.T., Whitmeyer, S.J., McDowell, R.R., Lewis, J.E., Spear, T.P., and Swezey, C.S., 2012. Geology of the Devonian Marcellus Shale—Valley and Ridge province, Virginia and West Virginia—A field trip guidebook for the American Association of Petroleum Geologists Eastern Section Meeting, September 28–29, 2011. U.S. Geological Survey Open-File Report 2012–1194, 55 p., available only at http://pubs.usgs.gov/of/2012/1194/.

Epstein, J.B., and Putnam, L.D., 2005. Introduction to three Field Trip Guides: Karst Features in the Black Hills, Wyoming and South Dakota- Prepared for the Karst Interest Group Workshop, September 2005. In: Kuniansky, E.L., ed., 2005, U.S. Geological Survey Karst Interest Group Proceedings, Rapid City, South Dakota, September 12–15, 2005. U.S. Geological Survey Scientific Investigations Report 2005-5160, pp. 193-231

Espinasa, L., Smith, D.M., and Lindquist, J.M., 2021. The Pennsylvania grotto sculpin: population genetics. Subterranean Biology 38: 47–63 (2021). doi: 10.3897/subtbiol.38.60865

Ewers, R. O., 1985. Patterns of cavern development along the Cumberland Escarpment in southeastern Kentucky. In: Dougherty, P.H. (ed.), Caves and Karst of Kentucky, Kentucky Geological Survey Special Publication 12, Series XI, Lexington, KY, pp. 97–118.

Fairchild, R.W., Hanson, R.L., and Davis, R.E., 1982. Hydrology of Arbuckle Mountain area, south-central Oklahoma. U.S. Geological Survey Open-File Report 82-775, Oklahoma City, OK, 156 p.

Farmer, N., 2021. Geologic Controls for Spring's from the East Snake Plain Aquifer 'Revisiting Russell, Stearns, Powers and Malde'. Idaho Department of Water Resources, September 21, 2021

Fay, R. O., 1989. Geology of the Arbuckle Mountains along Interstate 35, Carter and Murray Counties, Oklahoma. Oklahoma Geological Survey Guidebook 26, 50 p.

Feltis, R.D., and Shields, R.R., 1982. Streamflow losses to Madison Group rocks in the Little Belt and Big Snowy Mountains, Montana: U.S. Geological Survey Water-Resources Investigations Report 82-49.

Ferguson, G.E., Lingham, C.W., Love, S.K., and Vernon, R.O., 1947. Springs of Florida. Geological Bulletin No. 31, Florida Geological Survey, Tallahassee, 196 p.

Fisher, C.A., 1909. Geology and Water Resources of the Great Falls Region, Montana. U.S. Geological Survey Water Supply Paper 221, 89 p.

Fisher, C.A., 1908. Giant Springs at Great Falls, Montana Geological Society of America Bulletin 19 (1): 339–346

Feltis, R.D., and Shields, R.R., 1982. Streamflow losses to Madison Group rocks in the Little Belt and Big Snowy Mountains, Montana: U.S. Geological Survey Water-Resources Investigations Report 82-49.

Flanigan, T., 2023. America's largest underground springs gets even bigger with the discovery of another cave connection. WFSU, January 15, 2023. https://www.wusf.org/environment/2023-01-15/americas-largest-underground-springs-gets-even-bigger-discovery-another-cave-connection

Fleeger, G. M., 1999. The geology of Pennsylvania's ground- water (3rd ed.): Pennsylvania Geological Survey, 4th ser., Educational Series 3, 34 p.

Flippo, H.N., Jr., 1974. Springs of Pennsylvania. Pennsylvania Department of Environmental Resources, Office of Resources Management, Water Resources Bulletin 10, 46 p.

Florea, L.J., and Vacher, H.L., 2009. The Southeastern Coastal Plain: An Overview. Caves and Karst in America, 2009, pp. 181-184. Available at: http://digitalcommons.wku.edu/geog_fac_pub/22

Florea, L.J., Hasenmueller, N.R., Branam, T.D., Frushour, S.S., and Powell, R.L., 2018. Karst geology and hydrogeology of the Mitchell Plateau of south-central Indiana. In: Florea, L.J. ed., Ancient Oceans, Orogenic Uplifts, and Glacial Ice: Geologic Crossroads in America's Heartland. Geological Society of America Vol. 51, DOI https://doi.org/10.1130/fld0

Florida Springs Institute, 2016. King's Bay/Crystal River Springs Restoration Plan Executive Summary. Howard T. Odum Florida Springs Institute, High Springs, FL, 24 p.

Florida Springs Institute, 2020. Santa Fe River and Springs Environmental Analysis. Phase 3 – Final Report: Environmental Data. Howard T. Odum Florida Springs Institute, High Springs, FL, 121 p.

Florida Springs Task Force (Hartnett, F.M., editor), 2000. Florida's springs – Strategies for protection and restoration. Florida Department of Environmental Protection, 63 p.

Follman, J., and Buchanan, R., 2023. Springs Fever: A Field & Recreation Guide to 500 Florida Springs, 3rd Edition. http://thespringsfever.com/index.html

FLDEP (Florida Department of Environmental Protection), 2019. Ruth B. Kirby Gilchrist Blue Springs State Park. Advisory Group Draft Unit Management Plan. State of Florida Department of Environmental Protection, Division of Recreation and Parks, October 2019.

Florida Springs Institute, 2016. King's Bay/Crystal River Springs Restoration Plan Executive Summary. Howard T. Odum Florida Springs Institute, High Springs, FL, 24 p.

Florida Springs Institute, 2020a. Santa Fe River and Springs Environmental Analysis. Phase 3 – Final Report: Environmental Data. Howard T. Odum Florida Springs Institute, High Springs, FL, 121 p.

Florida Springs Institute, 2020b. Blueprint for Restoring Springs on the Santa Fe River. Howard T. Odum Florida Springs Institute, High Springs, FL.

Florida Springs Institute, 2023. Gilchrist Blue Spring Collapse Report. Howard T. Odum Florida Springs Institute, High Springs, FL, 11 p.

Ford, D.A., Williams, P., 2007. Karst Hydrogeology and Geomorphology. John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, England, 562 p.

Franz, R., and Slifer, D., 1971. Caves of Maryland. Maryland Geological Survey, Educational Series 3, 120 p. [reissued, 1976, 2001].

French, C.A. 1938. Pennsylvania's Spring Creek Project. Transactions of the American Fisheries Society 68:359-363.

Fuller, Jr., W.P., 1979. The Geological Background of Calaveras County, Preliminary Draft. Grant from The National Endowment for the Humanities to the Calaveras Heritage Council, 38 p.

Fulton, J.W., Koerkle, McAuley, S.S., Hoffman, S.A., and Zarr. L.F., 2005. Hydrogeologic setting and conceptual hydrologic model of the Spring Creek basin, Centre County, Pennsylvania, June 2005. U.S. Geological Survey, Scientific Investigations Report 2005-5091, Reston, Virginia, 83 p.

Fulton, J.W., Risser, D.W., Regan, R.S., Walker, J.F., Hunt, R.J., Niswonger, R.G., Hoffman, S.A., and Markstrom, S.L., 2015. Water-budgets and recharge-area simulations for the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, Water Years 2000–06: U.S. Geological Survey Scientific Investigations Report 2015–5073, 86 p, http://dx.doi.org/10.3133/sir20155073.

Funkhouser, J.E., Little, P.R., Brahana, J.V., Kresse, T.M., Anderson, M., Formica, Sandi, and Huetter, Thomas, 1999. Methodology to study the effects of animal production in mantled karst aquifers of the southern Ozarks, in Palmer, A.N., Palmer, M.V., and Sasowky, I.D., eds., Karst modeling—Special Publication 5: Charles Town, Va., Karst Waters Institute, p. 255–258.

Gale, M., Knox, R., Springston, G., and Becker, L., 2009a. Mean Yield (gpm) of Water Wells Compiled by Bedrock Unit, Vermont. Vermont Geological Survey Open File Report VG09- 8, Plate 4 of 7. VT Geological Survey, VT Dept. of Environmental Conservation, VT Agency of Natural Resources, Waterbury, VT

Gale, M., Springston, G., Knox, P. and Becker, L., 2009b. Statewide analyses of bedrock water well data: Vermont Geological Survey Open File Report VG09-8, 7 plates, scale 1:250,000

Gardner, J. H., 1935. Origin and development of limestone caverns: Geol. Soc. America Bull. 46:1255-1274.

Gardner, R. J., Hart, E., and Sutherland, C., 2018. Delineation of a Major Karst Basin with Multiple Input Points, Roaring River, Tennessee. In: W.B. White, J.S. Herman, E.K. Herman, and M. Rutigliano (Eds.), Karst Groundwater Contamination and Public Health (pp. 297–304). Springer, Cham. doi.org

Garton, E.R., Jr., 1977. The Effects of Highway Construction on the Hydrologic Environment at Bowden, West Virginia. In: Dilamarter, R.R., and Csallany, S.C. (eds.), Hydrologic Problems in Karst Regions, Western Kentucky University, Bowling Green, KY.

Geldon, A.L., 1989. Hydrogeology of the Leadville limestone and other paleozoic rocks in northwestern Colorado, with results of aquifer tests at Glenwood Springs. U.S. Geological Survey Water-Resources Investigations Report 87-4195, 96 p.

GeoConcept Engineering, 2017. Fracture Analysis and Dye Trace Report. Dominion ACP Augusta, Bath and Highland Counties, Virginia & Pocahontas and Randolph Counties, West Virginia. 18 p. + Appendices

George, A.I., 1976. Karst and Cave Distribution in North-central Kentucky. The NSS Bulletin, Vol. 38, No. 4, pp. 93-98

George, P.G., Mace, R.E., and Petrossian, R., 2011. Aquifers of Texas. Report 380, Texas Water Development Board, Austin, Texas, 172 p.

Geyer, A.R. and Bolles, W.H., 1979. Outstanding Scenic Geological Features of Pennsylvania. Environmental Geology Report 7, Pennsylvania Department of Environmental Resources, Bureau of Topographic and Geological Survey, 508 p.

Gittings, H.E., 2005. Hydrogeologic controls on springs in the Mukwonago River watershed, SE Wisconsin, Master's Thesis, University of Wisconsin-Madison.

Goodwin, P., Inkenbrandt, P., Menuz, D., Hurlow, H., and Dittmer, D., 2021. Snake Valley hydrologic monitoring—ten-year report: Utah Geological Survey Open-File Report 732, 36 p., 2 appendices, https://doi.org/10.34191/OFR-732.

Graham, J.P., 2020. Grand Canyon National Park Geologic Resources Inventory Report. Natural Resource Report NPS/NRSS/GRD/NRR—2020/2195. U.S. Department of the Interior, National Park Service, Natural Resource Stewardship and Science, Fort Collins, Colorado, 180 p.

Greene, E.A., 1993. Hydraulic properties of the Madison aquifer system from analysis of aquifer tests in the western Rapid City area, South Dakota. U.S. Geological Survey Water-Resources Investigations Report 93-4008, 77 p.

Greene, E.A., Shapiro, A.M., and Carter, J.M., 1999. Hydrogeologic characterization of the Minnelusa and Madison aquifers near Spearfish, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 98-4156, 64 p.

Gunn, J. et al., 2025. Project MIKAS (Most Important Karst Aquifers' Springs): Progress and request for information. Proceedings of the 19th International Congress of Speleology, Bello Horizonte, Brazil, Vol. II, pp. 227-230

Guyton, W.F., and Associates, 1979. Geohydrology of Comal, San Marcos, and Hueco Springs: Austin, Texas Department of Water Resources Report 234, 85 p.

Hallberg, G.R., Hoyer, B.E., Bettis, E.A., III, and Libra, R.D., 1983. Hydrogeology, water quality, and land management in the Big Spring basin, Clayton County, Iowa: Iowa Geological Survey Open-File Report 83-3, 190 p. + Appendices

Hallberg, G.R., Libra, R.D., Bettis, E.A., III, and Hoyer, B.E., 1984. Hydrogeologic and water quality investigations in the Big Spring basin, Clayton County, Iowa: Iowa Geological Survey Open-File Report 84-4, 231 p.

Ham, W. E., 1955. Geology of the Arbuckle Mountain region: Oklahoma Geological Survey Guidebook 3, 61 p.

Hanson, R.L., and Cates, S.W., 1994. Hydrogeology of the Chickasaw National Recreation Area, Murray County, Oklahoma. U.S. Geological Survey Water-Resources Investigations Report 94-4102, 86 p.

Harlow, G.E. Jr., Orndorff, R.C., Nelms, D.L., Weary, D.J., and Moberg, R.M., 2005. Hydrogeology and Ground-Water Availability in the Carbonate Aquifer System of Frederick County, Virginia, U.S. Geological Survey Scientific Investigations Report 2005-5161, 30 p.

Harris, C., 2012. Short Mtn (2092'). Online publication of Middle Tennessee State University. http://frank.mtsu.edu/~cdharris/GEOL100/TN (accessed 2 January 2012).

Harris, R.C., 2002. A review and bibliography of Karst Features of the Colorado Plateau, Arizona. Arizona Geological Survey Open File Report, OFR-02-07, 43p. https://library.azgs.arizona.edu/item/AOFR-1552427421088-565

Hart, D.J., Schoephoester, P.R., and Bradbury, K.R., 2008. Groundwater Recharge in Southeastern Wisconsin Estimated by a GIS-Based Water-Balance Model. Technical Report Number 47, Wisconsin Geological and Natural History Survey, University of Wisconsin-Extension, 23 p.

Hartnett, F.M., ed., 2000. Florida's springs strategies for protection and restoration. The Florida Springs Task Force, Tallahassee, 59 p.

Hasenmueller, N.R., Rexroad, C.B., Powell, R.L., Buehler, M.A., and Bassett, J.L., 2003. Karst Geology and Hydrology of the Spring Mill Lake and Lost River Drainage Basins in Southern Indiana. Guidebook 15, Indiana University, Indiana Geological Survey, Bloomington, IN, 30 p.

Hatcher, R.D. Jr., 1995. Structural Geology; Principles, Concepts, and Problems. Second Edition. Prentice Hall, Englewood Cliffs, New Jersey, 525 p.

