Karst Hydrogeology and the Potential for Associated Environmental Risks Resulting From the RAN 5 Project, Jefferson County, West Virginia

Submitted to

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by

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Note: Terms in the Glossary are underlined the text the first time they are used.

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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 sinks into the ground into these areas of highly permeable “Swiss Cheese” bedrock and flows underground in fractures and conduits—caves being those large enough for humans to explore—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 industrial, agricultural, urban, and other land use. As a result, karst groundwater, including that in West Virginia, is highly vulnerable to contamination.

Jones (1997, p.2) wrote that:

> The most important karst areas of West Virginia . . . are found on marine limestones exposed in the eastern and southeastern parts of the state. Carbonate aquifers are an important source of water everywhere they are found in West Virginia . . . The rapid recharge and flow rates through the aquifers make the water especially susceptible to pollution. Many unique aquatic organisms live in cave streams and within the more fractured or diffuse parts of the karst flow system. Karst waters and their accompanying ecosystems are especially vulnerable to man's activities - every sinkhole can act as an injection well to transmit contaminants into the aquifer.

He went on:

> Karst aquifers are susceptible to contamination anywhere within their drainage basin. Developers and planners need to be aware of the location of this fragile resource . . . The entire drainage basin or catchment for a karst spring or aquifer must be protected . . . Surface spills and contaminants can quickly infiltrate the land surface and be transmitted through a karst aquifer to spring or wells, *often several miles from the spill site.* Both the ground and surface water resource may be contaminated by a single spill in karst regions.

(emphasis added).

Even with these problems, continually increasing populations in many karst-rich areas of the US mean that avoiding development in karst landscapes is *not* an option, and research continues into best management practices (BMPs) 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).

In 2017, 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 Roxul USA, Inc. RAN 5 Project near Kearneysville (Figure 1), a facility for the manufacture of stone wool insulation. Construction began in November 2017, and although a series of actions and decisions followed that led to continued uncertainty in the regulatory status of the project beginning in November 2018, construction continued and does so today.

The footprint of the project lies on carbonate rocks with well-developed karst landscapes and aquifers. A series of evaluation and planning projects have been made for the site, which have paid varying attention to the impact of local karst hydrogeology on the potential environmental risks of site construction and operation (e.g. Specialized Engineering 2017; The Thrasher Group, Inc. 2017; 2019; Environmental Resources Management, Inc. 2019a, 2019b; 2020).

The purpose of this report is to evaluate risks associated with facility construction and operation within the karst area impacted by the RAN 5 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 an evaluation of these risks certainly informs consideration of the need and importance of measures designed to prevent hazards related to karst risk, an evaluation of the efficacy of particular designs for such measures is also beyond the scope of this report.

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 at the RAN 5 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

