Karst Hydrogeology and the Potential for Environmental Risks Resulting From the Route 9 Sewer Project, Jefferson County, West Virginia

Submitted to

Dr. Chrissy Wimer
Jefferson County Foundation, Inc.
PO Box 460
Ranson, WV 25438

by

Chris Groves, PhD, PG
Western Kentucky University
Bowling Green, KY 42101

July 14, 2020

Table of Contents

page

List of Figures

1. Introduction

Much of Jefferson County, West Virginia has well-developed *karst* landscapes and groundwater flow systems, or aquifers, developed on especially soluble types of bedrock such as limestone and dolomite. Features such as caves, sinkholes, underground rivers, and large springs are common. Although karst landscapes can be beautiful and fascinating, both above and below ground, they often present challenging conditions for urban development with potential for soil subsidence and/or bedrock collapse into underground voids and flooding of closed depressions, or sinkholes, even in areas that may be miles from the nearest surface stream. Water resource development is often impacted by the fact that much the water falling as rain quickly disappears underground into these areas of highly permeable "Swiss Cheese" bedrock and flows underground in underground fractures and caves rather than across the surface as in most landscapes. Perhaps the most widespread environmental problem in karst regions is that when water quickly and easily infiltrates the ground it can carry contaminants from agricultural, urban, and other types of land use. As a result, karst groundwater is typically highly vulnerable to contamination.

Even with these problems continually increasing populations in many karst-rich areas of the US means that avoiding development in karst landscapes is *not* an option, and research continues into best management practices and other strategies for safe, productive, and sustainable development and land use in these challenging areas (see, for example, Veni et al., 2001; Chesapeake Stormwater Network, 2009; Hunter, 2013). Development and application of a relevant legal and regulatory framework has made some progress (Groves, 2018), but is still hindered by limited understanding of how these complex landscape/aquifer systems function.

Eastern regions of West Virginia have spectacularly developed karst landscapes, and for the most part these are rural areas dominated by agricultural land use. Jefferson County, in West Virginia's panhandle, about 86% of which is underlain by karst-forming carbonate rocks (Kovar et al. 1991), is an exception because of its close proximity to Washington DC. While the overall population of West Virginia dropped by 3.3% between 2010 and 2019, Jefferson County's grew by 6.8% over the same period (US Census Bureau 2020).

On August 31, 2018, an application for registration was approved by the West Virginia Department of Environmental Protection (DEP) under the 2012 Construction Stormwater General Permit (WV/NPDES Water Pollution Control Permit No. WV 0115924) for construction of the "Rt. 9 Sewer Project" between Charles Town and Kearneysville (Figure 1). A series of actions and decisions followed that has led to continued uncertainty in the regulatory status of the project, although even so, construction began in early 2020.

The route of the project lies on carbonate rocks with well-developed karst landscapes and aquifers. The text of a subsequent 2019 Stormwater General Permit more explicitly recognizes methods for mitigation of karst hazards consistent with those described by the Chesapeake Stormwater Network (2009). And regulatory uncertainties notwithstanding, I am unaware of a technically adequate site investigation to inform planning to address amelioration of karst hazards, including the potential for environmental damage either through construction or ongoing operation of the project.

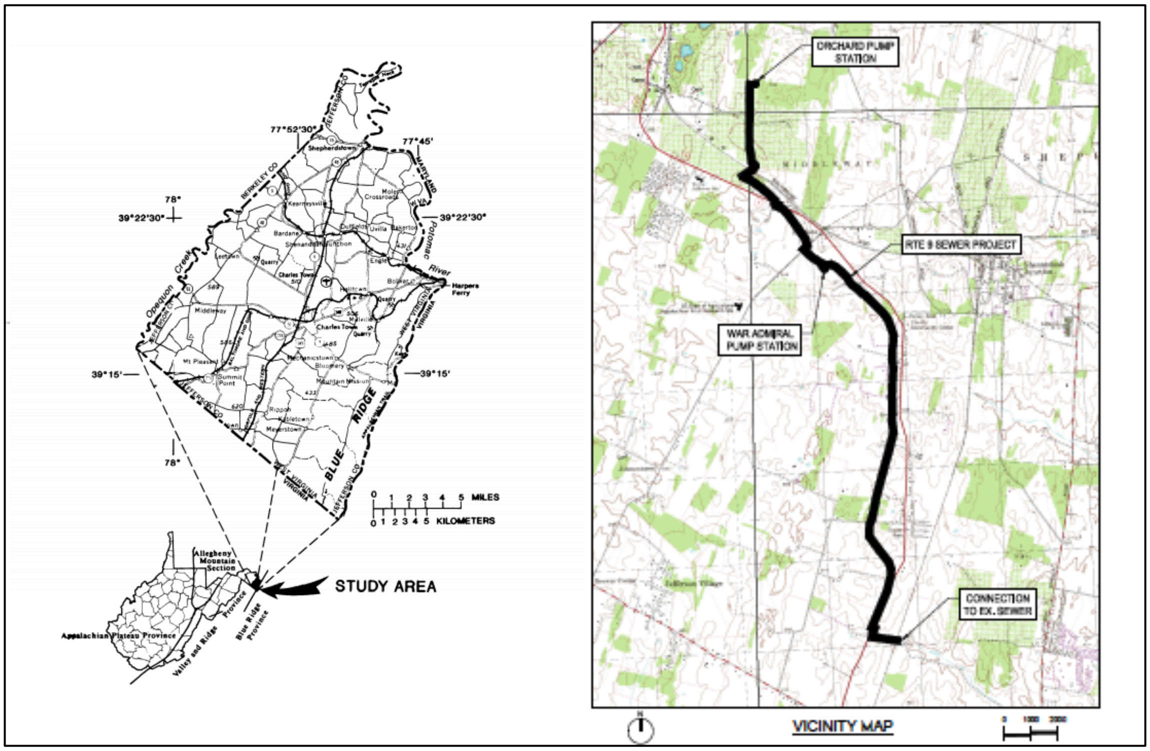

Figure 1. Map of the Route 9 Sewer Project, Jefferson County West Virginia. County location is shown at left (sewer route source 6/1/2018 Permit Application drawings and notes, Hatch Chester, location map on left from Kozar et al. 1991).

The purpose of this report is to evaluate risks associated with construction within the karst area impacted by the Route 9 Sewer project, based on a review of existing literature. It is limited to technical (hydrogeology) considerations, as I make no claim to have expertise in either legal matters nor detailed familiarity with West Virginia's environmental regulations.

Although I have been hired by the Jefferson County Foundation, Inc. to undertake this evaluation, my task as an expert in this case is to objectively describe the risks as a result of hydrogeologic conditions along the Sewer Project site and the potential for associated environmental impacts. I have not manipulated information to have it reflect any pre-determined outcome, and my contributions to this process, and all of my professional activities, reflect that philosophy. My comments are accurate and truthful to the best of my experience and abilities.

For full disclosure, when possible I often make site field visits to conduct such geological reviews but for a variety of reasons in this case a site visit was not feasible. However, based on the fact that the landscape and hydrology of Jefferson County are particularly well-studied (e.g. Beiber 1961; Davies 1965; Cardwell et al. 1968; Hobba et al 1971; Hatfield and Warner 1973; Trainer and Watkins, 1975; Hobba 1981; Jones and Deike 1981; McColloch, 1986; Dean et al. 1990; Kozar et al. 1991; Jones 1991, 1997; Kozar et al. 2008; Evaldi et al. 2009; Doctor and Doctor, 2012; Maloy and Carter, 2012) I am confident that the information in this report is complete and accurate for the intended scope and purpose.

This report has been written for a non-technical audience, but in such reports it is sometimes unavoidable to use vocabulary that may be unfamiliar to some readers. For this reason, I have compiled a glossary of terms at the end of this report. Any terms that I have included are underlined at the first location where they appear in the text.

2. Professional Qualifications

I am a licensed Professional Geologist in Kentucky, Tennessee and Virginia (West Virginia does not have a Professional Geology registration) with more than 35 years of professional experience in the study of surface and underground water in a wide variety of environments throughout the world, with an emphasis on karst landscapes and aquifers. I earned a BS degree in Geology (1984), and an MS degree in Geography (1987) from Western Kentucky University. In 1993 I received a PhD in Environmental Sciences from the University of Virginia (Geology track) with an emphasis in hydrogeology, geochemistry, and geomorphology and where my PhD dissertation *Early Development of Karst Systems* led to a series of papers in the highly-ranked journal *Water Resources Research* that have now collectively been cited over 400 times. I currently serve as University Distinguished Professor of Hydrogeology at Western Kentucky University, where I have written or coauthored 38 peer-reviewed journal papers or book chapters, 1 book, over 50 conference proceedings, technical reports, book reviews, or fieldtrip guides, as well as given more that 175 scientific presentations at international, national, regional scientific conferences or university seminars. I have published research in the leading professional water-related, peer-reviewed journals including *Journal of Hydrology*, *Groundwater*, *Water Resources Research,* and *Hydrogeology Journal* and leading geomorphology journals including *Earth Surface Processes and Landforms* and *Geomorphology.* I have served as an Associate Editor for the *Journal of Hydrology* and *Hydrogeology Journal*. I have been responsible for karst-related research, service or analysis under contracts, grants or other cooperative efforts for federal agencies that include the Bureau of Land Management, National Park Service, US Department of Agriculture, US Environmental Protection Agency, US Forest Service, US Department of Energy, US Army Corps of Engineers, the US Agency for International Development, and the US Department of State.