Hauwert, N., 2009. Groundwater Flow and Recharge Within the Barton Springs Segment of the Edwards Aquifer, Southern Travis and Northern Hays Counties, Texas. PhD Dissertation, University of Texas at Austin. 316 p.

Hauwert, N., and Vickers, S., 1994. Barton Springs/Edwards Aquifer hydrogeology and groundwater quality: Austin, Texas, Barton Springs/Edwards Aquifer Conservation District, report prepared for Texas Water Development Board under contract no. 93483-346, 92 p.

Hauwert, N.M., Johns, D.A., and Sharp, J., 2002. Evidence of discrete flow in the Barton Springs segment of the Edwards Aquifer, In Martin, J.B., Wicks, C.M., and Sasowsky, I.D., eds., Hydrogeology and biology of post-Paleozoic carbonate aquifers: Karst Waters Institute, Special Publication 7, p. 62–167.

Hauwert, N., Johns, D., Thomas., A., and, James, S., 2004. Groundwater Tracing Study of the Barton Springs Segment of the Edwards Aquifer, Southern Travis and Northern Hays Counties, Texas: Report by the Barton Springs/Edwards Aquifer Conservation District and City of Austin Watershed Protection and Development Review Department. 110 p. and appendices.

Hayes, T.S., 1999. Episodic sediment-discharge events in Cascade Springs, southern Black Hills, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 99-4 168, 34 p.

Hedin, M., and Milne, M.A., 2023. New species in old mountains: integrative taxonomy reveals ten new species and extensive short-range endemism in Nesticus spiders (Araneae, Nesticidae) from the southern Appalachian Mountains. ZooKeys 1145: I-130 (2023). https://zookeys.pensoft.net/article/96724/

Heilweil, V.M., and Brooks, L.E., eds., 2011. Conceptual model of the Great Basin carbonate and alluvial aquifer system: U.S. Geological Survey Scientific Investigations Report, 191 p. Available at http://pubs.usgs.gov/sir/2010/5193/

Helfrich, L.A., Parkhurst, J., and Neves, R., 2009. Managing Spring Wetlands for Fish and Wildlife Habitat. Virginia Cooperative Extension Publication 420-537, Virginia Polytechnic Institute and State University, Blacksburg, 6 p.

Heller, S.A. 1980. A Hydrogeologic Study of the Greenbrier Limestone Karst of Central Greenbrier County, West Virginia. Graduate Theses, Dissertations, and Problem Reports. 9020. https://researchrepository.wvu.edu/etd/9020

Heller, Matthew J., *compiler*, 2023. Carbonate formations in Virginia: Virginia Department of Energy, Geology and Mineral Resources Program Open-file report 2023-01, scale 1:250,000.

Henris, J.R., 2015. No finer trout-streams in the world than these: The Making of a Recreational Fishery in the Black Hills Forest Reserve. South Dakota History 45, no. 4 (Winter 2015): pp. 275–304

Herpers, 1947. New Jersey Geological Survey Permanent Note, Spring of Large Capacity near Stillwater, Atlas Sheet 21.34.7.2.1. September 10, 1947.

Herzog, B.L., B.J. Stiff, C.A. Chenoweth, K.L. Warner, J.B. Sieverling, and C. Avery, 1994, Buried bedrock surface of Illinois: Illinois State Geological Survey, Illinois Map 5, 1:500,000.

Hisert, R.A., 1994. A Multiple Tracer Approach to Determine the Ground and Surface Water Relationships in the Western Santa Fe River Basin, Florida (Doctoral dissertation, University of Florida, Gainesville).

Hobba, W.A., Jr., Fisher, D.W., Pearson, F.J., Jr., and Chemerys, J.C., 1979. Hydrology and geochemistry of thermal springs of the Appalachians. U.S. Geological Survey Professional Paper 1044-E, 36 p.

Hohn, M.E.; McCreery, S., Moore, J.P., and Dinterman, P., 2017. Developing a Karst Map for West Virginia. West Virginia Geological and Economic Survey.
https://www.wvgs.wvnet.edu/www/presentations/2017/Hohn_2017_Karst_Poster.pdf

Hollocher, K., Quintin, L., and Ruscitto, D., 2002. Geochemistry and source of the Saratoga springs. New York State Geological Association, Field Trip Guidebook, Lake George, New York, Trip C-11, pp. 1-15.

Holsinger, J.R. and Culver, D.C., 1990. Report on the subterranean biological resources of the Cedars Karst in Lee County, Virginia. Unpublished report prepared for the Virginia Department of Conservation and Recreation. 10 pp.

Hollyday, E.F., and Hileman, G.E., 1996. Hydrogeologic terranes and potential yield of water to wells in the Valley and Ridge physiographic province in the eastern and southeastern United States. U.S. Geological Survey Professional Paper 1422-C, 30 p.

Hollyday, E.F., Hileman, G.E., and Duke, J.E., 1997. The Elkton aquifer or Western Toe aquifer of the Blue Ridge Mountains— A regional perspective, in Younos, T., Burbey, T.J., Kastning, E.H., and Poff, J.A., eds., Proceedings, Karst Water Environment Symposium, October 30–31, 1997, Roanoke, VA. Virginia Water Resource, v. P3 1997, pp. 71–77.

Hoover, H. and Kutz, R., 1962. Aqua Cave Map. Nittany Grotto (National Speleological Society) News 11(2):37.

Horick, P.J., 1989. Water Resources of Northeast Iowa. Water Atlas Number 8. Iowa Department of Natural Resources, 133 p.

Hozik, M.J., editor, 2021. Karst Geology of NJ and Vicinity: Revisited. 2012 Conference Proceedings for the 37th Annual Meeting of the Geological Association of New Jersey, October 15 & 16, 2021, 76 p.

Hubbard, Jr. David, 1988. Selected Karst Features of the Central Valley and Ridge Province, Virginia. Virginia Division of Mineral Resources, Publication 83.

Hudson, M.R., and Cox, R.T., 2003. Late Paleozoic tectonics of the southern Ozark dome, *in* Cox, R.T., comp., Field trip guidebook for joint South-Central and Southeastern sections: Geological Society of America, Tennessee Division of Geology Report of Investigations 51, p. 15–32.

Hunt, B., Smith, B., Campbell, S., Beery, J., Hauwert, N., and Johns, D., 2005. Dye tracing recharge features under high-flow conditions, Onion Creek, Barton Springs Segment of the Edwards Aquifer, Hays County, Texas. Austin Geologic Society Bulletin, Vol. 1, p. 70-86.

Hunt, B., Smith, B., Adams, M., Hiers, S., and Brown, N., 2013. Cover-Collapse Sinkhole Development in the Cretaceous Edwards Limestone, Central Texas. Proceedings of the 13th Multidisciplinary Sinkhole Conference on Sinkholes and Engineering and Environmental Impacts of Karst, Carlsbad New Mexico, May 2013, p. 89-102.

Hunt, B.B., Smith, B.A., Bell-Enders, K., Dupnik, J., Gary, R., Johnson, S., Hauwert, N.M., and Camp, J., 2013a. Dye Tracing Results from the Arbor Trails Sinkhole, Barton Springs Segment of the Edwards Aquifer, Austin, Texas. BSEACD Report of Investigations 2013-0501, Barton Springs/Edwards Aquifer Conservation District, Austin, Texas, 18 p. + Appendices

Hunt, P.J., Burns, M.S., Tudek, J.K., Perkins, J.W., Brown, S.R., Dinterman, P.A., and McDowell, R.R., 2019. Bedrock Geologic Map of the Edray 7.5' Quadrangle, West Virginia. West Virginia Geological and Economic Survey, Publication OF-1802.

Huntoon, P.W. and Coogan, J.C, 1987. The strange hydrodynamics of Periodic Spring, Salt River Range, Wyoming. In: Wyoming Geological Association Guidebook—38th Field Conference, pp. 337-345.

Hurd, T.M., 2012. Determination of Preferential Groundwater Flow Patterns to Cumberland County Springs with Fluorescent Dye Tracing. Pennsylvania Geology, Vol. 42, No. 3, pp. 3-10

Hurd, T.M., Spicka, M.E., and Coates, J., 2007. Big Spring Watershed River Conservation Plan. Big Spring Watershed Association, Newville, PA, 107 p.

Hurd, T.M., Jesic, S., Jerin, J.L., Fuller, N.W., and Miller, D., Jr., 2008. Stable isotope tracing of trout hatchery carbon to sediments and foodwebs of limestone spring creeks. Science of The Total Environment, Volume 405, Issues 1–3, pp. 161-172

Hurd, T.M., Brookhart-Rebert, A., Feeney, T.P., Otz, M.H., and Otz, I., 2010. Fast, regional conduit flow to an exceptional-value spring-fed creek: implications for source-water protection in mantled karst of south central Pennsylvania. Journal of Cave and Karst Studies, v. 72, no. 3, p. 129–136. DOI: 10.4311/jcks2009es0112

Hurlow, H.A., editor, 2014. Hydrogeologic studies and groundwater monitoring in Snake Valley and adjacent hydrographic area, west-central Utah and east-central Nevada: Utah Geological Survey Bulletin 135, 294 p., 4 plates, https://doi. org/10.34191/B-135.

Hurlow, H., and Jordan, L., 2014. UGS Groundwater & Spring Flow Monitoring in Snake Valley. Survey Notes, Utah Geological Survey, Vol. 46, No. 2.

Hurlow, H., and Inkenbrandt, P.C., 2016. Analysis of groundwater-level records from Snake Valley, western Millard County, Utah, in Resources and Geology of Utah's West Desert: Salt Lake City, Utah Geological Association Utah Geological As sociation Guidebook 45, p. 221–246.

Hutson, W.F., 1898. Irrigation systems in Texas: US Geological Survey Water-Supply Paper 13.

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., 2004. Estimated use of water in the United States in 2000: U.S. Geological Survey Circular 1268, 46 p.

Imes, J. L., Plummer, L. N., Kleeschulte, M. J., and Schumacher, J. G., 2007. Recharge area, base-flow and quick-flow discharge rates and ages, and general water quality of Big Spring in Carter County, Missouri. U.S. Geological Survey Scientific Investigations Report 2007-5049, Reston, VA, 80p.

Indiana Geological and Water Survey, 2019. Geologic story of Spring Mill State Park: Indiana Geological and Water Survey State Park Guide 07-2019.

Intera Geosciences and Engineering, 2021. Data and Conceptualization Evaluation of The Alapaha River Sink Rise System. Prepared for Suwannee River Water Management District, 166 p.

Jackson, R.L., and Doctor, D.H., 2023. Enhanced Terrain Imagery of the State College 30 x 60 Minute Quadrangle from Lidar-Derived Elevation Models at 3-Meter Resolution: U.S. Geological Survey data release, https://doi.org/10.5066/P9WPVKNE.

Jackson, R.L. and Doctor, D.H., 2024a. Enhanced Terrain Imagery of the Tyrone 30 x 60 Minute Quadrangle from Lidar-Derived Elevation Models at 3-Meter Resolution: U.S. Geological Survey data release, https://doi.org/10.5066/P1PXMBKV

Jackson, R.L., and Doctor, D.H., 2024b. Enhanced Terrain Imagery of the Johnstown 30 x 60 Minute Quadrangle from Lidar-Derived Elevation Models at 3-Meter Resolution: U.S. Geological Survey data release

Jackson, R.L., and Doctor, D.H., 2024c. Enhanced Terrain Imagery of the Carlisle 30 x 60 Minute Quadrangle from Lidar-Derived Elevation Models at 3-Meter Resolution. U.S. Geological Survey data release, https://doi.org/10.5066/P97QS4YC.

Jackson, T.E., 2009. Prospects for Restoration of Flow at Historic Kissengen Spring Located near Bartow in Polk County, Florida. 5th Conference on Hydrogeology, Ecology, Monitoring, and Management of Ground Water in Karst Terrains. February 23-24, 2009, Safety Harbor, Florida. National Groundwater Association.

Jameson, R.A., and Alexander, E.C. Jr., 1994. The Waters of Mystery Cave, Forestville State Park, Minnesota. Mystery Cave Resource Evaluation (Groundwater). Interpretive Report. Minnesota Department of Natural Resources, Forestville State Park.

Janis, I.L., 1971. Groupthink. Psychology Today, **5**(6): 43–44, 46, 74–76

Janis, I.L., 1972. Victims of Groupthink: a Psychological Study of Foreign-Policy Decisions and Fiascoes. Houghton Mifflin, Boston.

Janis, I.L., 1982. Groupthink: Psychological Studies of Policy Decisions and Fiascoes. Houghton Mifflin, Boston.

Johnson, S.B., and Schindel, G.M., 2008. Evaluation of the option to designate a separate San Marcos pool for critical period management: San Antonio, Tex., Edwards Aquifer Authority, 109 p.

Johnson, P.W., and Sanderson, R.B., 1968. Spring flow into the Colorado River Lees Ferry to Lake Mead, Arizona: Arizona State Land Department, no. 34, 26 p.

Johnson, R.H., DeWitt, Ed, Wirt, Laurie, Arnold, L.R., and Horton, J.D., 2011. Water and rock geochemistry, geologic cross sections, geochemical modeling, and groundwater flow modeling for identifying the source of groundwater to Montezuma Well, a natural spring in central Arizona: U.S. Geological Survey Open-File Report 2011–1063, 62 p.

Johnson, R.H., DeWitt, E., and Arnold., L.R., 2012a. Part 1: using hydrogeology to identify the source of groundwater to Montezuma Well, a natural spring in central Arizona, USA. Environmental Earth Sciences 67:1821–1835. doi: 10.1007/s12665-012-1801-1.

Johnson, R.H., DeWitt, E., and Arnold., L.R., 2012b. Part 2: using geochemistry to identify the source of groundwater to Montezuma Well, a natural spring in central Arizona, USA. Environmental Earth Sciences 67:1837–1853. doi: 10.1007/s12665-012-1844-3.

Jones, C., Springer, A.E., and Tobin, B.W., 2016a. Spring hydrograph and recession curve analysis of extreme weather for Roaring Springs, in deep karst R-aquifer of the Grand Canyon. Geological Society of America Abstracts with Programs 48(7):np. https://gsa.confex.com/gsa/2016AM/webprogram/Paper280691.html (accessed 23 February 2018).

Jones, N.A., Tobin, B.W., and Zappitello, S.J., 2016b. Geospatial analysis of sinkholes to delineate karst catchment, Kaibab Plateau, Grand Canyon National Park. Geological Society of America Abstracts with Programs 48(7):np. https://gsa.confex.com/gsa/2016AM/webprogram/Paper281780.html (accessed 23 February 2018).

Jones, C., Springer, A.E., Tobin, B.W., Zappitello, S.J., and Jones, N.A., 2017a. Characterization and hydraulic behaviour of the complex karst of the Kaibab Plateau and Grand Canyon National Park, USA. In M. Parise, F. Gabrovsek, G. Kaufmann, and N. Ravbar, editors. Advances in karst research: theory, fieldwork and application. Special Publication 466. Geological Society of London, London, England.

Jones, N.A., Tobin, B.W., and Schenk, E.R., 2017b. Sinkhole geomorphology and distribution on the Kaibab Plateau, Grand Canyon National Park. Geological Society of America Abstracts with Programs 49(6):poster. https://gsa.confex.com/gsa/2017AM/webprogram/Paper304321.html (accessed 22 February 2018).

Jones,W.K.,1973.Hydrology of Limestone Karst in Greenbrier County, West Virginia. Bulletin 36,WestVirginia Geological and Economic Survey, Charleston, WV, 49 p.

Jones, W. K., 1977. Karst Hydrology Atlas of West Virginia. Special Publication 4, Karst Waters Institute, Charles Town, WV, 111p.

Jones, W., 2018. Hydrology of the Greenbrier Karst. In: W.B. White (ed.), *Caves and Karst of the Greenbrier Valley in West Virginia*. Cave and Karst Systems of the World, Springer International Publishing, pp. 21-44

Kaliser, B.N., 1972. Environmental Geology of Bear Lake Area, Rich County, Utah. Utah Geological and Mineralogical Survey Bulletin 96, 32 p + 1 plate

Kambesis, P., 2014. The Geology of the Caves and Karst of "Classic TAG" and Surrounding Areas. In: Brown, J.S., ed., 2014 NSS Convention Guidebook, National Speleological Society, Huntsville, Alabama, pp. 2-23

Kappel, W.M., and Jennings, M.B., 2012. Water resources of the Iroquois National Wildlife Refuge, Genesee and Orleans Counties, New York, 2009–2010. U.S. Geological Survey Scientific Investigations Report 2012–5027, 53 p. [Also available at https://doi.org/ 10.3133/ sir20125027.]

Karlstrom, K., L. Crossey, A. Mathis, and C. Bowman. 2021. Telling time at Grand Canyon National Park: 2020 update. Natural Resource Report NPS/GRCA/NRR—2021/2246. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/nrr-2285173.

Kasabach, et al, 5/22/1967. New Jersey Geological Survey Permanent Note, Spring of Large Capacity near Stillwater, Atlas Sheet 21.34.7.2.1.

Kaufmann, J.E., 2002. The karst hydrology of Boiling Spring, Pulaski County, Missouri. Master's Thesis, Missouri University of Science and Technology, Rolla, https://scholarsmine.mst.edu/masters_theses/2145

KellerLynn, K. 2009. Jewel Cave National Monument Geologic Resources Inventory Report. Natural Resource Report NPS/NRPC/GRD/NRR—2009/084. National Park Service, Denver, Colorado.

KellerLynn, K., 2018. Craters of the Moon National Monument and Preserve. Geologic Resources Inventory Report. Natural Resource Report NPS/NRSS/GRD/NRR—2018/1783. National Park Service, Natural Resource Stewardship and Science, Fort Collins, Colorado, 89 p.

KellerLynn, K. 2019. Montezuma Castle National Monument: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2019/2022. National Park Service, Fort Collins, Colorado.

Kemmerly, P.R., 1982. Spatial analysis of a karst depression population—Clues to genesis: Geological Society of America Bulletin, v. 93, no. 11, pp. 1078–1086

Kennedy, C.D., and Genereux, D.P., 2007. 14C Groundwater age and the importance of chemical fluxes across aquifer boundaries in confined Cretaceous aquifers of North Carolina, USA. Radiocarbon, Vol 49, No. 3, 2007, pp. 1181–1203

Kincaid, T.R., 1994. Groundwater and Surface Water Interactions in the Western Santa Fe River Basin near High Springs, Florida. M.S. Thesis, University of Florida, 105 p.

Kindle, E.M., and Taylor, F.B., 1913. Description of the Niagara quadrangle [New York]: U.S. Geological Survey Geologic Atlas of the United States Folio, Niagara folio, no. 190, 26 p

Kirby, S., and Hurlow, H., 2005. Hydrogeologic setting of the Snake Valley hydrologic basin, Millard County, Utah, and White Pine and Lincoln Counties, Nevada: Implications for possible effects of proposed groundwater withdrawal: Utah Geological Survey Report 122, 114 p.

Klemp, J.A., 1995. Source aquifers for large springs in northwestern Lawrence County, South Dakota: Unpublished M.S. Thesis, South Dakota School of Mines and Technology, Rapid City, S.D., 175 p.

Klimchouk, A.B., 1992. Large gypsum caves in the Western Ukraine and their genesis. Cave Science 19 (1), 3-11.

Klimchouk, A.B., 1994. Speleogenesis under confined conditions, with recharge from adjacent formations. Publ. Serv. Geol. Luxembourg, vol. XXVII: Comptes Rendus du Coll. Intern. de Karstologie a Luxembourg, pp. 85-95.

Klimchouk, A., 2011. Hypogene Speleogenesis: Hydrogeological and Morphogenetic Perspective. Second Edition. Special Paper No. 1, National Cave and Karst Research Institute Carlsbad, NM, 106 p.

Klimchouk, A.B., Ford, D., Palmer, A. and Dreybrodt, W. (Eds.), 2000. Speleogenesis: Evolution of Karst Aquifers. National Speleological Society, Huntsville, AL, 527 p.

Klimchouk, A.B., Samokhin, G.V., and Y.M. Kasian, 2009. The Deepest Cave in the World in the Arabika Massif (Western Caucasus) and its Hydrogeological and Paleogeographic Significance. Proceedings of the 15th International Congress of Speleology, Speleogenesis, pp. 898-905.

Knight, R.L. 2015. Silenced Springs – Moving from Tragedy to Hope. Howard T. Odum Florida Springs Institute press, High Springs, FL.

Knight, J.E., and Huntoon, P.W., 2022. Conceptual models of groundwater flow in the Grand Canyon region, Arizona: U.S. Geological Survey Scientific Investigation Report 2022–5037, 51 p., https://doi.org/10.3133/sir20225037.

Knight, R.L. and R.A. Clarke. 2016. Florida Springs–A Water-Budget Approach to Estimating Water Availability. Journal of Earth Science and Engineering, 6(2), pp. 59-73

Knight, R.R., and Kingsbury, J.A., 2007. Water resources of the Duck River watershed, Tennessee. U.S. Geological Survey Scientific Investigations Report 2007–5105, 46 p.

Kochanov, M.D., 2010. Pennsylvania's Top Ten Springs. Pennsylvania Geology, Vol. 40, No. 1, Pennsylvania Geological Survey, pp.15

Kochanov, W.E., 2015. Sinkholes in Pennsylvania (2nd ed.): Pennsylvania Geological Survey, 4th ser., Educational Series 11, 30 p.

Konieczki, A.D., and Leake, S.A., 1997. Hydrogeology and Water Chemistry of Montezuma Well in Montezuma Castle National Monument and Surrounding Area, Arizona. U.S. Geological Survey Water-Resources Investigations Report 97-4156, 49 p.

Kozar, M.D., Doctor, D.H., Jones, W.K., Chien, N., Cox, C.E., Orndorff, R.C., Weary, D.J., Weaver, M.R., McAdoo, M.A., and Parker, M., 2023. Hydrogeology, karst, and groundwater availability of Monroe County, West Virginia: U.S. Geological Survey Scientific Investigations Report 2023–5121, 82 p., https://doi.org/ 10.3133/ sir20235121.

Krakow, K.K., 1975. Georgia Place-Names: Their History and Origins. Winship Press, Macon, Georgia, pp. 180

Krause, R.E., and Randolph, R.B., 1989. Hydrology of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina. U.S. Geological Survey Professional Paper 1403–D, 65 p.

Kresic, N., 2009. Groundwater Resources. Sustainability, Management, and Restoration. McGraw Hill, New York, 852 p.

Kresic, N., 2010. Types and classification of springs. In: Kresic, N., and Stevanovic, Z. (eds.), Ground Water Hydrology of Springs; Engineering, Theory, Management and Sustainability. Elsevier, New York, pp. 31–85.

Kresic, N., 2013. Water in Karst; Management, Vulnerability, and Restoration. McGraw Hill, New York, 708 p.

Kresic, N., 2023. Hydrogeology 101. Introduction to Groundwater Science and Engineering. Blue Ridge Press, Warrenton, VA, 525 p.

Kresic, N., and Stevanovic, Z. (eds.), 2010. Groundwater Hydrology of Springs; Engineering, Theory, Management and Sustainability. Elsevier, New York, 573p.

Kresic, N., and Mikszewski, A., 2013. Hydrogeological Conceptual Site Models: Data Analysis and Visualization. CRC, Taylor & Francis Group, Boca Raton, FL, 552p.

Knight, R.L. 2015. Silenced Springs – Moving from Tragedy to Hope. Howard T. Odum Florida Springs Institute press, High Springs, FL.

LaFave, J.I., and Sharp, J.M. Jr., 1987. Origins of ground water discharging at the springs of Balmorhea. West Texas Geological Society Bulletin 26: 5-14.

Lampe, D.C., 2009. Hydrogeologic framework of bedrock units and initial salinity distribution for a simulation of ground water flow for the Lake Michigan Basin: U.S. Geological Survey Scientific Investigations Report 2009–5060, 49 p.

Lane, E., 1986. Karst in Florida. Special Publication No. 29, Florida Geological Survey, Tallahassee, 100 p.

Land, L., and Veni, G., 2018. Karst Hydrogeology Scoping Investigation of the San Solomon Spring Area: Culberson, Jeff Davis, and Reeves Counties, Texas. National Cave and Karst Research Institute Report of Investigation 8, Carlsbad, New Mexico, 20 p.

Landes, K.K., 1970. Petroleum geology of the United States: New York John Wiley, 571 p.

Lange, A. 1957. Studies on the origin of Montezuma Well and cave, Arizona. Cave Studies (Publication of Cave Research Associates) 9:39–53.

Lange, A.L., and Andrews-Jones, D.A., 1973. Geothermal Resources of Virginia and West Virginia. Geological and Geophysical Environment of Thermal Springs. Part I: Text and Figures.

Larsen, M.R., Green, J.A., Barry, J.D., Kasahara, S.M., Wheeler, B.J., and Alexander, E.C. Jr., 2018. 2017 York Blind Valley Dye Trace, Fillmore County, MN. Minnesota Department of Natural Resources, 9 p.

Lattman, L.H., and Parizek, R.R., 1964. Relationship between fracture traces and the occurrence of ground water in carbon ate rocks: Journal of Hydrology, v. 2, p. 73-91.

Lautier, J.C., 2001. Hydrogeologic framework and ground water conditions in the North Carolina central coastal plain: North Carolina Department of Environment and Natural Resources, 38 p.

Lautier, J.C., 2006. Hydrogeologic framework and ground water conditions in the North Carolina southern coastal plain: North Carolina Department of Environment and Natural Resources, Division of Water Resources, 32 p., 52 pls.

Lawton, D.E., Moye, F.J., Murray, J.B., O'Connor, B.J., Penley, H.M., Sandrock, G.S., Marsalis, W.E., Friddell, M.S., Hetrick, J.H., Huddlestun, P.F., Hunter, R.E., Mann, W.R., Martin, B.F., Pickering, S.M., Schneeberger, F.J., and Wilson, J.D., 1976. Geologic Map of Georgia; Scale 1:500,000. Georgia Geological Survey, Atlanta, Georgia. Available at https://ngmdb.usgs.gov/nationalgeology/

LBG-Guyton Associates, 2004. Evaluation of Augmentation Methodologies in Support of In-situ Refugia at Comal and San Marcos Springs, Texas. Prepared for the Edwards Aquifer Authority in association with BIO-WEST, Inc., Espey Consultants, Inc. and URS Corporation, June 2004.

Leach, D.L., and Rowan, E.L., 1986. Genetic link between Ouachita foldbelt tectonism and the Mississippi Valley-type lead-zinc deposits of the Ozarks: Geology, v. 14, no. 11, p. 931–935.

Leasor, Z., Bendorf, J., Cabrera-Garcia, J., Isele, E., Keay, J., Reall, T., Nowatzke, L., Baule, W., Andresen, J., Wilson, A. B., Todey, D., 2024. Climate Change Impacts on Missouri Agriculture. Ames, Iowa: United States Department of Agriculture Climate Hubs and Great Lakes Research Integrated Science Assessment, Aimes, Iowa.

Lenihan, D. 2011. Diving Montezuma Well: what's down there is still a mystery. Natural History 119(11):14–19.

Lessing, P., Hobba, W.A. Jr., Dean, S.L., and Kulander, B.R., 1991. Relations between warm springs and geology delineated by side-looking airborne-radar imagery in eastern West Virginia. U.S. Geological Survey Water-Resources Investigations Report 88-4096. Morgantown, West Virginia,

Lewis, J.J., Lewis, S.L., Orndorff, W., Orndorf, Z., Malard, F., Konecny-Dupré, L., Saclier, N., and Douady, C., 2023. The Groundwater Isopods of Virginia (Isopoda: Asellidae and Cirolanidae). Virginia Museum of Natural History Special Publication 19, Martinsville, Virginia, 44 p.

Lidke, D.J., and Blome, C.D., 2017. Geologic Map of the Fittstown 7.5' Quadrangle, Pontotoc and Johnston Counties, Oklahoma. U.S. Geological Survey Scientific Investigations Map 3371.

Lindgren, R.J., Dutton, A.R., Hovorka, S.D., Worthington, S.R.H., and Painter, S., 2004. Conceptualization and simulation of the Edwards Aquifer, San Antonio region, Texas: U.S. Geological Survey Scientific Investigations Report 2004–5277, 143 p.