Since 1995 I have been active with participation in and leadership of five karst-focused United Nations scientific programs within the United Nations Educational Scientific and Cultural Organization (UNESCO) International Geoscience Program as well as serving as an invited member of the Karst Commission of the International Association of Hydrogeologists. In these efforts and other research projects I have undertaken karst-focused fieldwork in 25 countries. In 2017 I travelled to Beijing's Great Hall of the People where China's President Xi Jinping personally presented me with the International Cooperation in Science and Technology Award of the People's Republic of China, that country's highest award for foreign scientists, for "great contributions to China's hydrogeology and karst geology fields."

I have long been interested in, and studied, cave and karst landscapes of West Virginia, and indeed my first trip into a wild (not developed for tourists) cave in the state was an expedition as a teenager to Sinnet Cave in Pendleton County in 1973. My first visit into a Jefferson County cave was the following year.

3. Karst Landscapes of Jefferson County

3.1 Background on Karst Landscapes and Aquifers

Karst landscapes and aquifers are formed in especially soluble rocks in which features from the resulting dissolution of bedrock such as caves, springs, underground rivers and sinkholes are common (Figure 2). Most commonly, karst features form in carbonate rocks such as limestone and dolomite. Typical, characteristic behaviors of such landscapes result in a variety of potential environmental challenges including soil subsidence or bedrock collapse into underlying cavities, flooding of sinkholes, and arguably the most widespread problem, that groundwater in karst areas is typically very vulnerable to contamination. The bedrock in well-developed karst flow systems is typically so permeable, that is, it transmits water so readily, that water and contaminants can infiltrate the ground and move quickly through the subsurface. Because of this, it is common that surface drainage is often lacking in karst landscapes (Figure 2)—even in climates where there is plenty of rainfall, instead of flowing across the surface as is typically the case in other landscapes, often water quickly infiltrates and flows underground through solutionally-enlarged fractures and caves, eventually to emerge at springs. Whereas groundwater in most geologic settings flows very slowly through small spaces between soil or rock grains or through fine fractures, sometimes moving only a few feet in a year, karst groundwater can travel many feet, or sometimes even miles, through networks of underground streams in a single day. Whatever dissolved substances or suspended sediments are in the water can also be carried along into and through the subsurface, so that karst groundwater systems, including those in West Virginia, are among the most vulnerable type of aquifer to contamination (e.g. White, 1988; Goldscheider, 2006; Ford and Williams , 2007; Croskrey and Groves, 2008; Maloy and Carter, 2012).

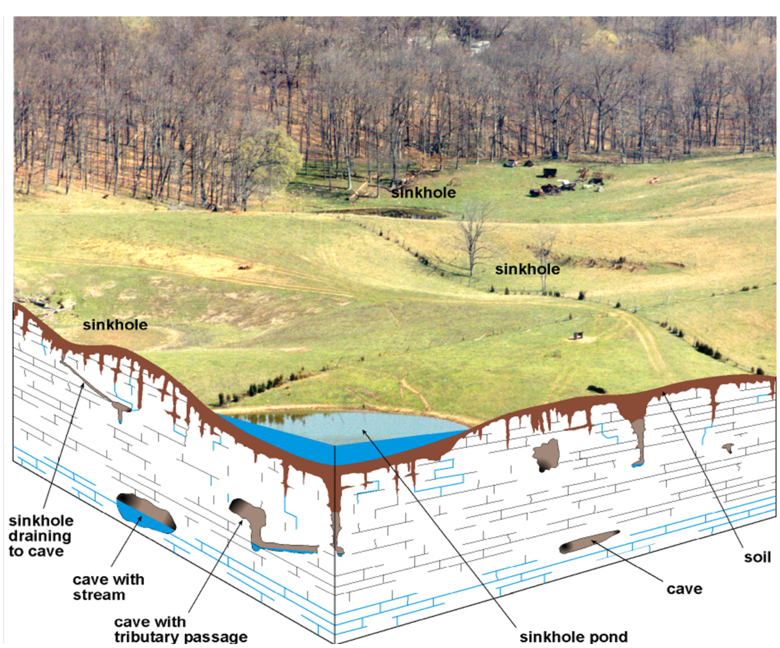

Figure 2. Block diagram showing common surface and subsurface karst features such as caves, sinkholes, and underground streams (Kentucky Geological Survey, 2015). There is a lack of surface drainage except for a pond filling a plugged sinkhole. Note this diagrammatic illustration shows flat-lying rocks while the geologic structure in Jefferson County is more complicated. That does not, however, impact the illustrations of common karst features representative of the area discussed in the report.

3.2 Geology and Hydrogeology of Jefferson County

The landscapes and related properties of groundwater movement and characteristics in Jefferson County depend on an interplay of bedrock types and climate, and as the precipitation is more or less evenly distributed across the county (Hobba et al. 1972) the rock type forms the most important influence.

The geologic maps in Figure 2 show the distributions of rock types that would be exposed if all of the overlying materials—soil, trees, towns, roads, etc.—were somehow washed away down to bare bedrock. The different colored regions in Figure 2 are geologic *formations*, or homogeneous regions of bedrock that have been subdivided and named by geologists. The rocks that underlie the project route are the karst-forming Conococheague (O€c) and Stonehenge (Os) Limestones. An important aspect of understanding the geology of Jefferson County concerns the obvious linear "grain" of the formations running roughly north-south, which results from the fact that in the deep geologic past forces of continental movement created continental-scale interactions between what would become Africa and North America, with a slow but relentless compression from the east and west that deformed the rock layers into folds as if a carpet was being pushed from both sides. Millions of years later these rocks have been worn down, with more resistant rocks forming linear ridges and the soluble and/or less resistant rocks like limestone forming valleys like the Shenandoah Valley, also called the Great Valley, where the Charles Town lies.

Altogether, relatively soluble karst-forming limestone and dolomite carbonate rocks cover about 86% of the county (Figure 3, purple central region) (Meloy and Carter, 2012), and a more generalized geologic map can show three relatively homogeneous <u>hydrogeologic regions</u> of the county. Lumping together the carbonate rock formations shows a region covering much of the county called the Folded Carbonate Central Unit, where karst landscapes and aquifers are common. Both the Western Faulted Unit and the Eastern Metamorphic Unit are formed from rocks other than limestone and dolomite that form non-karst landscapes.

Because of variation in rock properties, different parts of the Folded Carbonate Central Unit have different intensities of karst development, that is to say, how dissolution has modified the permeability of the underlying bedrock and made it easier for water to flow underground. The whole region, however, has been influenced by these processes to some degree. This is apparent by examining a map of the county's sinkholes (Figures 5), the most apparent surface expression of karst landscape forming processes. Sinkholes are closed depressions in karst landscapes (Figure 6) that form from a variety of mechanisms but share in common that the soil and/or rock that was formerly at the location where the depression is now has moved downwards into solutionally-enlarged voids in the bedrock below. The sinkholes shown in Figure 5 are ones that were present at the time that the survey was done—these are actively forming landscapes and new sinkholes can form as time goes on. These can either be from a slow, gradual process of soil subsidence into the subsurface, or sudden, catastrophic collapses of soil and/or rock. Soil washing down into the aquifer below, in turn, becomes a groundwater contaminant.

Another important surface expression of karst hydrogeology concerns the presence, or lack, of integrated surface drainage. Where karst is especially well-developed rainwater landing on the ground and can quickly infiltrate into the soil and bedrock below, so that surface flow may be totally lacking. A map of surface flow in Jefferson County (Figure 7) shows that surface flow in the part of the county in the vicinity of the Route 9 Sewer Project is almost wholly lacking. This is where karst is especially well developed with a relatively high level of rock dissolution in the

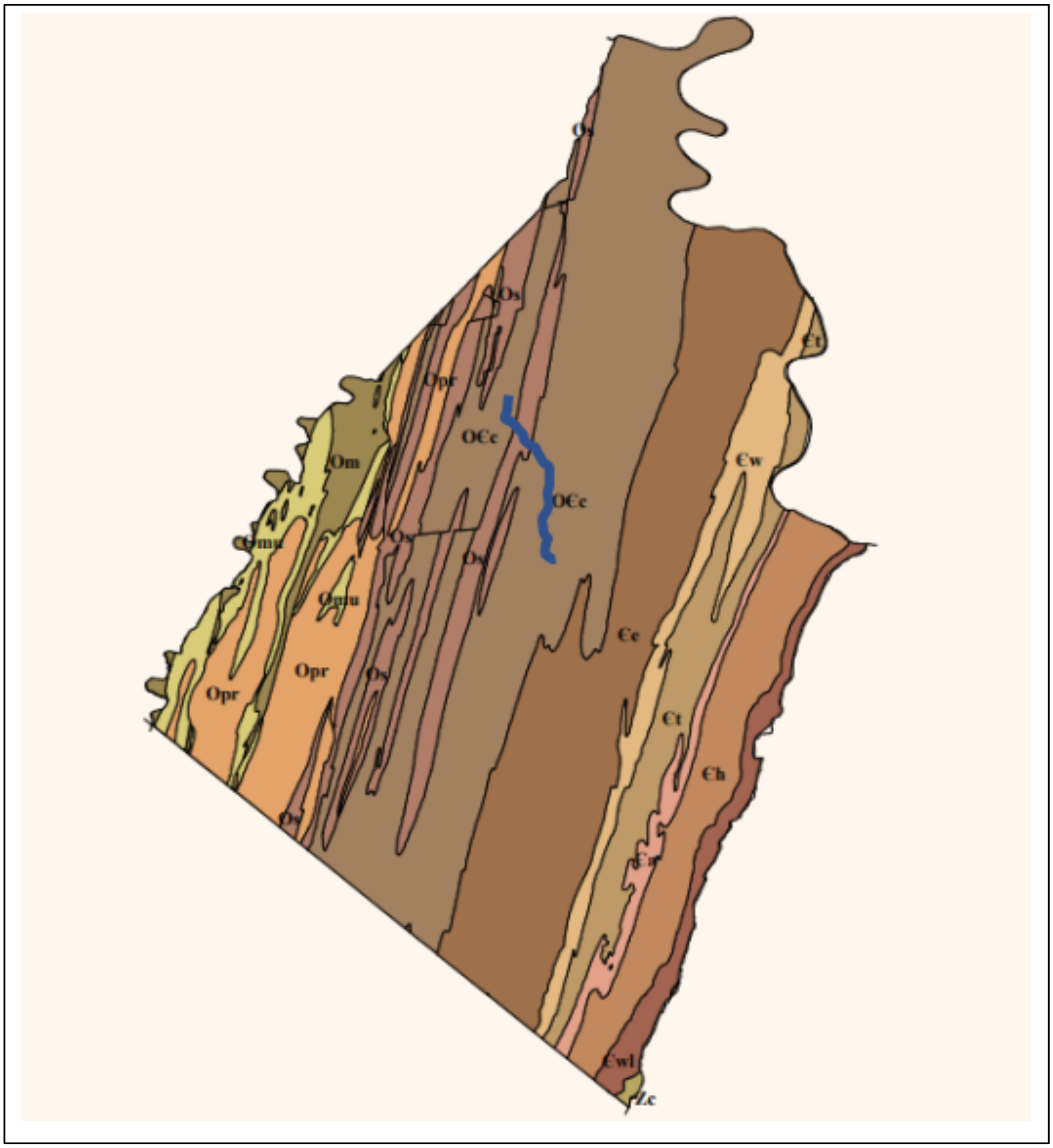

Figure 3. Geologic map of Jefferson County as described in the text, with approximate route of the sewer project. The Conococheague (designated as O€c) and Stonehenge (Os) Limestones, both of which are karst-forming rocks, underlie the project route. The linear trend of the geologic formation reflects the folded geometry of the Appalachian Mountains. This map has been modified (approximate sewer route added) from Meloy and Carter (2012).

subsurface and so water infiltrates easily. Although the entire central part of the county is developed on soluble carbonate rock, the detailed interaction between surface and underground flow in any particular area are a complex interplay of rock properties (how pure the limestone is, for example) and structure, soil, and in some cases urban modifications to the landscape. Clearly, it can be seen the surface flow is almost wholly lacking in the vicinity of the Route 9 ground surface.

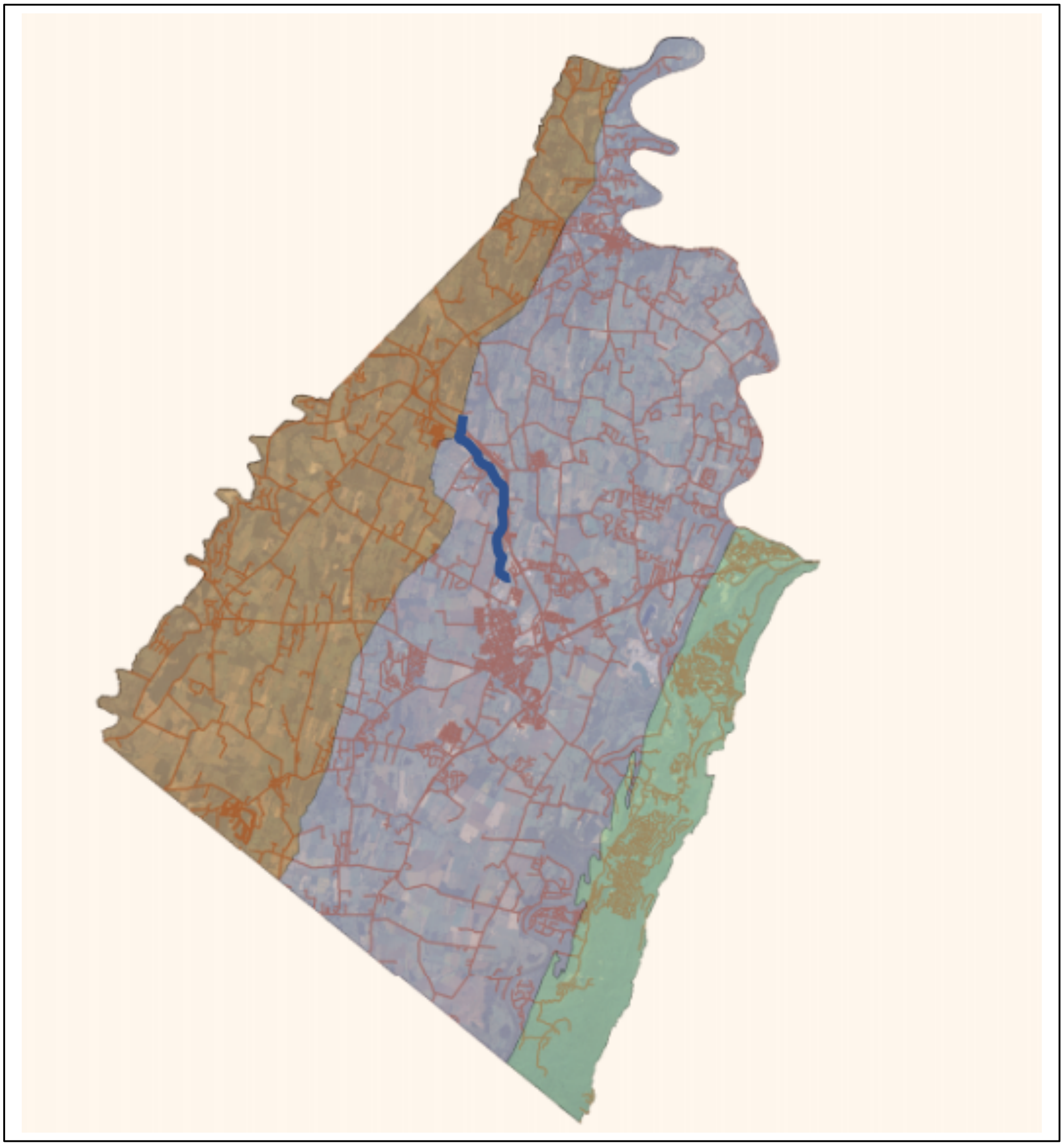

Figure 4. More generalized geologic map showing the central (purple) region of carbonate rocks where karst landscapes have formed, and with the eastern and western part of the county underlain by non-karst forming rocks. This map has been modified (approximate sewer route added) from Meloy and Carter (2012).

3.3 Risks Associated With Sewer Line Construction in the Route 9 Project Area

Taken together, each of these observations confirms that the area of the Route 9 Sewer Project traverses a well-developed karst landscape and aquifer. Hazards associated with construction and urban development in well-developed karst areas are well known (e.g. Goldscheider, 2006; Ford and Williams, 2007; Palmer 2007; De Waele et al. 2011; Hunter, 2013) and there are strategies to minimize or ameliorate these impacts, even if challenging (e.g. Parise and Gunn,