Lindholm, G.F., 1996. Summary of the Snake River Plain regional aquifer-system analysis in Idaho and eastern Oregon (Regional aquifer-system analysis Snake River Plain, Idaho). U.S. Geological Survey Professional Paper 1408-A., 59 p.

Lindsey, B.D., Zimmerman, T.M., Chapman, M.J., Cravotta, C.A.III, and Szabo, Z., 2014. The quality of our Nation's waters—Water quality in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge regions, eastern United States, 1993–2009: U.S. Geological Survey Circular 1354, 107 p., https://dx.doi.org/10.3133/cir1354.

Lloyd, O.B., and Carswell, L.D., 1981. Groundwater resources of the Williamsport Region, Lycoming County, Pennsylvania. Pennsylvania Geological Survey, 4th ser., Water Resources Report 51, 68 p.

Long, A.J., and Putnam, L.D., 2002. Flow-system analysis of the Madison and Minnelusa aquifers in the Rapid City area, South Dakota--Conceptual Model. U.S. Geological Survey Water-Resources Investigations Report 02 4185, 100 p., 2 pl.

Lucas, P., 2017. In Pursuit of Losing Streams & Springs. 7p. Cowpasture River Preservation Association. https://cowpastureriver.org/wp-content/uploads/2019/08/Essay-No.-6-In-Pursuit-of-Losing-Streams-Caves-and-Springs.pdf).

Lund, J.W., 1997. Hot Springs, South Dakota. Oregon Institute of Technology, Geo-Heat Center, Klamath Falls, OR, 6 p.

Lyke, W., and Coble, R.W., 1987. Regional study of the Castle Hayne Aquifer of eastern North Carolina: U.S. Geological Survey Open-File Report 87-571, 2 p. :maps ;28 cm., https://doi.org/10.3133/ofr87571.

Maas, J.C., 2009. Drawdown, recovery, and hydro stratigraphy in Wisconsin's northeast groundwater management area (Brown, Outagamie, and Calumet Counties): M.S. thesis, University of Wisconsin Green Bay, 196 p. plus CD-ROM.

Malott, C.A., 1932. Lost River at Wesley Chapel Gulf, Orange County, Indiana. Proceedings of the Indiana Academy of Science, 1931, v. 41, pp. 285–316 https://digitalcommons.usf.edu/kip_articles/3374

Malott, C. A., 1938. Invasion theory of cavern development (abs.) : Geol. Soc. America Proc, 1937, p. 232.

Malott, C. A., 1952, The swallow-holes of Lost River, Orange County, Indiana: Indiana Acad. Sci. Proc. 61:187-231.

Martin, J.B., and Screaton, E.J., 2001. Exchange of Matrix and Conduit Water with Examples from the Floridan Aquifer. In Eve L. Kuniansky, editor, U.S. Geological Survey Karst Interest Group Proceedings, Water-Resources Investigations Report 01-4011, pp. 38-44

Martin, J.B., and Dean, R.W., 2001. Exchange of water between conduits and matrix in the Floridan aquifer. Chemical Geology, 179(1), pp. 145–165. DOI: 10.1016/S0009-2541(01)00320-5

Mashburn, S.L., Kirby, E.A., and Wagner, D.L., 2025. Soil-Water-Balance model and data for Phase 1 (2003–08) and Phase 2 (2018–23) hydrologic and water-budget analyses of the eastern part of the Arbuckle-Simpson aquifer, south-central Oklahoma, 2019–22. U.S. Geological Survey data release, https://doi.org/10.5066/P14UXYVV.

Maryland Geological Survey, 1990. The Physical Features of Allegany County. The Johns Hopkins Press, Baltimore, MD, 323 p.

Maynard, J.P., 2023. Springs of Virginia. Virginia Department of Environmental Quality Open File Report 23-01, 236 p.

Masbruch, M.D., and Gardner, P.M., 2014. Potential effects of existing and proposed groundwater withdrawals on water levels and natural groundwater discharge in Snake Valley, Juab and Millard Counties, Utah, White Pine County, Nevada, and surrounding areas in Utah and Nevada: U.S. Geological Survey Open-File Report, 2014-1176, 24 p. http://dx.doi.org/10.3133/ofr20141176.

McCallie, S.W., 1905. Experiment relating to problems of well contamination at Quitman, Georgia. U.S. Geological Survey Water-Supply Paper 110, pp. 45-54.

McCallie, S.W., 1908. A Preliminary Report on the Underground Waters of Georgia. Geological Survey of Georgia, Bulletin No. 15. 370 p.

McCallie, S.W., 1913. A preliminary report of the mineral springs of Georgia. Geological Survey of Georgia Bulletin No. 20, 190 p.

McColloch, J.S., 1986. Springs of West Virginia. West Virginia Geological and Economic Survey. Volume V-6A, 493 p.

McDowell, R.R., Hunt, P.J., Hitzig, J.E., Dinterman, P.A., Case, G.N., and Sidney, J.A., 2013. Bedrock Geologic Map of the West Virginia Portion of the Minnehaha Springs and Sunrise 7.5' Quadrangles, WV-VA. Geologic Quadrangle Maps of West Virginia OF 1202, West Virginia Geological and Economic Survey.

McGlynn, S.E., 2020. Wakulla Springs Dark Water: Causes and Sources, Phase III Final Report, 07/17/20. McGlynn Laboratories, Inc. for the Wakulla Springs Alliance

McKee, E.D., and Resser, C.E., 1945. Cambrian history of the Grand Canyon region: Washington, D.C., Carnegie Institution of Washington Publication 563, 232 p.

McKee, E.D., Hastings, H., and Colton, H.S., 1947. Montezuma Well: Result of Preliminary Soundings July 16, 1947. Flagstaff, Museum of Northern Arizona, 2 p.

McKee, E.D., 1960. Lithologic subdivisions of the Redwall Limestone in northern Arizona—Their paleogeographic and economic significance: U.S. Geological Survey Professional Paper 400-B, B243–B245.

McKnight, E.T., 1935. Zinc and lead deposits of northern Arkansas: U.S. Geological Survey Bulletin 853, 311 p., accessed September 25, 2015, at http://pubs.er.usgs.gov/publication/b853.

McSwain, K.B., Gurley, L.N., and Antolino, D.J., 2014. Hydrogeology, hydraulic characteristics, and water-quality conditions in the surficial, Castle Hayne and Peedee aquifers of the greater New Hanover County area, North Carolina, 2012–13: U.S. Geological Survey Scientific Investigations Report 2014–5169, 52p., http://dx.doi.org/10.3133/sir20145169.

Mehrtens, C.J., 1988. The Cambrian Platform and Platform Margin in Northwestern Vermont. In J.R. Selleck (Ed.), New York State Geological Association 60th Annual Meeting Field Trip Guidebook, pp. 83–106. Plattsburgh, NY: NYSGA

Meinzer, O. E., 1923. Occurrence of ground water in the United States, with a discussion of principles: U.S. Geological Survey Water-Supply Paper 489, 321 p.

Meinzer, O.E., 1927. Large Springs in the United States. U.S. Geological Survey Water-Supply Paper 557, Washington, D.C., 94 p.

Melis, T.S., Phillips, W.M., Webb, R.H., and Bills, D.J., 1996. When the blue-green waters turn red, historical flooding in Havasu Creek, Arizona: U.S. Geological Survey Water Resources Investigation Report 96-4059, 136 p.

Menuz, D., Jones, J., Sempler, R., and Emerson, R., 2024. Wetland Monitoring in Snake Valley, Utah. Developing A Method to Understand Wetland Conditions. Survey Notes, Utah Geological Survey, Vol. 46, No. 2.

Milanović, P.T., 1976. Water regime in deep karst—Case study of the Ombla Spring drainage area, in Yevjevich, V., ed., Karst hydrology and water resources—Proceedings of the U.S.-Yugoslavian symposium, Dubrovnik, June 2–7, 1975: Fort Collins, Colo., Water Resources Publications, p. 165–191.

Milewski, A.M, Thomas, M.B., Seyoum, W.M., and Rasmussen, T.C., 2019. Spatial Downscaling of GRACE TWSA Data to Identify Spatiotemporal Groundwater Level Trends in the Upper Floridan Aquifer, Georgia, USA. *Remote Sensing*, 11, 2756; doi:10.3390/rs11232756

Miller, J.A., 1986, Hydrogeologic Framework of the Floridan Aquifer system in Florida and in Parts of Georgia, Alabama and South Carolina. U.S. Geological Survey Professional Paper 1403-B, 91 p.

Miller, J.A., 1990. Ground Water Atlas of the United States—Alabama, Florida, Georgia, and South Carolina: U.S. Geological Survey Hydrologic Atlas 730-G.

Miller, R.L. and Brosge. W.P., 1954. Geology and oil resources of the Jonesville District, Lee County, Virginia. U.S. Geological Survey Bulletin No. 990. 210 p.

Miller, L.D., and Driscoll, D.G., 1998. Streamflow characteristics for the Black Hills of South Dakota, through water year 1993. U.S. Geological Survey Water-Resources Investigations Report 01-4129, 118 p.

Milske, J.A., Alexander, E.C. Jr., and Lively, R.S., 1983. Clastic sediments in Mystery southeastern Minnesota. National Speleological Society Bulletin, vol. 45, p. 55-75.

Missouri Department of Conservation, 2023a. Big Spring. https://mdc.mo.gov/discover-nature/places/natural-areas/big-spring.

Missouri Department of Conservation, 2023b. Greer Spring. https://mdc.mo.gov/discover-nature/places/natural-areas/greer-spring

Missouri Department of Conservation, 2023c. Blue Spring. https://mdc.mo.gov/discover-nature/places/natural-areas/blue-spring

Missouri Department of Conservation, 2023d. Alley Spring. https://mdc.mo.gov/discover-nature/places/natural-areas/alley-spring

Missouri Geological Survey, 2021. Follow the Water. Understanding Springs in the Missouri Ozarks. July 26, 2021. https://storymaps.arcgis.com/stories/b046232085004488a24ec12e2631e793

Montes Chamorro, K.R., 2024. Groundwater Movement in Boiling Spring, Onyx Spring, Yelton Spring, Wilkins Spring, Hudgens Spring and Natural Bridge Spring. Master's Thesis, Missouri University of Science and Technology, Rolla, 81 p. https://scholarsmine.mst.edu/masters_theses/8213

Monteverde, D.H., and Dalton, R.F., 2002. Structural and lithologic control of karst features in northwestern New Jersey. U.S. Geological Survey Water-Resources Investigations Report 02-4174, pp. 49-50.

Monteverde, D.H., and Herman, G.C., 2021. Geologic Map of the Newton West Quadrangle, Sussex County, New Jersey. Geologic Map Series GMS 21-3

Monteverde, D.H., and Witte, R.W., 2021. Field Guide. In: Hozik, M.J., editor, 2021, Karst Geology of NJ and Vicinity: Revisited. 2012 Conference Proceedings for the 37th Annual Meeting of the Geological Association of New Jersey, October 15 & 16, 2021. pp. 21-76

Monteverde, D.H., Epstein, J.B., and Herman, G.C., 2021. Geologic Map of the Flatbrookville Quadrangle Sussex and Warren Counties, New Jersey, and Monroe County, Pennsylvania. Geologic Map Series GMS 21-1

Morgan, L.A., Shanks, W.C.P., Lowenstern, J.B., Farrell, J.M., and Robinson, J.E., 2017. Geologic field-trip guide to the volcanic and hydrothermal landscape of the Yellowstone Plateau. U.S. Geological Survey Scientific Investigations Report 2017–5022–P, 100 p. https://doi.org/10.3133/sir20175022P

Moser, J., Simpson, L., and Shuman, B., 2014. Investigation of structural control of seemingly anomalous groundwater flow at Boiling Springs, Pennsylvania. Geological Society of America Abstracts with Programs, v. 46, no. 2, p. 49.

Mott, D.N., Hudson, M.R., and Aley, T.J., 2000. Hydrologic investigations reveal interbasin recharge contributes significantly to detrimental nutrient loads at Buffalo National River, Arkansas. In Proceedings of Arkansas Water Resources Center Annual Conference MSC–284, Fayetteville, Ark., p. 13–20.

Mozejko, A., 1981. Environmental assessment—Proposed land acquisition for Moapa dace (Moapa coriacea), an endangered species, Clark County, Nevada (rev. ed.): Portland, Oregon, U.S. Department of Interior, U.S. Fish and Wildlife Service, 101 p.

Mugel, D.N., Richards, J.M., Schumacher, J.G., 2009. Geohydrologic investigations and landscape characteristics of areas contributing water to springs, the Current River, and Jacks Fork, Ozark National Scenic Riverways, Missouri, U.S. Geological Survey Scientific Investigations Report 2009–5138, 80 p.

Mull, D.S., Alexander, A.G., and Schultz, P.E., 1989. Geohydrology and ground-water quality at selected sites in Meade County, Kentucky, 1987-88. U.S. Geological Survey, Water Resources Investigations Report 89-4108, 67 p.

Munch, D.A., D.J. Toth, C. Huang, J.B. Davis, C.M. Fortich, W.L. Osburn, E.J. Phlips, E.L., Quinlan, M.S. Allen, M.J. Woods, P. Cooney, R.L. Knight, R.A. Clarke, and S.L. Knight, 2006. Fifty-year retrospective study of the ecology of Silver Springs, Florida. Special Publication SJ2007-SP4. Palatka, Florida, St. Johns River Water Management District.

Mundorff, J.C., 1971. Nonthermal Springs of Utah. Water-Resources Bulletin 16. Utah Geological and Mineralogical Survey, Salt Lake City, Utah, 70 p + 2 Plates

Musgrove, M., and Crow, C.L., 2012. Origin and characteristics of discharge at San Marcos Springs based on hydrologic and geochemical data (2008–10), Bexar, Comal, and Hays Counties, Texas. U.S. Geological Survey Scientific Investigations Report 2012–5126, 94 p.

NPS (National Park Service (NPS), 2021 Geology of Montezuma Well.
https://home.nps.gov/moca/planyourvisit/geology-of-montezuma-well.htm

National Park Service (NPS), 2024. Rogers Spring. https://www.nps.gov/lake/learn/nature/rogers-spring.htm

NRCS (Natural Resources Conservation Service), 2024. *SNOTEL data from Tony Grove Lake (823)*. https://wcc.sc.egov.usda.gov/nwcc/site?sitenum=823

Naus, C.A, Driscoll, D.G., and Carter, J.M., 2001. Geochemistry of the Madison and Minnelusa aquifers in the Black Hills area, SD: U.S. Geological Survey Water-Resources Investigations Report 01-4129, 118 p.