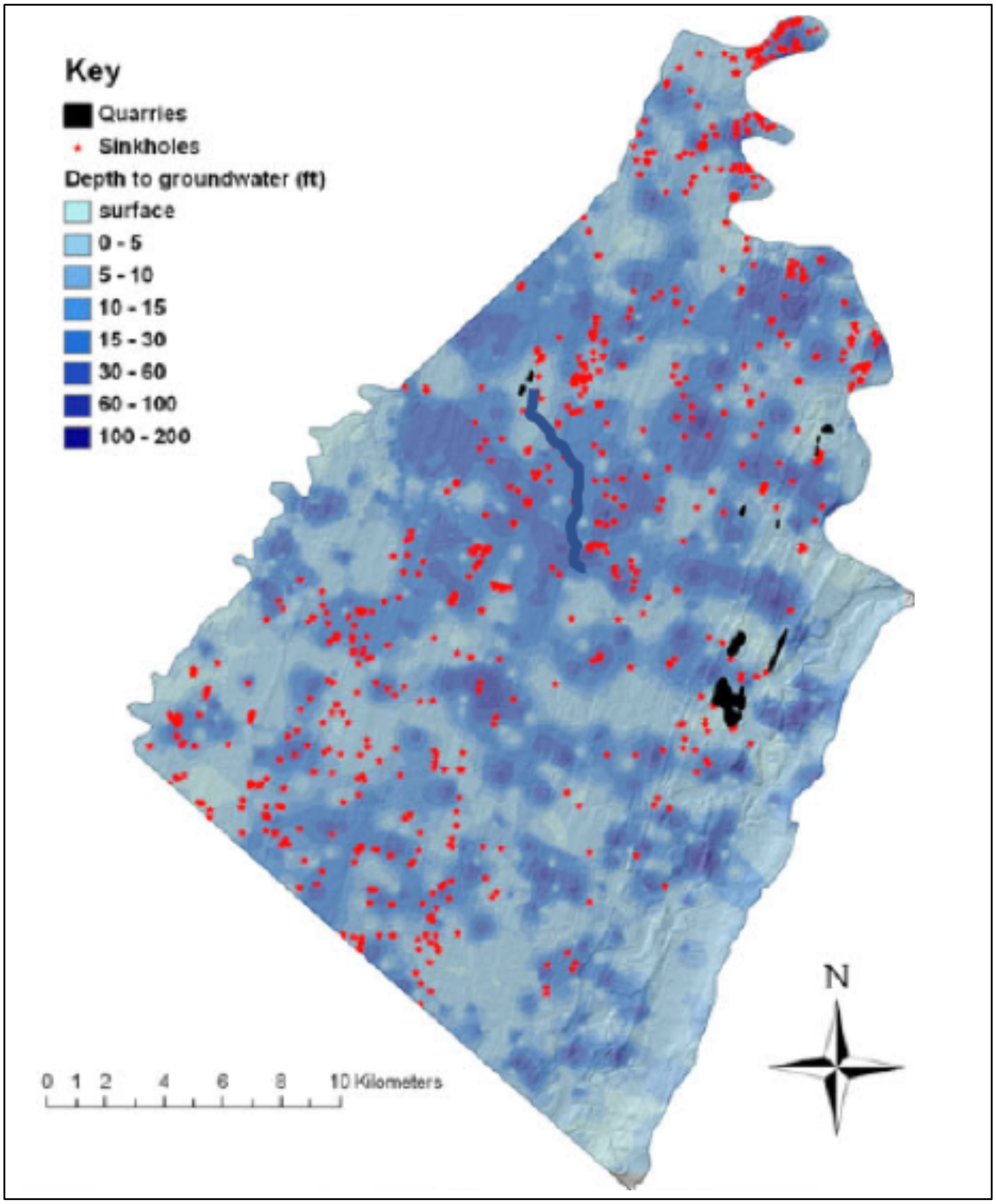

Figure 5. Sinkhole distribution for Jefferson County. Modified (approximate project route added) from Doctor and Doctor, 2012. Sinkhole formation requires void space in the subsurface which has resulted from carbonate rock dissolution, and so the locations of sinkholes in closely match the location of the Central Folded Carbonate Unit hydrogeologic region (Figure 5). This indicates very well-developed conditions of karst evolution.

2007; Veni et al., 2001; Chesapeake Stormwater Network, 2009). These are related to the of bedrock dissolution in the subsurface which has created networks of solutionally-enlarged fractures, conduits and caves into which water, sediments, and other contaminants can flow. In the area of the Route 9 Sewer Project, it is likely that the two most relevant, potential karst hazards are contamination of groundwater (and potentially, contaminants can eventually reach surface water resources where those underground flows return to the surface) and development

Figure 6. Closed depression or sinkhole in the Central Folded Carbonate Unit hydrogeologic area of northern Jefferson County (WVDEP 2018) in the general vicinity of the northern end of the Route 9 Sewer Project. All of the rock and soil where the depression is now has moved down through fractures into solutionally-enlarged voids in the bedrock beneath. This sediment is, in turn, a contaminant in groundwater (photographer not named).

of sinkholes. These are related, in that sinkholes form by soil and sometimes rock moving down into the subsurface, and the soil itself can become a contaminant. In addition, a particular synergy can exist in karst areas of underground sewer lines and other pipelines carrying liquids. Loss of structural support where soil washes down into the bedrock, even if gradual, can put stress on pipes, potentially to the point where they leak or rupture. Not only can this create a concentrated source of groundwater contamination from sewage or other contaminants, but the liquid infiltrating the ground can indeed enhance additional transport of sediment, further making the collapse problem worse in a positive feedback loop. Once these contaminants reach the groundwater, they can travel quickly.

Describing the hydrogeology of Jefferson County, Kozar (1991, p. 2) wrote that

> Most of the county is underlain by carbonate rocks, most of which have undergone some degree of karstification. Ground-water recharge in the karst areas occurs directly through sinkholes, caves, streams, and by direct infiltration of precipitation. Ground-water velocities can be rapid, and contaminants entering the ground-water-flow system can affect a large part of the aquifer in a short period of time.

Figure 7. Surface drainage (light blue lines) in Jefferson County. It can be clearly seen that surface flow in the part of the county in the vicinity of the Route 9 Sewer Project is almost wholly lacking. This map has been modified (approximate sewer route added) from Meloy and Carter (2012).

Meloy and Carter (2012, p. 3) noted that

> Karst features are common in carbonate rocks of the Great Valley. Formed by dissolution of calcium carbonate rock by slightly acidic rainwater, these features are apt to form along preexisting structural features in limestone that serve as conduits for groundwater. Karst can lead to accelerated rates of groundwater flow, and to increased sensitivity to groundwater contamination due to rapid influx of surface water.

They continued (p. 19):

> Because of its relatively high solubility, the carbonate bedrock in Jefferson County has undergone varying degrees of karstification. Dissolution channels formed within the bedrock of karst terrain can provide conditions for preferential flow pathways, enabling rapid spread of groundwater contamination. Such conditions can have the potential to quickly transport contaminants from surface or near surface conditions to the underlying bedrock aquifer. In most geologic settings, thick soil overburden acts as nature's water purification system, filtering recharge water as it percolates downward to the water table; but in karst areas this natural filter can sometimes be bypassed by preferential rapid flow paths and drainage features such as sinkholes. Consequently, the carbonate aquifer underlying the Central Unit area is susceptible to groundwater contamination from non-point sources.

4. Where Would Groundwater Contamination Go?

One the principal challenges of understanding the behavior of water and contamination in karst areas is that in contrast to normal typical (non-karst) hydrogeologic environments, where much of the flow is in surface streams and rivers that can be seen on maps, once water and contaminants get into the ground they are hidden from view. They will flow underground and eventually reemerge back to the surface at springs, typically then flowing into the nearest <u>base level stream</u> or river, in this case the Shenandoah or Potomac Rivers. But there is not a direct way to know what the directions of the underground flow will be, what spring it will flow to.

There are several methods for determining this information, and the most powerful of these is called <u>fluorescent dye tracing</u>. In this work, certain types of environmentally safe dyes are injected into a sinkhole, sinking stream (<u>swallet</u>) (Figure 8), or even injected directly through the soil by flushing with water. Although the idea is rather simple, in practice the methods are relatively complex (see, for example, Taylor and Greene 2001; Groves 2007; Goldscheider 2008; Gouzie et al. 2015). It is a not a case of putting, say, green dye in a sinking stream and waiting to see where the water turns green at a spring, because its generally not known in advance where the dye will go and when it will get there. The dosing is also generally done in a way to have the dye be sufficiently diluted by the time it comes out at a spring to be invisible to the naked eye, because the dyes can be easily detected in the laboratory in far lower concentrations. Springs where the dye might emerge are monitored in one of several ways, including using automatic water samplers that take water samples at programmed intervals that are then collected and analyzed for the presence of dye back in the laboratory, or computer-based *in situ* <u>data sondes</u> called <u>field fluorometers,</u> which are devices placed directly in the water flow that electronically measure and record dye concentrations.

Another commonly employed method involved placing activated charcoal <u>dye receptors</u> (Figure 9) in the flow of any springs to which the dye might travel. If the dye flows past that point it will adsorb onto the charcoal, which as collected and taken back to the laboratory. The methods

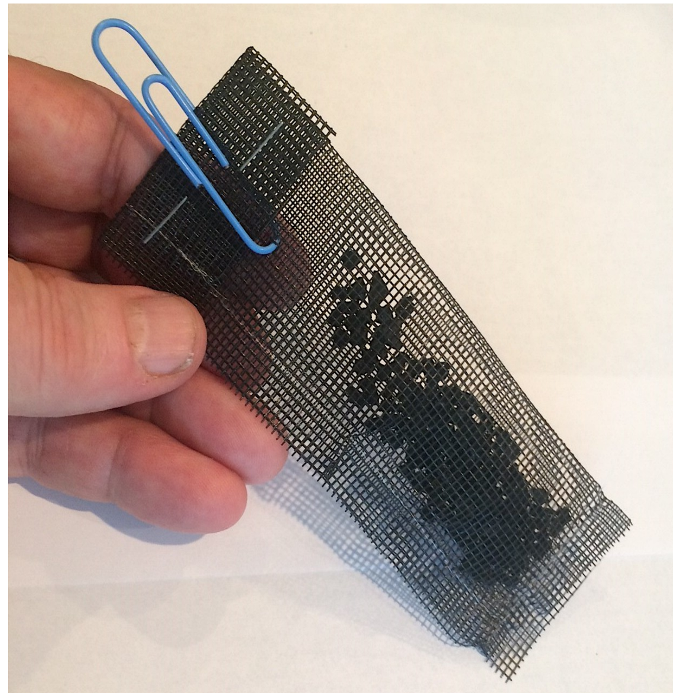

Figure 8. Injection of fluorescent dye into a swallet where the stream in the photo sinks underground at the base of the waterfall. This picture, at a field site in Kentucky, is shown to illustrate the method (Photo by Autumn Singer).