Neilson, B. T., Tennant, H., Stout, T. L., Miller, M. P., Gabor, R. S., Jameel, Y., Millington, M., Gelderloos, A., Bowen, G. J., and Brooks, P. D., 2018. Stream Centric Methods for Determining Groundwater Contributions in Karst Mountain Watersheds. *Water Resources Research, 54(9).* https://doi.org/10.1029/2018WR022664

Neilson, B. T., Tennant, H., Strong, P. A., and Horsburgh, J. S., 2021. Detailed streamflow data for understanding hydrologic responses in the Logan River Observatory. *Hydrological Processes*, *35*(8), e14268. https://doi.org/10.1002/hyp.14268

Nelms, D.L., and Moberg, R.M., Jr., 2010, Hydrogeology and groundwater availability in Clarke County, Virginia. U.S. Geological Survey Scientific Investigations Report 2010–5112, 119 p. (available online at http://pubs.usgs.gov/sir/2010/5112/)

Nelson, W.J., 1999. Structural features in Illinois: Illinois State Geological Survey, Bulletin 100, 144 p.

New Hampshire Department of Environmental Services, 2025. Sinkholes and Subsidence in New Hampshire. Environmental Fact Sheet, GEO-15, Concord, NH, GEO-15: Sinkholes and Subsidence in New Hampshire

New York State Department of Environmental Conservation, 2020, Aquifers in New York state. Available at http://www.dec.ny.gov/ lands/ 36119.html.

Newson, M.D., 1971,. A model of subterranean limestone erosion in the British Isles based on hydrology, Trans. Inst. Brit. Geographers, v. 54, pp. 55-70.

Nicholas, J.R., Rowe, G.L., and Brannen, J.R., 1996. Hydrology, water quality, and effects of drought in Monroe County, Michigan. U.S. Geological Survey Water-Resources Investigations Report 94-4161. U.S. Geological Survey, Reston, VA.

Niemiller, M.L., Zigler, K.S., Stephen, C.D.R., Carter, E.T., Paterson, A.T., Taylor, S.J., and Engel, A.S., 2016. Vertebrate fauna in caves of eastern Tennessee within the Appalachians karst region, USA. National Speleological Society Journal of Cave and Karst Studies, v. 78, no. 1, pp. 1–24

Niemiller, M.L., Zigler, K.S., Hinkle, A., Stephen, C.D.R., Cramphorn, B., Higgs, J., Mann, N., Miller, B.T., Niemiller, K.D.K., Smallwood, K., et al., 2023. The Crystal-Wonder Cave System: A New Hotspot of Subterranean Biodiversity in the Southern Cumberland Plateau of South-Central Tennessee, USA. Diversity 2023, 15, 801. https://doi.org/10.3390/ d15070801

Niles, J.H., D.E. Owen, M.A. Kuntz, R.H. Lefebre, D.E. Champion, A.C. Barnes, B.R. Brulet, S.M. Chemtob, R.P. Clennon, N. Hansen, S.M. Keane, R.M. Kohler, B.L. Mocsny, T.A. Rivera, E.K. Shirley, K.E. Truitt, A.J. Tveter, and K.A. Wetherell. 2011. Geologic map of the core visitation area of the Craters of the Moon National Monument and Preserve, south-central Idaho (scale 1:24,000), with descriptions of 38 points of geologic interest [on accompanying poster]. National Park Service, Geological Society of America, Bureau of Land Management, and US Geological Survey. Prepared for Craters of the Moon National Monument and Preserve, Arco, Idaho.

Northwest Florida Water Management District (NWFWMD), 2021. Recommended Minimum Flows for Wakulla and Sally Ward Springs Wakulla County, Florida, Final, March 2021. Program Development Series 21-XX Havana, Florida, 164 p.

Northwest Florida Water Management District (NWFWMD), 2025. Recommended Minimum Flow for Middle Econfina Creek, including Gainer Spring, Williford Spring, and Sylvan Spring Groups Washington and Bay Counties, Florida, Final. Havana, Florida, 150 p.

Nutter, L.J., 1973. Hydrogeology of the Carbonate Rocks, Frederick and Hagerstown Valley, Maryland. Maryland Geological Survey Report of Investigations No. 19, 70 p.

Ogden, A.E., 1976. The hydrogeology of the central Monroe County karst, West Virginia (Doctoral dissertation). West Virginia University, Morgantown, WV. 265 p.

Ogden, A.E., Quick, R.A., Rothermel, S.R., and Lundsford, D.L., 1986. Hydrological and hydrochemical investigation of the Edwards aquifer in the San Marcos area, Hays County, Texas: San Marcos, Tex., Edwards Aquifer Research and Data Center, 364 p.

Ohio Division of Geological Survey, 1999 (rev. 2002, 2006). Known and probable karst in Ohio. Ohio Department of Natural Resources, Division of Geological Survey Map EG-1, generalized page-size version with text, 2 p., scale 1:2,000,000.

Olcott, P.G., 1992. Ground Warter Atlas of the United States; Iowa, Michigan, Minnesota, Wisconsin, HA-730-J. https://pubs.usgs.gov/ha/ha730/ch_j/

Orchard, D.C., 1983. Relative to the Historic Gathering of Peyote in South Texas. La Tierra, Vol. 10, #4, pp. 40-42.

Orndorff, R.C. and Harlow, G.E., Jr., 2002. Field Trip Guide, Hydrogeologic framework of the Northern Shenandoah Valley carbonate aquifer system, in Kuniansky, Eve L., ed., U.S. Geological Survey Karst Interest Group Proceedings, Shepherdstown, W.Va., August 20–22, 2002: U.S. Geological Survey Water-Resources Investigations Report 02-4174, pp. 81–89.

Orndorff, R.C., Epstein, J.B., and McDowell, R.C., 2007. Geologic map of the Middletown quadrangle, Frederick, Shenandoah, and Warren Counties, Virginia, Geologic Quadrangle 1803 https://doi.org/10.3133/gq1803

Osborn, N.I., 2009. Arbuckle-Simpson Hydrology Study; Final Report to the U.S. Bureau of Reclamation. Oklahoma Water Resources Board, 42 p.

Otton, E.G., and Hilleary, J.T., 1985. Maryland springs—their physical, thermal, and chemical characteristics. Maryland Geological Survey Report of Investigations No. 42,

Paleontological Research Institution, 2021. Earth Science of the Southeastern United States, Topography of the Inland Basin. Earth@Home project. Available at https://earthathome.org/hoe/se/topography-ib/#valley-and-ridge

Pallis, T., Domber, S.E., Bousenberry, R., Filo, R., Walz, K.S., Henning, B., Caraballo, Y.A., and Wu, M., 2002. Springs of New Jersey. New Jersey Geological and Water Survey Open-File Report 21-3, Trenton, New Jersey, 276 p. Available at https://digitalcommons.montclair.edu/waterscience_reports/6

Palmer, A.N., 1968. The Survey of Blue Spring Cave Lawrence Co., Indiana. In: Eberly, W.R., Editor, Proceedings of the Indiana Academy of Sciences, Volume 77, 1967. Indianapolis, Indiana, pp. 245-249

Palmer, A.N., 1975. The origin of maze caves. National Speleological Society Bulletin, vol. 37, no. 3, p. 56-76.

Palmer, A.N., 1985. The Mammoth Cave region and Pennyroyal Plateau. In: Dougherty, P. H. (ed.), Caves and Karst of Kentucky, Kentucky Geological Survey Special Publication 12, Series XI, pp. 97–118.

Palmer, A.N., 1991, Origin and morphology of limestone caves: Geological Society of America Bulletin, v. 103, no. 1, pp. 1–21. [Also available at https://doi.org/ 10.1130/ 0016- 7606(1991)1032.3.CO;2.]

Palmer, A.N., 2007. Cave Geology. Cave Books, Trenton, NJ, 454p.

Palmer, A.N., and Palmer, M.V., 1993. Geology and origin of Mystery Cave, Forestville State Park, Minnesota. Interpretive Report. LCMR Mystery Cave Resources Evaluation. Department of Natural Resources, Forestville State Park, 92 p.

Palmer, A., and Palmer, M., 2023. Saratoga Springs, New York. Spring Survey. NIKAS (Nationally Important Springs). Karst Commission, International Association of Hydrogeologists.

Palmer, A.N., Rubin, P.A., Palmer, M.V., Engel, T.D., and Morgan, B., 2003. Karst of the Schoharie valley, New York, in New York State Geological Association, 75th annual meeting, September 12–14, 2003, Oneonta, N.Y.: New York State Geological Association field trip guidebook, pp. 141–176.

Palmer A.N., Taylor, P.M., and Terrell, L.A., 2017. Hypogene karst springs along the northeastern border of the Appalachian Plateau, New York state: in: Klimchouk A., Palmer. A.N., De Waele, J., Auler, A.S., Audra, P. (eds). Hypogene karst regions and caves of the world. Springer, pp. 709-719.

Panno, S.V., Weibel, C.P., and Li, W., 1997. Karst Regions of Illinois. Open File Series 1997-2, Illinois State Geological Survey, Champaign, Illinois, 42 p.

Panno, S.V., and Weibel, C.P., 1999. Groundwater quality in karst regions of Illinois: Sources of natural and man-made contaminants: Groundwater Protection Field Day Proceedings, Southern Illinois Groundwater Protection Committee, Waterloo, IL, May 14, 1999, p. 49–58.

Panno, S.V., Hackley, K.C., Hwang, H.H., and Kelly, W.R., 2001. Determination of the sources of nitrate contamination in karst springs using isotopic and chemical indica tors: Chemical Geology, v. 179, no. 1-4, p. 113–128.

Panno, S.V., Kelly, W.R., Weibel, C.P., Krapac, I.G., and Sargent, S.L., 2003. Water Quality and Agrichemical Loading in Two Groundwater Basins of Illinois' Sinkhole Plain. Environmental Geology 156, Department of Natural Resources, Illinois State Geological Survey, 36 p.

Panno, S.V., Greenberg, S.E., Weibel, C.P., and P.K. Gillespie, 2004a. Guide to the Illinois Caverns State Natural Area: Illinois State Geological Survey, Geoscience Education Series 19, 106 p.

Panno, S.V., and Kelly, W.R., 2004b. Nitrate and herbicide loading in two groundwater basins of Illinois' sinkhole plain. Journal of Hydrology, Volume 290, Issues 3–4, pp 229-242

Panno, S.V., D.E. Luman, and J.C. Angel, 2009b. Sinkhole density and distribution and density of Cahokia Quadrangle: Illinois State Geological Survey, Illinois Geologic Quadrangle Map, IGQ Cahokia-SD, 1:24,000.

Panno, S.V., Hackley, K.C., Kelly, W.R., and Luman, D.E., 2011. Illinois' Sinkhole Plain: Classic Karst Terrain of the Midwestern United States. Geological Field Trip Guidebook for the 12th Multidisciplinary Conference on Sinkholes and the Engineering & Environmental Impacts of Karst January 10–14, 2011 St. Louis, Missouri, USA. University of Illinois at Urbana-Champaign, Illinois State Geological Survey, Champaign, Illinois.

Panno, S.V., and Kelly, W., 2015. Driftless Area Karst of Northwestern Illinois and its Effects on Groundwater Quality. 63-74. 10.5038/9780991000951.1094.

Parkhurst, D.L., and Appelo, C.A.J., 1999. User's guide to PHREEQC (v. 2)—A computer program for speciation, reaction-path, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Water-Resources Investigations 99–4259, 312 p.

Pavlicek, D.J., 1996. Karst Hydrogeology and Hydrochemistry of the Cave Springs Basin Near Chattanooga, Tennessee. U.S. Geological Survey Water-Investigations Report 96-4248, 35 p.

Peek, H.M., 1951. Cessation of flow of Kissengen Spring in Polk County, Florida. In: Water Resource Studies, Florida Geological Survey Report of Investigations No. 7, Tallahassee, p. 73-82.

Pennsylvania Fish and Boat Commission, 2026. Class A Trout Waters. https://www.pa.gov/content/dam/copapwp-pagov/en/fishandboat/documents/fishing/all-about-fish/catch-pa-fish/trout/classa.pdf

Parizek, R.R., and Drew, L.J., 1966. Random drilling for water in carbonate rock—Proceedings of a symposium and short course on computers and operations research in mineral industries: University Park, Pa., Mineral Industries Experiment Station, v. 3, (Special Publication 2-65), The Pennsylvania State University, p. 1-22.

Pat Shanks III, W.C., Morgan, L.A., Gray, J.E., Manning, A.H., and Gremery-Hill, P.A., 2008. The Waters of Big Bend: Geochemical Variations, Ages, and Sources. In: Gray, J.E., and Page, W.R., eds., 2008, Geological,

geochemical, and geophysical studies by the U.S. Geological Survey in Big Bend National Park, Texas. U.S. Geological Survey Circular 1327, pp. 65-76.

Perry, T. G., and N. M. Smith, 1958. The Meramec-Chester and intra Chester boundaries and associated strata in Indiana : Indiana Geol. Survey Bull. 12, 110 p. 6 pis., 1 fig.

Peter, K.D., 1985. Availability and quality of water from the bedrock aquifers in the Rapid City area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 85-4022, 34 p.

Piper, A. M., 1932. Ground water in north-central Tennessee: U. S. Geol. Survey Water-Supply Paper 640, 238 p.

Pittman, C., 2014. Florida's vanishing springs. Tampa Bay Times.
https://www.tampabay.com/news/environment/water/floridas-vanishing-springs/1262988/

Plebuch, R.O., Faust, R.J., and Townsend, M.A., 1985. Potentiometric surface and water quality in the principal aquifer, Mississippian Plateaus Region, Kentucky. Water-Resources Investigations Report 84-4102, U.S. Geological Survey, Louisville, Kentucky. 45 p.

Pohl, E. R. 1936. Geologic investigations at Mammoth Cave, Kentucky: Am. Geophys. Union Trans., App. C, Hydrology, pp. 332-334.

Poindexter, O.F., 1935. A study of underground waters bearing on the source of Big Spring, Schoolcraft County, Michigan: Michigan Acad. Sci. Papers, v. 20, p. 477-483.

Poindexter, O.F., 1936. Sinkholes in the Indian Lake Region, Schoolcraft County, and other Michigan sinks: Michigan Acad. Sci. Papers, v. 21, pp. 439-444.

Pool, D.R., Blasch, K.W., Callegary, J.B., Leake, S.A., and Graser, L.F., 2011. Regional groundwater-flow model of the Redwall-Muav, Coconino, and alluvial basin aquifer systems of northern and central Arizona: U.S. Geological Survey Scientific Investigations Report 2010-5180, v. 1.1, 101 p

Powell, R.L., 1963. Alluviated Cave Springs of South-Central Indiana. In: Laubengayer, R.A., Editor, Proceedings of the Indiana Academy of Sciences, Volume 72, 1962. Indianapolis, Indiana, pp. 182-189

Puckette, J., Halihan, T., and Faith, J., 2009. Characterization of the Arbuckle-Simpson Aquifer. Oklahoma State University, Boone Pickens School of Geology, Stillwater, OK, 53 p.

Putnam, L.D., and Long, A.J., 2007. Analysis of ground-water flow in the Madison aquifer using fluorescent dyes injected in Spring Creek and Rapid Creek near Rapid City, South Dakota, 2003-2004. U.S. Geological Survey Scientific Investigations Report 2007-5137, 29 p.

Putnam, L.D., Sawyer, J.F., Rahn, P.H., and Anderson, M.T., 2010. Karst and Fractured Aquifer Hydrogeology in the Rapid City Area, South Dakota. In: Terry, M.P., Duke, E.F., and Tielke, J.A., editors, Geologic Field Trips in the Black Hills Region, South Dakota. South Dakota School of Mines and Technology Bulletin No. 21, Rapid City, South Dakota, pp. 36-48

Prudic, D.E., Harrill, J.R., and Burbey, T.J., 1995. Conceptual evaluation of regional ground-water flow in the carbonate rock province of the Great Basin, Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409–D, 102 p.

Prudic, D.E, Sweetkind, D.S., Jackson, T.L., Dotson, K.E., Plume, R.W., Hatch, C.E., and Halford, K.J. 2015. Evaluating connection of aquifers to springs and streams, Great Basin National Park and vicinity, Nevada: U.S. Geological Survey Professional Paper 1819, 188 p., http://dx.doi.org/10.3133/pp1819

Quinlan, J.F., Ewers, R.O., Ray, J.A., Powell, R.L., and Krothe, N.C., 1983. Ground-water hydrology and geomorphology of the Mammoth Cave region, Kentucky, and of the Mitchell Plain, Indiana (Field Trip 7), in Shaver, R.H., and Sunderman, J.A., eds., Field trips in midwestern geology: Geological Society of America, Indiana Geological Survey and Department of Geology, Indiana University, v. 2, pp. 1–85, 48 figs.

Rahn, P.H., and Gries, J.P., 1973. Large springs in the Black Hills, South Dakota and Wyoming. South Dakota Geological Survey, Report of Investigations No. 107, 46 p.

Rawling, G.C., 2009. Geology of the Ruidoso Area, Lincoln and Otero Counties, New Mexico, New Mexico Bureau of Geology and Mineral Resources, Open-File Report OFR-507, scale 1:24,000.

Ray, J.A., O'dell, P.W., and Moody, J.R., 2005. Identification and Prioritization of Karst Groundwater Basins in Kentucky for Targeting Resources for Nonpoint Source Pollution Prevention and Abatement. Groundwater Branch Kentucky Division of Water, Frankfort, Kentucky, 136 p. + Appendices

Ray, J.A., Moody, J.R., Blair, R.J., Currens, J.C., and Paylor, R.L., 2009. Mapped Karst Groundwater Basins in the Tell City and Part of the Jasper 30x60 Minute Quadrangles. Map and Chart 196, Series XII, Kentucky Geological Survey, Lexington, KY

Reddy, J.E., Kappel, W.M., and Root, J.C., 2020. Data for statewide assessment of New York's karst aquifers with an inventory of closed-depression and focused-recharge features: U.S. Geological Survey data release, https://doi.org/10.5066/P9HGN5IJ.

Reese, S.O., 2016. Nippenose Valley, Clinton and Lycoming Counties. Outstanding Geologic Feature of Pennsylvania. Pennsylvania Geological Survey, Trail of Geology16-083.0

Reese, S.O., and Kochanov, W.E., 2005. Density of mapped karst features in Centre County, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Map 70, scale 1:300,000. [Available online.]

Reeves, F., 1932. Thermal springs of Virginia. Virginia Geological Survey Bulletin 36, 56 p.

Reimondo, A., 2020. Canyon Mine; Why No Uranium Mine Is "Safe" for the Grand Canyon Region. Grand Canyon Trust, Flagstaff, Arizona, 35 p. Available at https://www.grandcanyontrust.org/Canyon-Mine-Report

Revels, T.J., 2016. Upon the Face of the Waters. A Brief History of Wakulla Springs. Sentry Press, Tallahassee, Florida, 128 p.

Richins, J.G., 2020. Analytical modeling of conductivity chemographs of Byrds Mill Spring. Oklahoma State University, Stillwater, Oklahoma. Master's Thesis, Oklahoma State University, 63 p.

Richins, J., Halihan, T., and Igwebuike, N., 2026. Influence of a hydraulic siphon on groundwater mixing: Byrds Mill Spring, Oklahoma. Journal of Hydrology: Regional Studies, Volume 64, April 2026, https://doi.org/10.1016/j.ejrh.2026.103274

Roble, D., Brown, T., and Koch, L.M., 1997. Lee County Cave Isopod (*Lirceus usdagalun*) Recovery Plan. U.S. Fish and Wildlife Service, Hadley, Massachusetts, 39 p.

Robson, S.G., and Banta, E.R., 1995. Ground Water Atlas of the United States, Arizona, Colorado, New Mexico, Utah. HA 730-C. U.S. Geological Survey, https://pubs.usgs.gov/ha/ha730/ch_c/

Roddy, D. (editor). 2018. Coldwater Fish Production, Statewide Hatchery Report 2018. Report No. 19-01. Tennessee Wildlife Resources Agency, Nashville, TN.

Rosenau, J.C., Faullmer, G.L., Hendry, C.W., Jr., and Hull, R.W., 1977. Springs of Florida. Florida Geological Survey Bulletin 31 Revised, Tallahassee, 461 p.

Rubey, W., Oriel, S., and Tracey, J.I., 1980. Geologic map and structure sections of the Cokeville 30-minute Quadrangle, Lincoln and Sublette counties Wyoming. U.S. Geological Survey IMAP 1129, 1 map : col. ;88 x 66 cm. +13 structure sections on sheet 125 x 80 cm., https://doi.org/10.3133/i1129.

Rugel, K., Jackson, C.R., Romeis, J.J., Golladay, S.W., Hicks, D.W., and Dowd, J.F. 2012. Effects of irrigation withdrawals on streamflows in a karst environment: Lower Flint River Basin, Georgia, USA. Hydrol. Process. 26, 523–534.

Ruhl, J.F., and Wolf, R.J., 1983. Hydrogeologic and water-quality characteristics of the Upper Carbonate aquifer, Southeast Minnesota: U.S. Geological Survey Water-Resources Investigations Report 84-4150, 2 Plates: 40.33 x 34.85 inches and 40.28 x 34.87 inches, https://doi.org/10.3133/wri844150.

Ryder, P.D., 1996. Ground Water Atlas od the United States, Oklahoma, Texas, HA 730-E. U.S. Geological Survey. Available online at https://pubs.usgs.gov/ha/ha730/ch_e/index.html

Sando, W. J., 1974, Ancient solution phenomena in the Madison Limestone (Mississippian) of north-central Wyoming. U.S. Geological Survey Journal of Research, v. 2, no. 2, p. 133-141.

Sasowsky, I.D. and White, W.B., 1994. The role of stress release fracturing in the development of cavernous porosity in carbonate aquifers: Water Resources Research, v. 30, no. 12, pp. 3523-3530.

Schroeder, A.H., and Hastings, F., 1958. Montezuma Castle National Monument, Arizona. National Park Service Historical Handbook Series No. 27, Washington, D.C. (reprint 1961), 39 p.

Schumacher, J.G., 2008. Water-quality trends and effects of lead and zinc mining on Upper Logan Creek and Blue Spring, southeastern Missouri, 1925–2006, 42 p., in Kleeschulte, M.J., ed., 2008. Hydrologic investigations concerning lead mining areas in southeastern Missouri: U.S. Geological Survey Scientific Investigations Report 2008–5140, 238 p.

Schwartz, B.F., 2003. Preliminary Analysis of an Igneous Intrusion and Metamorphic Xenoliths found in Highland County, Virginia. Unpublished Report, Radford, Va., Geology Department Radford University, p. 17.

Schwartz, B.F., and Doctor, D.H., 2009. Geomorphic and hydrogeologic evolution in the Burnsville Cove, Virginia, USA: New evidence and perspectives. Proceedings of 15th International Congress of Speleology, Kerrville, TX, International Union of Speleology, pp. 984-990

Schwartz, B.F., Doctor, D.H., Swezey, C.S., and Piatak, N.M., 2008. Geologic and Geomorphic Controls on Karst Conduit Development and Drainage Rearrangement in Burnsville Cove, Bath County, Virginia. Proceedings of Geological Society of America Annual Meeting, Houston, Texas, p. 194

Schwartz, G.M., 1936. The geology of the Minneapolis-St. Paul metropolitan area. Minnesota Geological Survey Bulletin 27, The University of Minnesota Press, Minneapolis 267 p. illus., diagrs. 24 cm.

Schwartz, G.M., and Thiel, G.A., 1954. Minnesota's Rocks and Waters; A Geological Story. Minnesota Geological Survey Bulletin 37, The University of Minnesota Press, Minneapolis, 366 p. Retrieved from the University Digital Conservancy, https://hdl.handle.net/11299/57024.

Scott, T.M., 1992. A Geological Overview of Florida. Open File Report No. 50, Florida Geological Survey, Tallahassee, 78 p.

Scott, T.M., Means, G.H., Means, R.C., and Meegan, R.P., 2002. First Magnitude Springs of Florida. Open File Report No. 85, Florida Geological Survey, Tallahassee, 138 p.

Scott, T.M., Means, G.H., Meegan, R.P., Means, R.C., Upchurch, S.B., Copeland, J.J., Roberts, T., and Willet, A., 2004. Springs of Florida. Bulletin No. 66. Florida Geological Survey, Tallahassee, 658 p. Available at http://publicfiles.dep.state.fl.us/FGS/FGS_Publications/B/B66.pdf

Scott, T.M., 1991. The Geology of the Santa Fe River Basin, Central-northern Peninsular Florida, Hydrogeology of the Western Santa Fe River Basin, Field Trip Guidebook No. 32, Southeastern Geological Society.

Seaber, P.R., Brahana, J.V., and Hollyday, E.F., 1988. Region 20-Appalachian Plateaus and Valley and Ridge, in Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: Geological Society of America, The Geology of North America, v. 0-2, pp. 189-200.

Shanks, P., 2021. An outlier of Yellowstone's thermal areas: the travertine of Mammoth Hot Springs. Caldera Chronicles, Yellowstone Volcano Observatory, United States Geological Survey, July 11, 2021.

https://www.usgs.gov/observatories/yvo/news/outlier-yellowstones-thermal-areas-travertine-mammoth-hot-springs

Sharp, J.M. Jr., Boghici, R., and Uliana, M., 2003. Groundwater systems feeding the springs of West Texas. In: Garrett GP, Allan NL, editors. Aquatic fauna of the Northern Chihuahuan Desert, Special Publications, Museum of Texas Tech University 46, p. 1-11.

Sherrill, J., 1989. Stemler Cave-Sparrow Spring drainage basin, in Southern Illinois MVOR 89 Decca Mecca: Mississippi Valley-Ozark Region: National Speleological Society, Windy City Grotto, p. 15–16.

Sherzer, W.H. 1900. Geological survey of Michigan lower peninsula 1896-1900, Vol VII, Part I, Geological report on Monroe County, Michigan. Geological Survey of Michigan, Lansing, MI, Robert Smith Printing Co., State Printers and Binders.

Sheets, R.A. and Simonson, L.A., 2006. Compilation of regional ground-water divides for principal aquifers corresponding to the Great Lakes Basin, United States: U.S. Geological Survey Scientific Investigations Report 2006–5102, 23 p.

Simmons, R., 2003. Attack of the killer trout! Diving Mt. Solon's Sapphire Pool/Blue Hole Spring: Virginia Cellars, v. 8, no. 1, p. 10.

Simpson, L.C., and Florea, L.J., 2009. The Cumberland Plateau of Kentucky: Caves and Karst of America, 2009, pp. 70-79.

Sinclair, W.C., 1959. Reconnaissance of the ground-water resources of Schoolcraft County, Michigan. Michigan Geological Survey Progress Report Number 22, 84 p.

Slade, R.M., Jr., Dorsey, M.E., and Stewart, L.M., 1986. Hydrogeology and water quality of the Edwards Aquifer in the Austin area, Texas. U.S. Geological Survey Water-Resources Investigations Report 86-4113, Austin, TX.

Slaughter, T.H., 1962. The Ground-Water Resources, in: The Water Resources of Allegany and Washington Counties. Maryland Geological Survey, Bulletin 24, pp. 1-243.

Sloto, R.A., Cecil, L.D., and Senior, L.A., 1991. Hydrogeology and ground-water in the carbonate rocks of the Little Lehigh Creek Basin, Lehigh County, Pennsylvania. U.S. Geological Survey Water-Resources Investigations Report 90-4076, Lemoyne, PA, 83 p.

Smart, P.L., Beddows, P.A., Coke, J., Doerr, S., Smith, S., and Whitaker, F.F., 2006. Cave development on the Caribbean coast of the Yucatan Peninsula, Quintana Roo, Mexico, in Harmon, R.S., and Wicks, C., eds., Perspectives on karst geomorphology, hydrology, and geochemistry—A tribute volume to Derek C. Ford and William B. White: Geological Society of America Special Paper 404, p. 105–128, doi: 10.1130/2006.2404(10).