Figure 9. Activated charcoal dye receptor used in fluorescent dyes tracing of karst groundwater. The receptor is placed in the flow of a spring, and if the dye passes that location it adsorbs onto the charcoal. The charcoal is then analyzed in a laboratory for the presence of dye (Photo by Chris Groves).

that employ charcoal dye receptors are sometimes done first to establish point to point contacts, and then the traces repeated to a now-known spring using an automatic water sampler or field fluorometer, as the data from those procedures can be analyzed to measure the velocity of water flow and to quantify other characteristics of flow and aquifer structure (Groves, 2007; Goldscheider et al 2008).

Several dye traces have been done to begin mapping out the directions of ground water flow in the karst aquifer of Jefferson County (Jones, 1997), including in the vicinity of the Route 9 Project. In 1987-89 Kozar et al. (1991) conducted five tracing experiments using activated charcoal dye receptors and water samples. Two of the traces that used fluorescein dye were inconclusive because of high background fluorescence, but three conducted with rhodamine WT dye showed cleared results (Figure 10). Two traces in the vicinity of project route showed direct connections to numerous springs in a radial pattern. Trace A, with rhodamine WT dye injected near the southern end of the project route, flowed to nine springs flowing in turn to the Shenandoah River, with groundwater estimated groundwater flow velocities ranging from 150 to 235 feet per day. Rhodamine dye from test D flowed north to six springs, at least two of which (and perhaps all) flow to the Potomac River. Estimated groundwater flow velocities for the traces to sites other than flow D7 (Figure 10) ranged from 150 to 185 feet per day. The trace to D7 was much faster with an estimated velocity of 840 feet per day, or a mile every 6.3 days. This was interpreted to be flow in a solutionally-enlarged conduit likely associated with a mapped fault. These are known to exist with the karst aquifer of Jefferson County. Indeed, Davies (1965) described and mapped 16 caves of explorable size in the county.

The radial flow pattern emanating out from near the ends of the Route 9 Sewer Project indicate the there is a groundwater divide—a line underground that divides groundwater flow directions separating flow toward the Shenandoah River from that towards the Potomac River—somewhere beneath project route. This means that sediment or other contamination entering the aquifer either from construction, or potentially a catastrophic leak of sewage could flow to springs in either direction, and with velocities of hundreds of feet per day. While some highly-developed karst aquifers at other places in the US have shown velocities in miles per day, these are still quite high numbers compared to virtually all non-karst aquifers and it can be imagined what this would mean for remediation of contamination with groundwater moving this quickly. It would take more detailed dye tracing to more accurately determine the location of this divide.

Jones (1997) summarized additional dye traces that have been done in the Central Folded Carbonate Unit (Figure 11) including traces from west of the Route 9 Project route (Jones and Deike 1981). They showed that these traces flowed to the west, and one trace arriving at Balch Spring at the US Geological Survey Leetown Science Center (LSC). Subsequent hydrologic work (Kozar et al. 2007) including fluorescent dye tracing has clarified the flow in the vicinity of the LSC and the summary map of their traces also shows the trace from Browns Corner Sinkhole trace to Balch Spring at the LSC (Jones 1997). Blue circles on both Figure 11 and 12 show the location of Browns Corner Sinkhole.

Dye traces have also been conducted in the vicinity of the Leetown Pesticide Site and the Jefferson County Landfill area (NUS 1986), but these are less relevant to the focus of the current report.

Similar to the discussion above about the groundwater divide apparent in Figure 10, the additional traces to west of the Project route (Figure 11) reveal a similar but more complex situation where, depending on the exact location of the injection, dye can flow to the north, south, or west in a radial flow pattern. The Route 9 Sewer Project overlies the center of this area of radial flow, and beyond the current understanding provided by the injection locations shown in Figures 9-11, without additional detailed tracing work, there is uncertainty about which direction contamination introduced into the aquifer would travel. Whichever direction it did go, there is a reasonable probability that in these limestones it would be capable of traveling hundreds of feet per day.

An additional source of information about groundwater flow that is often useful concerns the geometry of hydraulic gradient, which in simple terms describes the direction and steepness of the water table in a particular area. Using data from water wells, the water table can be mapped out as a three-dimensional surface, and unless influenced by other factors, water generally moves from high areas of the water table to lower areas, in way similar to how a car will roll from an area of high elevation to a lower one. There are good water table maps for central Jefferson County (Figure 10) but because the complexity of the geologic structure and the complex geometry of the fractures and conduits through which the groundwater is constrained to flow, Kozar (1991, p. 12) pointed out that dye tracing shows depending on the location, water here can flow either perpendicular or parallel to the water table contours.

5. Conclusions

An evaluation of risks associated with construction within the area impacted by the Route 9 Sewer project, based on a review of existing literature, shows that the route is located on a well-developed karst landscape and aquifer and is subject to the typical environmental risks expected in such a hydrogeologic setting. These include the potential for sinkhole development, but in my view the most concerning potential risk from both construction and operation of sewer line is for groundwater contamination. In the case of a pipeline failure (more common in karst areas than others because of the potential for loss of structural support) groundwater contamination could be catastrophic in ecological terms (the federally threatened Madison Cave isopod lives within the karst aquifer of Jefferson county) and creating human disruptions by polluting groundwater, springs, and the surface waters to which these springs flow.

This is a very well-studied groundwater system, and dye tracing shows the project route overlies the center of an area of radial flow. Contaminants introduced along the route could potentially flow northward towards the Potomac River, eastward towards the Shenandoah River, or westward toward springs at the US Geological Leetown Science Center.

Although I have focused on an analysis of hydrogeological conditions that could lead to risk in the construction and operation of the Route 9 Sewer Project, rather than any engineering solutions, there are strategies and practices that can help to mitigate these risks. I encourage those responsible for project planning and implementation to take these ideas into consideration.

6. References

Beiber, P.B., 1961, Ground-water features of Berkeley and Jefferson Counties, West Virginia: West Virginia Geological Survey Bulletin 21, 79 p.

Cardwell, D.H., Erwin, R.B., and Woodward, H.P., 1968, West Virginia Geological and Economic Survey, Geologic Map of West Virginia, 1:250,000 scale, in two sheets.

Chesapeake Stormwater Network. 2009. *Stormwater Design Guidelines for Karst Terrain in the Chesapeake Bay Watershed Version 2.0*. CSN Technical Bulletin No. 1, 39 p. Available at <https://dep.wv.gov/WWE/Programs/stormwater/csw/Documents/Karst%20Design%20Guidelines%20Chesapeake%20Bay.pdf>.

Croskrey, A., & Groves, C. (2008). Groundwater sensitivity mapping in Kentucky using GIS and digitally vectorized geologic quadrangles. *Environmental Geology*, *54*(5), 913-920.

Dean, S.L., B.R. Kulander, and P. Lessing. 1990. Geology of the Berryville, Charles Town, Harpers Ferry, Middleway, and Round Hill Quadrangles, Jefferson County, WV. WV Geological and Economic Survey: MAP-WV35. 1990.