Smith, B.A., Hauwert, N.M., and Hunt, B.B., 2009. Fieldtrip guidebook: Recharge and discharge features of the Edwards and Trinity aquifers, Central Texas. Fieldtrip conducted by the Barton Springs/Edwards Aquifer Conservation District (BS/EACD) for Karst Horizons 15th International Congress of Speleology, Kerrville, Texas

Smith, B., Hunt, B., and Johnson, S., 2012. Revisiting the Hydrologic Divide Between the San Antonio and Barton Springs Segments of the Edwards Aquifer: Insights from Recent Studies: Gulf Coast Association of Geological Societies Journal, Vol. 1, p. 55-68.

Society for Mining, Metallurgy & Exploration, 2026. The Role of Arsenic in the Mining Industry. Accessed August 20, 2026. https://www.smenet.org/What-We-Do/Technical-Briefings/The-Role-of-Arsenic-in-the-Mining-Industry

Sorey, M.L., Colvard, E.M., Nimick, D.A., Shields, R.R., and Thordsen, J.J., 1991. Hydrologic investigations in the Corwin Springs known geothermal resources area and adjacent parts of Yellowstone National Park, chap. G of Sorey, M.L., ed., Effects of potential geothermal development in the Corwin Springs known geothermal resources area, Montana, on the thermal features of Yellowstone National Park: U.S. Geological Survey Water-Resources Investigations Report 91–4052,p. G1–G41. https://pubs.er.usgs.gov/publication/wri914052.

Southwest Florida Water Management District (SWFWMD), 2008. Rainbow River Technical Summary. Brooksville, Florida. 25 p.

Southwest Florida Water Management District (SWFWMD), 2017a. Homosassa River Surface Water Improvement Management (SWIM) Plan; A Comprehensive Conservation and Management Plan, August 2017, 122 p.

Southwest Florida Water Management District (SWFWMD), 2017c. West-Central Florida's Aquifers. Florida's Great Unseen Water Resources. 8 p.

Southworth, S., 1996. The Martic fault in Maryland and its tectonic setting in the central Appalachians. In Brezinski, D.K., and Reger, J.P., eds, Studies in Maryland Geology, in commemoration of the centennial of the Maryland Geological Survey. Maryland Geological Survey Special Publication No. 3, p. 205-221.

Spangler, L.E., 2019. Ricks Spring, in Milligan, M., Biek, R.F., Inkenbrandt, P., and Nielsen, P., editors, Utah Geosites, Utah Geological Association Publication 48, 6 p., https://doi.org/10.31711/geosites.v1i1.64.

Spangler, L.E., 2012. Hydrogeology of the Mammoth Spring groundwater basin and vicinity, Markagunt Plateau, Garfield, Iron, and Kane Counties, Utah: U.S. Geological Survey Scientific Investigations Report 2012–5199, 56 p.

Spangler, L.E., 2001. Delineation of Recharge Areas for Karst Springs in Logan Canyon, Bear River Range, Northern Utah. In Eve L. Kuniansky, editor, 2001, U.S. Geological Survey Karst Interest Group Proceedings, Water-Resources Investigations Report 01-4011, pp. 186-193

Spechler, R.M., and Schiffer, D.M., 1995. Springs of Florida. U.S. Geological Survey Fact Sheet FS-151-95

Speece, J. H., 1973. Alexander Caverns, Mifflin County, Pennsylvania. Self-published / American Spelean History Association, 28 p.

Staubitz, W.W., and Miller, T.S., 1987. Geology and hydrology of the Onondaga aquifer in eastern Erie County, New York; with emphasis on ground-water-level declines since 1982. U.S. Geological Survey Water-Resources Investigations Report 86–4317, 50 p., 4 pls. [Also available at https://doi.org/ 10.3133/ wri864317.]

Stein, R.B., 1962. Sandusky River Basin (Lower Portion) Underground Water Resources. Ohio Department of Natural Resources, Division of Water, Columbus, Ohio,

Stevanovic, Z., and Milanovic, P. (eds.), 2005. Water Resources and Environmental Problems in Karst—Cvijić 2005, Proceedings of International Symposium, University of Belgrade, Institute of Hydrogeology, Belgrade.

Stevanovic, Z., and Kresic, N., 2024. Wakulla Springs, United States of America. Geoheritage Sites, International Commission on Geoheritage, International Union of Geological Sciences, https://iugs-geoheritage.org/geoheritage_sites/wakulla-spring/

Stephenson, L.W., and Veatch, J.O., 1915. Underground waters of the Coastal Plain of Georgia, and a discussion of The quality of the waters, by R.B. Dole: U.S. Geological Survey Water-Supply Paper 341, 539 p.

Stone, R.W., Barnsley, E.R., Hickok, W.O., 4th, and Mohr, C.E., 1932. Pennsylvania caves, 2nd ed., rev., Pennsylvania Geological Survey, 4th ser., General Geology Report 3, 143 p.

Stringfield, V.T., 1966. Artesian Water in Tertiary Limestone in the Southeastern States. U.S. Geological Survey Professional Paper 517, 226 p.

Sun, C.P., Criner, J.H., and Poole, J.L., 1963. Large Springs of East Tennessee. U.S. Geological Survey Water-Supply Paper 1766. Washington, D.C., 52 p.

Susquehanna River Basin Commission, 2011. Morrison Cove Water Resources Availability Study. Executive Summary. Publication 277a, December 31, 2011. Full report is available on SRBC's web site at http://www.srbc.net/pubinfo/techdocs/ Publication_277/techreport277.htm

Sutton, J., 2020. Wakulla Spring—Spring Creek Spring Group Analysis. Interactions with Spring Creek and long-term trends in discharge. PowerPoint Presentation, Northwest Florida Water Management District. http://wakullaspringsalliance.org/wp-content/uploads/2016/11/Wakulla-Discharge-Analysis_WSA.Sutton.09-25-20.pdf

Swain, L.A., Mesko, T.O., and Hollyday, E.F., 2004. Summary of the hydrogeology of the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces in the Eastern United States. U.S. Geological Survey Professional Paper 1422-A, 23 p.

Swain, E.D., Lohmann, M.A., and Goodwin, C.R., 2019. The hydrologic system of the south Florida peninsula—Development and application of the Biscayne and Southern Everglades Coastal Transport (BISECT) model: U.S. Geological Survey Scientific Investigations Report 2019–5045, 114 p., https://doi.org/10.3133/sir20195045.

Swanson, S.K., Graham, G.E., and Hart, D.J., 2019. An inventory of springs in Wisconsin. Wisconsin Geological and Natural History Survey Bulletin 113, 24 p.

Swezey, C.S., 2008. Regional Stratigraphy and Petroleum Systems of the Michigan Basin, North America. U.S. Geological Survey Scientific Investigation Map 2978

Swezey, C.S, Haynes, J.T, Lambert, R.A., White, W.B., Lucas, P.C., and Garrity, C.P., 2015. The Geology of Burnsville Cove, Bath and Highland Counties, Virginia. Chapter 16 in W.B. White (ed.), The Caves of Burnsville Cove, Virginia, Cave and Karst Systems of the World, DOI 10.1007/978-3-319-14391-0_16

Swezey, C.S., Haynes, J.T., Lucas, P.C., and Lambert, R.A., 2017. Geologic controls on cave development in Burnsville Cove, Bath and Highland Counties, Virginia. In: Bailey, C.M., Shelley, J. (Eds), From the Blue Ridge to the Beach. Geological Field Excursions across Virginia. The Geological Society of America Field Guide 47, pp. 89-123

Sweetkind, D.S., Cederberg, J.R., Masbruch, M.D., and Buto, S.G., 2012. Chapter B: Hydrogeologic Framework. In: Heilweil, V.M., and Brooks, L.E., eds., 2011. Conceptual model of the Great Basin carbonate and alluvial aquifer system: U.S. Geological Survey Scientific Investigations Report, pp. 15-50. Available at http://pubs.usgs.gov/sir/2010/5193/

Swinnerton, A.C, 1932. Origin of limestone caverns: Geol. Soc. America Bull. 43:663-694

Taylor, T.U., 1904. The water powers of Texas, U.S.G.S. Water Supply and Irrigation Paper No. 105, 116 p.

Taylor, C.J., and Nelson Jr., H.L., 2008. compilation of provisional karst geospatial data for the Interior Low Plateaus physiographic region, central United States: U.S. Geological Survey Data Series 339, 26 p.

Teichert, J.A., 1958. Geology of the Southern Stansbury Range, Tooele County, Utah. Master's Thesis, University of Utah, Salt Lake City, Utah, 79 p.

Tennant, H., and Neilson, B.T., 2024. Karst Springs in Utah. Civil and Environmental Engineering, Utah Water Research Laboratory, Utah State University, Logan, Utah, in preparation.

Tennessee Cave Survey (TCS), 2020, Cave records and data tables: Tennessee Cave Survey web page, accessed February 5, 2020, at http://www.subworks.com/tcs/

The Maryland Office of Planning, 1998. Managing Maryland's Growth, Models and Guidelines, Sensitive Areas, Volume II. 94 p. The Maryland Economic Growth, Resource Protection, and Planning Act of 1992, The Maryland Department of Natural Resources, 94 p.

The Nature Conservancy, 1993. A Natural Areas Inventory of Lycoming County, Pennsylvania. Science office of The Nature Conservancy, Middletown, Pennsylvania. 2000 update includes the original 1992 full report followed by the 1998 update addendum. Available at https://www.naturalheritage.state.pa.us/cnai_pdfs/lycoming%20county%20nai%201993_2000.pdf

Thiros, S.A., Paul, A.P., Bexfield, L.M., and Anning, D.W., 2014. The quality of our Nation's waters—Water quality in basin-fill aquifers of the southwestern United States: Arizona, California, Colorado, Nevada, New Mexico, and Utah, 1993–2009: U.S. Geological Survey Circular 1358, 113 p.

Thornberry-Ehrlich, T. L. 2012. Stones River National Battlefield: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2012/566. National Park Service, Fort Collins, Colorado.

Thrailkill, J., and Gouzie, D.R., 1984. Discharge and Travel Time Determinations in the Royal Spring Groundwater Basin, Kentucky. KWRRI Research Reports. 54. https://uknowledge.uky.edu/kwrri_reports/54

Thornberry-Ehrlich, T. L. 2025. Appalachian National Scenic Trail: Geologic and soil resources inventory summary. Unpublished report. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2314058.

Thornbury, W.D., 1950. Glacial sluiceways and lacustrine plains of southern Indiana: Indiana Div. Geology Bull. 4, 21 p.

Tihansky, A.B., 1999. Sinkholes, West-Central Florida, A link between surface water and ground water. In: Galloway, D., Jones D., and S.E. Ingebritsen, eds., Land Subsidence in the United States. U.S. Geological Survey Circular 1182, pp. 121-140

Tilousi, C., 2019. Testimony for Support for HR 1373 and permanent protection of the Grand Canyon watershed from mining: Washington D.C., National Parks, Forests, and Public Lands Subcommittee Legislative Hearing, Natural Resources Committee. https://www.congress.gov/116/meeting/house/109586/witnesses/HHRG-116-II10-Wstate-TilousiC-20190605.pdf

Tilousi, E., 2022. The Havasupai Tribe letter of opposition regarding the Pinyon Plain Mine individual aquifer protection permit: Havasupai Tribal Council, accessed November 9, 2023, at https: //www.biol ogicaldive rsity.org/ programs/ public_ lands/ pdfs/ Havasupai- Letter- to- ADEQ- Opposing- Pinyon- Plain- Mine- 2022- 05- 31.pdf.

Tilousi, C., and Hinck, J.E., 2024. Expanded conceptual risk framework for uranium mining in Grand Canyon watershed—Inclusion of the Havasupai Tribe perspective (ver. 1.1, February 2024): U.S. Geological Survey Open-File Report 2023–1092, 25 p., https://doi.org/ 10.3133/ ofr20231092.

Tobin, B.D., and Weary, D.J., 2004. Digital Engineering Aspects of Karst Map: A GIS Version of Davies and Others (1984). U.S. Geological Survey Open-File Report 2004-1352,

Toeppen-Sprigg, B., 2023. Guide to the Silver Springs State Park. Friends of Silver Springs State Park, Ocala, Florida, 166 p.

Tooker, E.W., 1983. Variations in structural style and correlation of thrust plates in the Sevier foreland thrust belt, Great Salt Lake area, Utah. Geological Society of America Memoir 157, pp. 61-73.

Torak, L.J., and Painter, J.A., 2006. Geohydrology of the lower Apalachicola–Chattahoochee–Flint River Basin, southwestern Georgia, northwestern Florida, and southeastern Alabama: U.S. Geological Survey Scientific Investigations Report 2006-5070, 80 p

Tucker, W. M., 1911. Water power of Indiana: Indiana Dept. Geology and Nat. Resources, Ann. Rept. 35, pp. 30-38

Tudek, J.K. Jr., 2010. Further hydrogeologic investigations in the Davis Spring drainage Further hydrogeologic investigations in the Davis Spring drainage basin, Greenbrier County, West Virginia. Master Thesis, West Virginia University, Morgantown, West Virginia, 157 p. https://doi.org/10.33915/etd.2982

Tweet, J. S., V. L. Santucci, and I. Ashton. 2022. Katahdin Woods and Waters National Monument: Paleontological resource inventory (public version). Natural Resource Report NPS/KAWW/NRR— 2022/2472. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/2294810

Unterreiner, G.A., 2006. Hydrogeology of Harrison County, Indiana. Indiana Department of Natural Resources, Division of Water, Bulletin 40, 35 p.

Upchurch, S.B., 2014). Hydrogeology of the swallet and resurgence system in the Alapaha River, Hamilton County, Florida. Lawn A (comp.), Karst hydrogeology of the upper Suwannee River basin, Alapaha River area, Hamilton County, Florida. Tallahassee, Southeastern Geol Soc Field Trip Guidebook, 63, pp. 30-45.

U.S. Department of the Interior [DOI], 2012. Record of decision, Northern Arizona withdrawal, Mohave and Coconino Counties, Arizona.

U.S Environmental Protection Agency Region III, 2018. Statement of Basis, Former Cerro Metals Products Plant, 2022 Axemann Road, Bellefonte, Pennsylvania, ERPA ID NO. PAD086733540. Prepared by Office of Pennsylvania Remediation, Land and Chemical Division.

U.S Environmental Protection Agency Region, 2026. Superfund Site: Anniston Army Depot (Southeast Industrial Area) Anniston, AL, Cleanup Activities. (accessed September22, 2026) https://cumulis.epa.gov/supercpad/SiteProfiles/index.cfm?fuseaction=second.cleanup&id=0400443

U.S. Fish and Wildlife Service, 1992. Endangered and threatened wildlife and plants: Determination of endangered status for the Lee County cave isopod (*Lirceus usdagalun*).Federal Register 57 (225): 54722-54726.

USGS, 2013. Origin and Characteristics of Discharge at San Marcos Springs, South-Central Texas. USGS Fact Sheet 2013–3080

USGS, 2014. Appalachians Plateaus Groundwater Availability. Info Sheet 2014.

USGS, 2020. Groundwater Quality in the Biscayne Aquifer, Florida. Fact Sheet 2019–3056.

USGS, 2021. Karst Aquifers. https://www.usgs.gov/mission-areas/water-resources/science/karst-aquifers

USGS (United State Geological Survey), 2024. Karst Aquifers: Basin and Range and Bear River Range Carbonate Aquifers. https://www.usgs.gov/mission-areas/water-resources/science/karst-aquifers-basin-and-range-and-bear-river-range-carbonate

Van Couvering, J.A., 1962. Characteristics of large springs in Kentucky. Kentucky Geological Survey, Series 10, Information Circular 8, 37 p.

Vance, M.M., 2014. Montezuma Well, Overview. Fact Sheet prepared for National Park Service / Southwest Learning. Available at https://swvirtualmuseum.nau.edu/docs/factsheets/Well_Prehist_Overview_032614.pdf

Vandike, J.E., 1992. The hydrogeology of the Bennett Spring area, Laclede, Dallas, Webster, and Wright Counties, Missouri. Missouri Department of Natural Resources, Division of Geology and Land Survey, Water Resources Report Number 38, 112 p., 44 figs., 26 tbls, 14 photos.

Vandike, J.E., 1992a. A hydrologic analysis of the Ozark aquifer in the Rolla area, Missouri. Missouri Department of Natural Resources, Division of Geology and Land Survey, Water Resources Report 41, 93 p., accessed May 1, 2015, at http://dnr.mo.gov/pubs/WR41.pdf.

Vandike, J.E., 1994. Estimated recharge areas of springs sampled in the Ozark Plateau in conjunction with the National Water Quality Assessment. Missouri Department of Natural Resources, Division of Geology and Land Survey, Water Resources Report, 64 p.

Vandike, J.E., 1996. The Hydrology of Maramec Spring. Missouri Department of Natural Resources, Division of Geology and Land Survey, Water Resources Report Number 55, 104 p., 33 figs., 8 tbls., 1 app.

Vandike, J.E., 1997. Guidebook to the geology and hydrology of the Current River Basin: Missouri Division of Geology and Land Survey, 27 p. unpublished manuscript

Vardy, R., 2011. Characterization of Urban Impact on Water Quality of Karst Springs in Eureka Springs. In Kuniansky, E.L., 2011, U.S. Geological Survey Karst Interest Group Proceedings, Fayetteville, Arkansas, April

26-29, 2011, U.S. Geological Survey Scientific Investigations Report 2011-5031, pp. 44-53. Online copies of the proceedings are available at: http://water.usgs.gov/ogw/karst/

Vance, M., 2014. Montezuma Well Overview. Southwestlearning.org, 4 p.
Available at https://swvirtualmuseum.nau.edu/docs/factsheets/Well_Prehist_Overview_032614.pdf

Ver Ploeg, A.J., Larsen, M.C., Taboga, K.G., 2016. Characterization of evaporite karst features in the southern Laramie Basin, Wyoming: Wyoming State Geological Survey Report of Investigations No. 70, 34 p.

Ver Steeg, K., and Yunck, G., 1932. The Blue Hole of Castalia. The Ohio Journal of Science, 32(5), 425–435.

Vineyard, J.D. and Feder, G.L., 1974 (reprinted in 1982). Springs of Missouri. Water Resources Report No. 29, Missouri Department of Natural Resources, Division of Geology and Land Survey, 212 p.

Waltham, T., 2016. Control the drainage: the gospel accorded to sinkholes. Quarterly Journal of Engineering Geology and Hydrogeology. doi:10.1144/qjegh2015-088

Watson, M., 2015. Touring the Springs of Florida. A Guide to the States' Best Springs. Falcon Guides, Guilfgord, CT, and Helena, MT, 247 p.

Way, J.H., 1986. Your Guide to the Geology of the Kings Gap Area, Cumberland County, Pennsylvania. Pennsylvania Geological Survey 4th Series, Environmental Geology Report 8, 31 p.

WDNR (Wisconsin Department of Natural Resources), 2015. Paradise Spring self-guided nature trail (pamphlet). PUB-PR-228, Wisconsin Department of Natural Resources, Bureau of Parks and Recreation, 11 p.

Webb, G.E., 1994. Paleokarst, paleosol, and rocky-shore deposits at the Mississippian-Pennsylvanian unconformity, northwestern Arkansas. Geological Society of America Bulletin, v. 106, no. 5, p. 634–648

Weary, D.R., 2008. Preliminary map of potentially karstic carbonate rocks in the central and southern Appalachian states. U.S. Geological Survey Open-File Report 2008–1154, 1 pl. [Also available at https://doi.org/ 10.3133/ ofr20081154.]

Weary, D.J., Doctor, D.H., and Orndorff, R.C., 2022. Geologic maps of the Stephenson and Winchester quadrangles, Frederick and Clarke Counties, Virginia, and Inwood and White Hall quadrangles, Berkeley and Jefferson Counties, West Virginia: U.S. Geological Survey Scientific Investigations Map 3487. Winchester quadrangle, sheet 2 of 4, scale 1:24,000, https://doi.org/10.3133/sim3487.

Weibel, C.P., and Panno S.V., 1997. Karst terrains and carbon ate bedrock of Illinois. Illinois State Geological Survey, Illinois Map Series 8, 1:500,000 Scale.

Welch, A.H., Bright, D.J., and Knochenmus, L.A., 2007, Water resources of the Basin and Range carbonate-rock aquifer sys tem, White Pine County, Nevada, and adjacent areas in Nevada and Utah: U.S. Geological Survey Scientific Investigations Report 2007-5261, 96 p.

Werner, E., 1972. Development of solution features in the Cloverlick Valley, Pocahontas County. WV Speleol. Survey, Bull. 2, 53p.

Westerman, D.A., Gillip, J.A., Richards, J.M., Hays, P.D., Clark, B.R., 2016. Altitudes and thicknesses of hydrogeologic units of the Ozark Plateaus aquifer system in Arkansas, Kansas, Missouri, and Oklahoma: U.S. Geological Survey Scientific Investigations Report 2016–5130, 32 p., http://dx.doi.org/10.3133/sir20165130

Western Michigan University, 1981. Hydrogeologic atlas of Michigan-Hydrogeology for underground injection control in Michigan. Kalamazoo, MI, 35 pls.

Whalen, P.J., 1994. Source aquifers for Cascade Springs, Hot Springs, and Beaver Creek Springs in the southern Black Hills of South Dakota: Rapid City, South Dakota School of Mines and Technology, unpublished M. S. thesis, 299 p.

White, D.E., Fournier, R.O., Muffler, L.J.P., and Truesdell, A.H., 1975. Physical results of research drilling in thermal areas of Yellowstone National Park, Wyoming: U.S. Geological Survey Professional Paper 892, 70 p. https://pubs.er.usgs.gov/publication/pp892

White, E.L., 1977, Sustained flow in small Appalachian watersheds underlain by carbonate rocks: J. of Hydrol., v. 32, 71-86.

White, W.B., 1988. Geomorphology and hydrology of karst terrains. Oxford University Press, New York, 464 p.

White, W.B., 2015. Geology of the Butler Cave–Sinking Creek System. In White, W.B., ed., The Caves of Burnsville Cove, Virginia. Springer International Publishing, Cham, Switzerland, pp. 365–384

White, W.B. (ed.), 2018. Caves and Karst of the Greenbrier Valley in West Virginia. Springer International Publishing AG, Cham, Switzerland, 411 p.

White, W.N., Gale, H.S., and Nye, S.S., 1941. Geology and ground-water resources of the Balmorhea area, western Texas. U.S. Geological Survey Water Supply Paper 849-C, Contributions to the hydrology of the United States, 1940, pp. 83-146.

Whitlock, J., Wood, K., Centofanti, M., Jones, B., Sweeney, K., and Lambert, R., 2025. Dye Trace Analysis of the Thermal Karst System of Warm Springs, Virginia. Virginia Geological Research Symposium 2025 Poster Presentations, 7p

Wilkinson, R.W., 2000. Water resources of Bellmont Park, Coconino County, Arizona: Flagstaff, Ariz., Northern Arizona University, M.S. thesis, 198 p.

Williams, L.J., and Kuniansky, E.L., 2016. Revised Hydrogeologic Framework of the Floridan Aquifer System in Florida and Parts of Georgia, Alabama, and South Carolina. (ver. 1.1, March 2016). U.S. Geological Survey Professional Paper 1807, 140 p., 23 pls., http://dx.doi.org/10.3133/pp1807.

Wilson, J.T., 2012. Water-quality assessment of the Cambrian-Ordovician aquifer system in the northern Midwest, United States: U.S. Geological Survey Scientific Investigations Report 2011–5229, 154 p.

Wilson, J.L., and Guan, H., 2004. Mountain-block hydrology and mountain-front recharge, in Phillips, F.M., Hogan, J., and Scanlon, B., editors, Groundwater recharge in a desert environment—the southwestern United States: Washington, D.C., American Geophysical Union, p. 113–137.

Wilson, M., 2020. Water authority gives up 30-year proposal to pump groundwater to Las Vegas: Las Vegas Sun Newspaper, on line: https://lasvegassun.com/news/2020/may/21/water-authority-gives-up-30-year-proposal-to-pump/, accessed August 5, 2026.

Wilson, W.L., and Skiles, W.C., 1989. Partial reclassification of first-magnitude springs in Florida: in: Beck, B. F., (ed.), The proceedings of the 3rd multidisciplinary conference on sinkholes and the environmental impacts of karst: Rotterdam, A. A. Balkema, pp. 65-72.

Wilson, W.L. and Skiles, W.C., 1988. Aquifer Characterization by Quantitative Dye Tracing at Ginnie Spring, Northern Florida, The Proceedings of the Second Conference on Environmental Problems in Karst Terranes and Their Solutions, The Association of Groundwater Scientists and Engineers, Nashville, Tennessee.

Wilson, J.R., 1979. Glaciokarst in the Bear River Range, Utah. National Speleological Society Bulletin, v. 41, pp. 89–94.

Wilson, M.T., and Thomas, H.E., 1964. Hydrology and hydrogeology of Navajo Lake, Kane County, Utah: U. S. Geol. Survey Prof. Paper 417-C, C-1 to C26.

Witte, R.W., and Monteverde, D.H., 2006. Karst in the Delaware Water Gap National Recreation Area. Unearthing New Jersey, Vol. 2, No. 1, Winter 2006, New Jersey Geological Survey, pp. 1-6

Witte, R.W., and Monteverde, D.H., 2012. Geologic History of New Jersey's Valley and Ridge Physiographic Province. New Jersey Geological and Water Survey Information Circular, 8 p.

Wynn, S., Borisova, T., and Hodges, A., 2014. Economic Value of the Services Provided by Florida Springs and Other Water Bodies: A Summary of Existing Studies. University of Florida, Food & Economic Resource Department. Gainesville, FL.

Wolfe, W.K., Haugh, C.J., Webbers, S., and Diehl, T.H., 1997. Preliminary Conceptual Models of the Occurrence, Fate, and Transport of Chlorinated Solvents in Karst Regions of Tennessee. U.S. Geological Survey Water-Resources Investigations Report 97-4097, 80 p.

Wolter, F., McKay, R.M., Liu, H., Bounk, M.J., and Libra, R.D., 2011. Geologic Mapping for Water Quality Projects in the Upper Iowa River Watershed. Iowa Geological and Water Survey Technical Information Series 54 C.

Wood, C.R., 1980. Summary groundwater resources of Centre County, Pennsylvania. Pennsylvania Geological Survey, 4th ser., Water Resource Report 48, 60 p. + Map Scale 1:100,000

Work, P.M., 1934. Some Observations on the Thermal Springs of the Southeastern Black Hills of South Dakota. Proceedings of the Iowa Academy of Science, 41(1), 203-208.

Young, J.R., 1978. The puzzle of Saratoga – An old solution with a new twist, Empire State Geogram, v. 14, n. 2, pp. 17-31

Zachariasen, G., 2016. Caves and karst of the Niagara Escarpment: A caver's perspective**.** Geoscience Wisconsin, Vol. 22, Part 5, Wisconsin Geological and Natural History Survey, published online Wisconsin's Niagara Escarpment (Geoscience Wisconsin, vol. 22)

Zappittelo, S.J., and Johns, D.A., 2018. 2017 Groundwater Tracing in the Barton Springs Edwards Aquifer: Onion Creek and Little Bear Creek. City of Austin Watershed Protection Department Short Report SR-18-10. 29 p.

Zappitello, S.J., Johns, D.A., and Hunt, B.B., 2019. Summary of Groundwater Tracing in the Barton Springs Edwards Aquifer from 1996 to 2017, DR-19-04. City of Austin, Watershed Protection. Available at https://bseacd.org/2019/12/summary-of-groundwater-tracing-in-the-barton-springs-edwards-aquifer-from-1996-to-2017/

Zerga, B., 2024. Karst topography: Formation, processes, characteristics, landforms, degradation and restoration: A systematic review. Watershed Ecology and the Environment, Volume 6, pp. 252-269

Zimny, M., 2015. History of the Hot Springs bath houses and holistic health retreats. South Dakota Public Broadcasting Radio. https://www.sdpb.org/rural-life-and-history/History-of-the-Hot-Springs-bath-houses-and-holistic-health-retreats





GROUNDWATER
ACADEMY