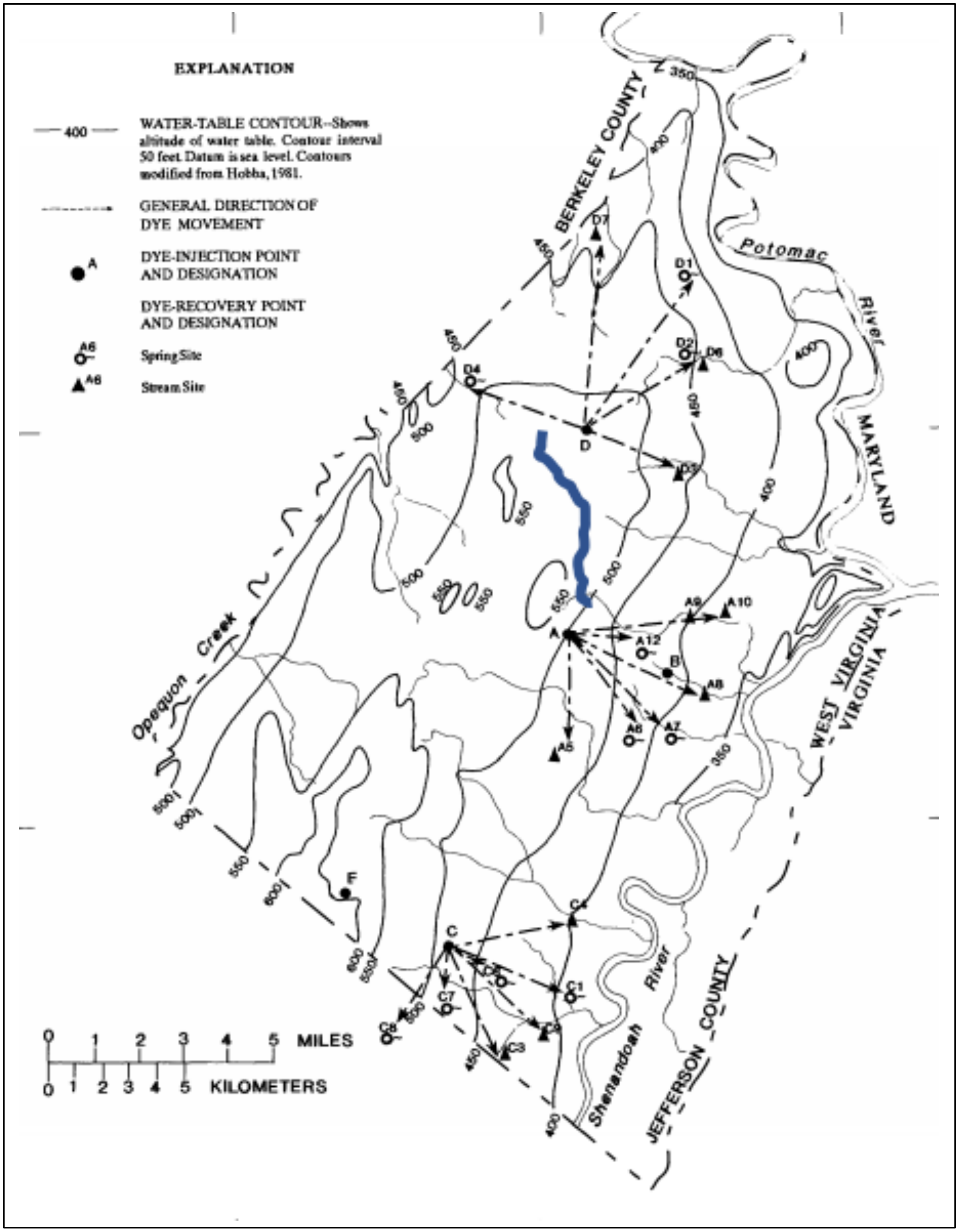

Figure 10. Results from three dye traces conducted from 1987-89 by Kozar et al. (1991) with approximate route of project shown. Two traces in the vicinity of project route showed direct connections to numerous springs in a radial pattern. Trace A, with rhodamine WT dye injected near the southern end of the route flowed to nine springs flowing in turn to the Shenandoah River, and test D flowed north to six springs, at least two of which flow to the Potomac River.

Figure 11. Dye traces were summarized by Jones (1991), including those shown in Figure 10 along with other injections to the west of the project route (Jones and Deike 1981) that flow westward to springs at the US Geological Survey Leetown Science Center (LSC). The blue circle shows the injection location at Browns Corner Sink that flowed to Balch Spring at the LSC (See Figure 12).

See Supplement
Figures 11a and 11b
on next pages, 19a and 19b.

Doctor, D.H. and K.Z. Doctor. 2012. Spatial analysis of geologic and hydrologic features relating to sinkhole occurrence in Jefferson County, West Virginia. *Carbonates and Evaporites*, *27*(2), 143-152.

Doctor, D.H. and J.A. Young. 2013. An evaluation of automated GIS tools for delineating karst sinkholes and closed depressions from 1-meter LiDAR-derived digital elevation data. *Sinkholes and the Engineering and Environmental Impacts of Karst.* Proceedings of the 13th Multidisiplinary Conference, Carlsbad, New Mexico, pp. 449-458.

EPA (2002), *A lexicon of cave and karst terminology with special reference to environmental karst hydrology*. Office of Research and Development, US Environmental Protection Agency, 1999.

Evaldi, R.D., Paybins, K.S., and Kozar, M.D., 2009, Hydrogeologic factors affecting base-flow yields in the Jefferson County area, West Virginia, October-November 2007: U.S. Geological Survey Scientific Investigations Report 2009-5145, 13 p., 1 plate.

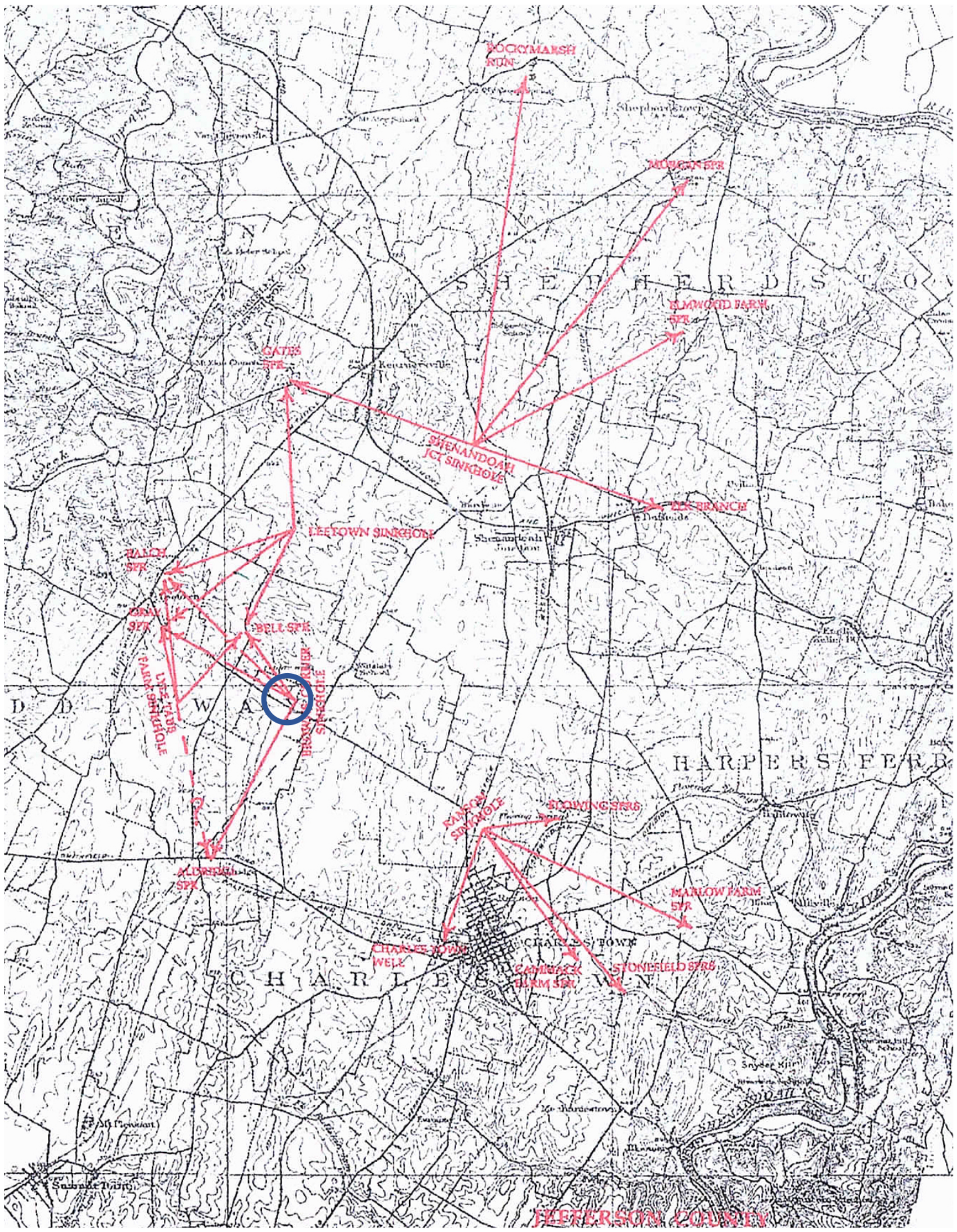

Figure 11A. Dye traces in the vicinity of the Rt. 9 Sewer Project, Jefferson County WV (source Jones, 1997).

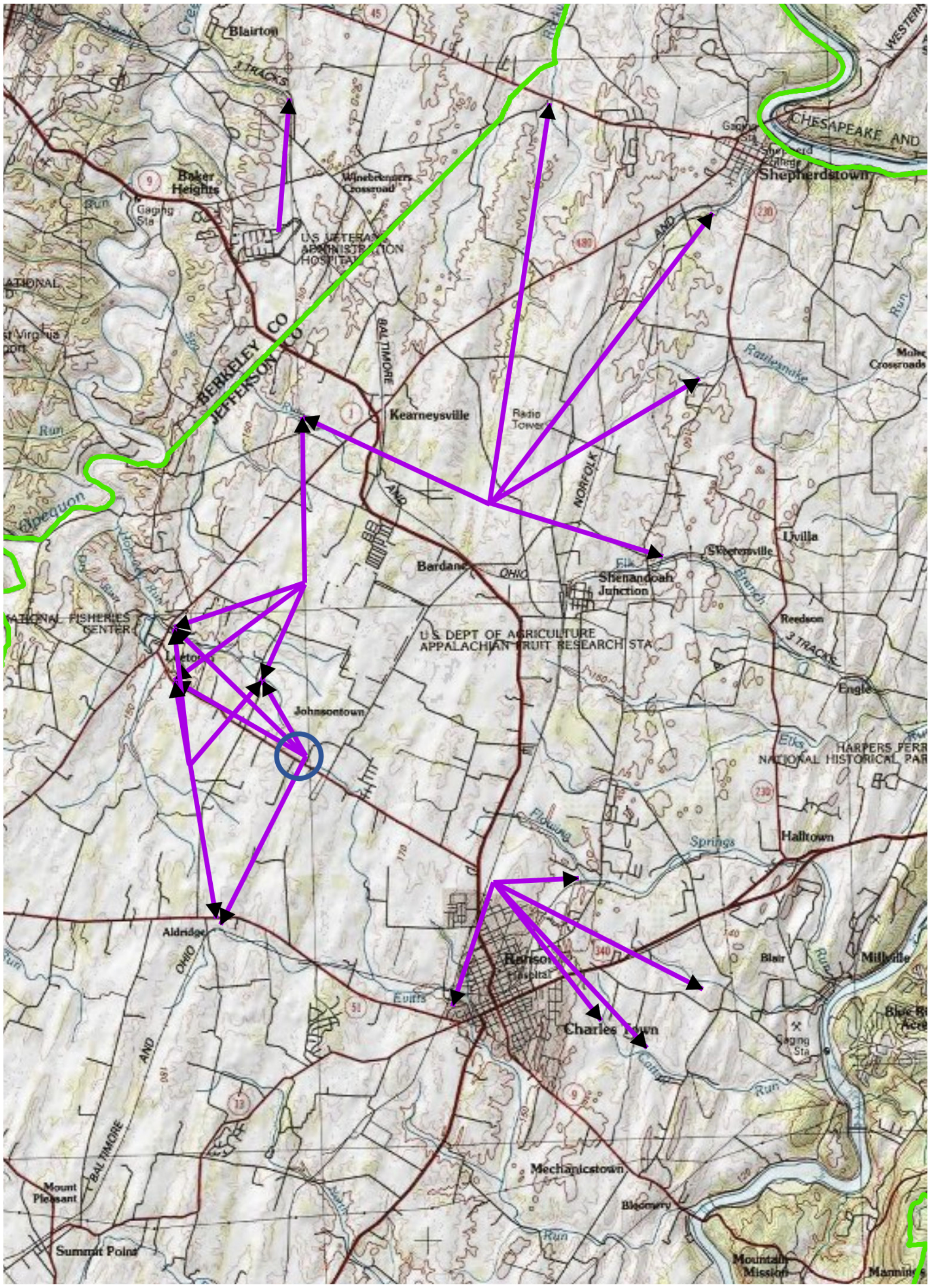

Figure 11B. Geographic Information Systems (GIS) map replicating Figure 11A for clarity and showing dye traces in the vicinity of the Rt. 9 Sewer Project, Jefferson County WV (source Jones, 1997).

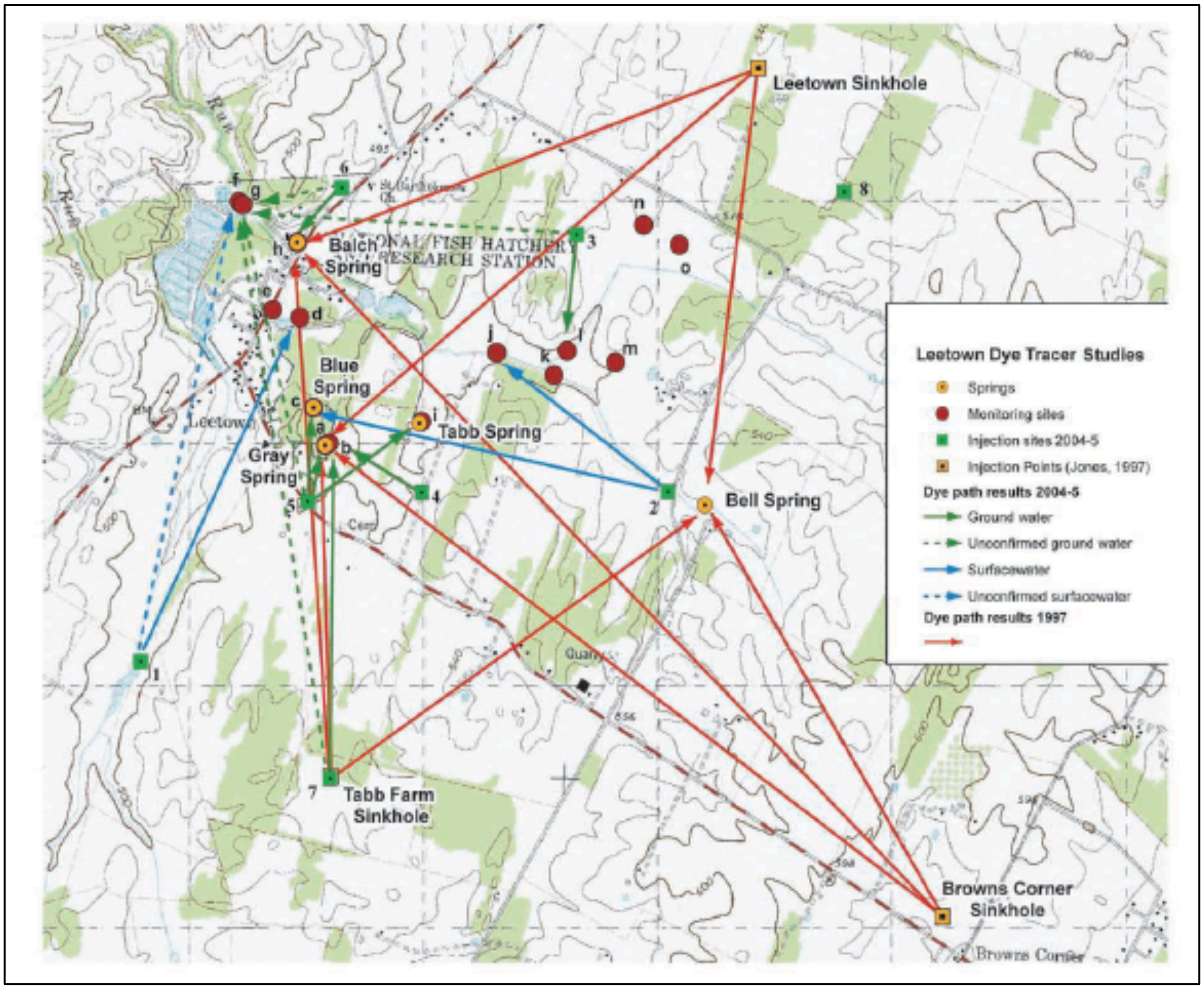

Figure 12. Dye tracing in the vicinity of the US Geological Survey Leetown Science Center (Kozar et al. 2008) with earlier traces (Jones 1997) shown more clearly than on Figure 11. The blue circle shows the injection location at Browns Corner Sinkhole that flowed to Balch Spring at the LSC, also shown on Figure 11.

Ewers, R. (2016), On the efficacy of monitoring wells in karstic carbonate aquifers. *The Geological Society of America Special Paper 516.*

Ford, D. and Williams, P. (2007), "Karst Hydrogeology and Geomorphology", John Wiley & Sons, Ltd, Hoboken, NJ.

Goldscheider, N. (2005). Karst groundwater vulnerability mapping: application of a new method in the Swabian Alb, Germany. *Hydrogeology Journal*, *13*(4), 555-564.

Goldscheider, N., Meiman, J., Pronk, M., & Smart, C. (2008). Tracer tests in karst hydrogeology and speleology. *International Journal of speleology*, *37*(1), 27-40.

Gouzie, D., Berglund, J., & Mickus, K. L. (2015). The application of quantitative fluorescent dye tracing to evaluate karst hydrogeologic response to varying recharge conditions in an urban area. *Environmental Earth Sciences*, *74*(4), 3099-3111.

Groves, C. (2007), Hydrologic techniques, in *Methods in Karst Hydrogeology*. New York: Taylor and Francis, pp. 45-64

Groves, C. (2018) Editor's Message: US Environmental Protection Agency's Coal Combustion Residuals Rule strengthens regulatory recognition of karst groundwater flow. *Hydrogeology Journal*, 26(2):361-365|.

Hatfield, W.F., and Warner, J.W., 1973, Soil survey of Jefferson County, West Virginia: U.S. Department of Agriculture, Soil Conservation Service, 81 p.

Hobba, W.A., Jr., 1981, *Ground-water hydrology of Jefferson County, West Virginia*: West Virginia Geological Survey Environmental Geology Bulletin 16, 21 p.

Hobba, W.A., Jr., Friel, E.A., and Chisholm, J.L., 1972, Water resources of the Potomac River Basin, West Virginia: West Virginia Geological Survey River Basin Bulletin 3, 110 p.

Hunter, D. 2013. Living (and Sometimes Dying) With Karst. *Scientific American*, March 23, 2013. Available at <https://blogs.scientificamerican.com/rosetta-stones/living-and-sometimes-dying-with-karst/>

Jones. W.K. 1991. The carbonate aquifer of northern Shenandoah Valley of Virginia and West Virginia. Proceedings of the 1991 Appalachian Karst Symposium, 217-222.

Jones, W.K., 1997, *Karst Hydrology Atlas of West Virginia*. Karst Waters Institute Special Publication 5, Karst Waters Institute, Charles Town, West Virginia, 111 p

Jones, W.K., and Deike, G.H., III, 1981, *A hydrogeologic study of the watershed of the National Fisheries Center at Leetown, West Virginia.* Prepared for the U.S. Fish and Wildlife Service by Environmental Data, Frankford, West Virginia, 84 p.

Kozar, M.D., W.A. Hobba, Jr., and J.C. Macy. 1991. *Geohydrology, Water Availability, and Water Quality of Jefferson County West Virginia, With Emphasis on the Carbonate area*. US Geological Survey US Geological Survey Water-Supply Paper 1899-K.

Kozar, M.D., McCoy, K.J., Weary, D.J., Field, M.S., Pierce, H.A., Schill, W.B., and Young, J.A., 2008, *Hydrogeology and water quality of the Leetown area, West Virginia:* U.S. Geological Survey Open-File Report 2007–1358, 212 p., 6 appendices.

McColloch, J.S., 1986, Springs of West Virginia. West Virginia Geological and Economic Survey, Volume V-6A, 493 p.

Maloy M. and A. Carter, 2012, *County-Wide Groundwater Assessment Jefferson County, West Virginia.* Jefferson County Commission, 27 p. plus appendices.

Milanović, P.T. (1981), Karst Hydrogeology, Water Resources Publications, Littleton, CO.

Monroe, W.H. (1970), *A Glossary of Karst Terminology*. US Geological Survey Water-Supply Paper 1899-K.

NUS. 1986. *Remedial Investigation Report, Leetown Pesticide Site, Jefferson County, West Virginia*, EPA Work Assignment 65-3L52, Contract Number 68-01-6699, NUS Project Number S794, 47 p.

Palmer, A.N. (2007), *Cave Geology* (Vol. 454). Dayton: Cave books.

Parise, M., & Gunn, J. (eds.). 2007. Natural and anthropogenic hazards in karst areas: recognition, analysis and mitigation. Geological Society of London. 216 p.

Taylor, C. J., & Greene, E. A. (2001). Quantitative approaches in characterizing karst aquifers. *US Geological Survey Karst Interest Group Proceedings*, 164-166.

Trainer, F.W. and F.A. Watkins, 1975, Geohydrologic reconnaissance of the Upper Potomac River Basin US Geological Survey Water Supply Paper 2035

US Census Bureau. 2020. Quick facts West Virginia. Available at <https://www.census.gov/quickfacts/WV>.

Veni, G., H. DuChene, N.C. Crawford, C. Groves, G.N. Huppert, E.J. Kastning, R. Olson, and B.J. Wheeler. 2001. Living With Karst A Fragile Foundation. American Geological Institute Environmenal Awareness Series 4, 66 p. Available at <https://www.americangeosciences.org/sites/default/files/karst.pdf>.

White, W.B. (1988). *Geomorphology and Hydrology of Karst Terrains*. New York: Oxford university press.

West Virginia Department of Environmental Protection (WVDEP). 2018. Construction stormwater permit site evaluation, October 2, 2018.

7. Appendix 1: Glossary of Technical Terms Used in This Report

Definitions have been compiled from a variety of sources including, but not limited to Monroe (1970), Freeze and Cherry (1977), White (1988) and Walker at el. (2012).

allogenic karst recharge: Water that starts off as surface runoff flowing across relatively impermeable (non-karst) rocks and then sinks underground at one or more discrete points upon flowing onto a soluble limestone layer. This is opposed to autogenic recharge that lands directly onot the karst surface and sinks underground (see recharge).

alluvial deposits: Unconsolidated sediment that has been deposited by a surface stream stream or river.

aquifer: A saturated body of rock that can transmit significant quantities of water under normal conditions. For those paying close attention, technically this means normal hydraulic gradients, but for the purposes of this report “normal conditions” is just fine.

aquiclude/aquitard: Saturated bodies of rock with relatively low permeability that are unable to transmit significant quantities of water under normal conditions (see aquifer). These are to different degrees along a continuum of conditions, where aquicludes “preclude” flow and aquitards “retard” flow. Fpr the purposes of this report these terms can be used more synonymously with “confining layer.”

autogenic karst recharge: Water that that lands directly onto the karst surface as precipitation and sinks underground. This is opposed to autogenic recharge starts off as surface runoff flowing across relatively impermeable (non-karst) rocks and then sinks underground at one or more discrete points upon flowing onto a soluble limestone layer (see recharge).

base level stream: the local stream or river in a karst region that has cut downward into the limestone bedrock and towards which the groundwater in the karst aquifer flows. This is where the karst groundwater emerges, typically at a spring where an underground stream flows out at the base level stream or river’s edge. The Cumberland River is the base level stream for the karst flow system of Odom’s Bend, and there are one or more springs along the edge of the bend draining about 4,000 acres of sinkhole plain. These are now hidden beneath Old Hickory Lake and the flow from them is influenced by decades of unlined CCR disposal .

bentonite: a clay mineral that makes up thin layers interspersed within the limestones of the Central Basin. These layers retard the movement of groundwater because they have very low permeability that does not allow water to pass through easily.

blind valley: large closed depression in a karst region that contains a swallet serving as the terminal sink point for a stream or river.

carbonate rocks: A family of rocks that include limestone and dolomite, which are especially soluble in natural waters and which often, especially in limestone, form karst landscapes and aquifers.

Dolomite: a carbonate sedimentary rock closely related to limestone. Although some magnesium in the chemical structure makes dolomite some less soluble than limestone, well developed karst features can form on dolomite in West Virginia.

evapotranspiration : the combined actions of evaporation and transpiration, the processes that transfer liquid water on the landscape to the atmosphere as water vapor.

formation: used in this context, a (geologic) formation is a relatively homogenous layer of rock that can be discriminated from other layers by its properties. In Jefferson County, for example the Conococheague and Stonehenge Limestones form karst aquifers with much of the drainage underground while the volcanic rocks of the Catoctin Formation has very low permeability.

hydrogeology: the branch of science concerned with the behavior, distribution and movement of water in the soil and rocks beneath the earth's surface.

hydrogeologic regions: areas of bedrock in which the behavior of surface and ground water show generally similar behavior.

karst: A term which refers to landscapes and aquifers that have been created through the dissolving of especially soluble rock, most commonly limestone, resulting in characteristic features such as caves, underground rivers, large springs, and closed surface depressions called sinkholes.

karst aquifer: An aquifer with relatively high to sometimes extreme permeability with water that flows through solutionally-enlarged fractures, conduits and or caves.

Karst hydrogeology: the study of the behavior, distribution and movement of water in the soil and rocks beneath the earth's surface within karst flow systems.

limestone: a type of rock common in parts of West Virginia that is especially soluble in natural waters, such that in many places solution of the bedrock forms caves, sinkholes, and other landscape features typical of karst landscapes and aquifers. Relatively pure limestones such as the Carters Limestone can dissolved readily to form highly permeable karst aquifers, while those with significant clay impurities such as the Hermitage Formation (the layer above the Carters) and the Lebanon Limestone (below the Carters) do not dissolve well and form aquitards that inhibit groundwater flow.

Ordovician Period: Interval of geologic time from about 485 to 444 million years ago, during which the many of the rocks of Tennessee's Central Basin, including of those that comprise the bedrock beneath Odom's Bend, were formed. This means that the sediments that comprise a particular layer were deposited on the sea floor during that interval of time.

permeability: the ability of a rock mass to transmit fluids. This requires that a rock mass has porosity, but also that the various space elements—fractures for example—form an interconnected set of pathways to provide routes by the which the fluid can move through the rock. Swiss cheese has high porosity, but if the "bubbles" are not connected to one

porosity: the volume of space compared to the total volume of a sample of rock or other otherwise solid material, expressed as a percentage. A rock mass with 25% porosity, for example, has 25% space and 75% solid rock, for a total of 100%.

Quaternary Geologic Period: Interval of geologic time from about 2.6 million years ago to the present, during which the river-deposited alluvium of Tennessee's Central Basin, including that beneath Odom's Bend, was formed.

recharge: rainwater or snowmelt that soaks into the ground and which in many places, including Tennessee's Central Basin, is the source of groundwater.

shale: a very fine-grained and rock that typically have very low permeability and thus a limited ability to transmit water.

spring: in karst landscapes, a spring is an area where and underground stream or river emerges back to the surface

swallet: location where a stream sinks into the subsurface within karst landscapes.

transpiration: the processes by which water is converted to water vapor and transferred from the landscape to the atmosphere through the actions of plants.