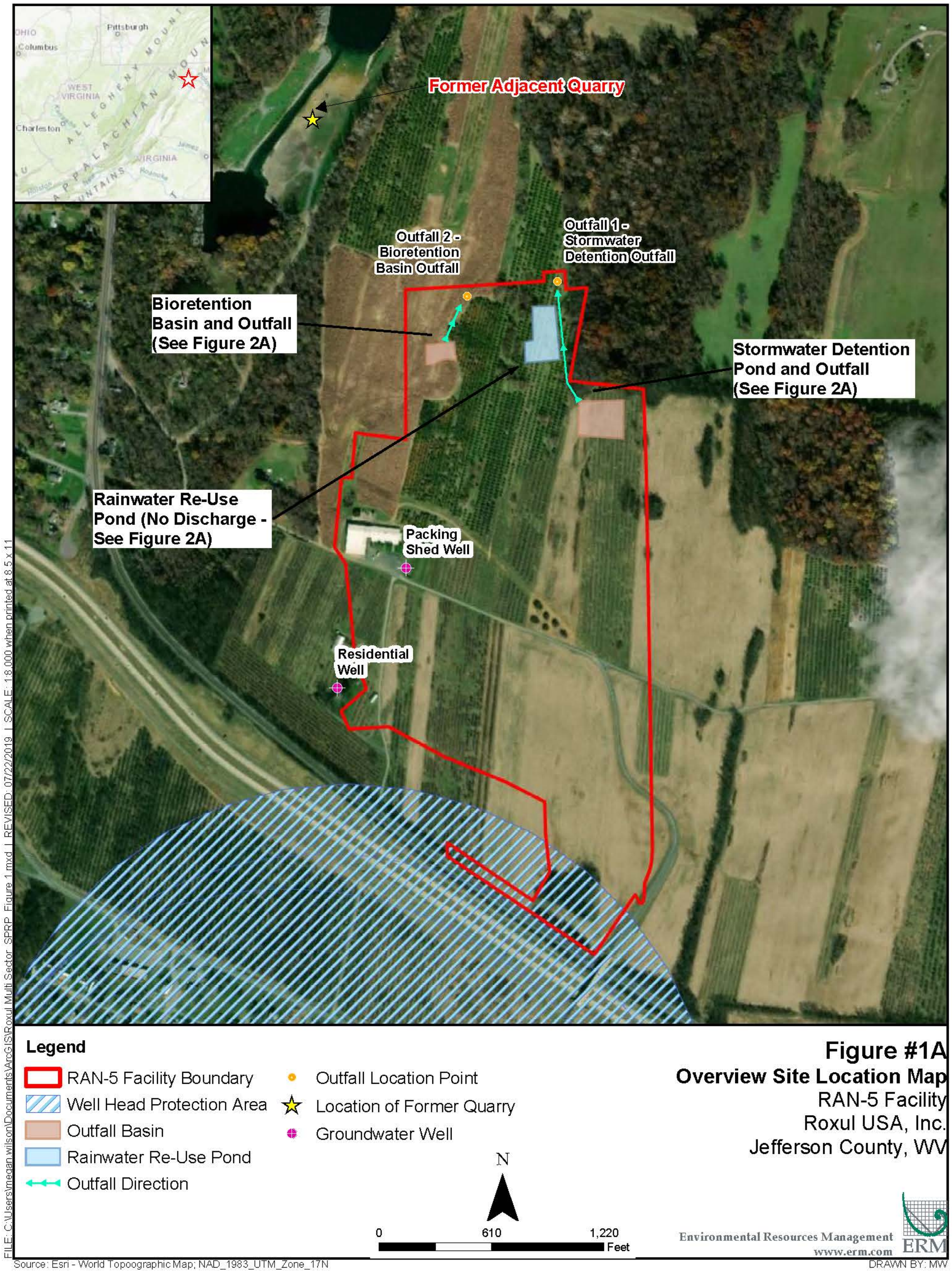

Figure 1. Location of the RAN 5 Project facility (source: Environmental Resources Management, 2019a)

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 Sinnett 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 is 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; Jones, 1997; Goldscheider, 2006; Ford and Williams , 2007; Croskrey and Groves, 2008; Maloy and Carter, 2012).

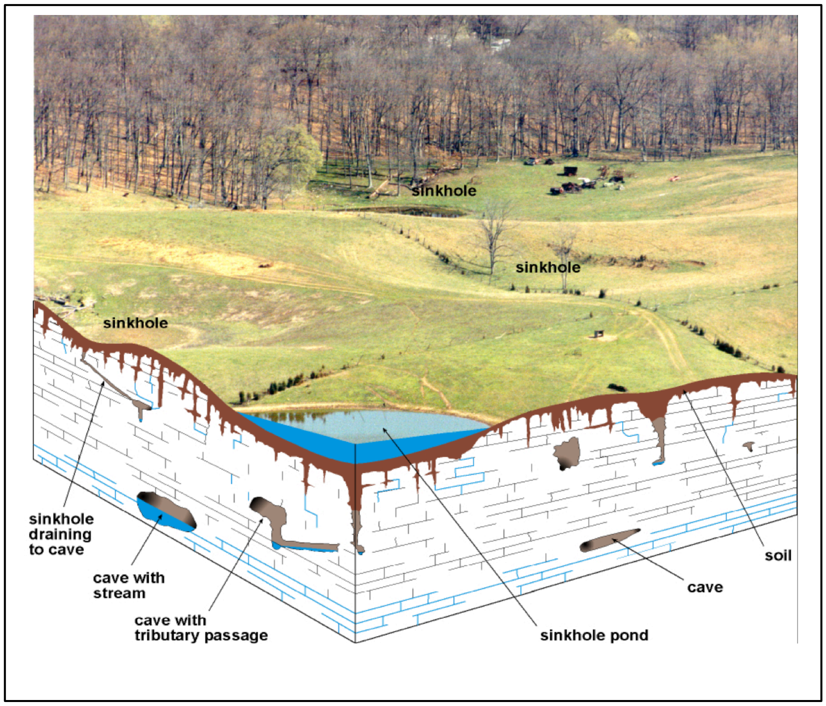

Figure 2. Block diagram showing common surface and subsurface karst features such as caves, sinkholes, and underground streams (Kentucky Geological Survey, 2015). There is a lack of surface drainage except for a pond filling a plugged sinkhole. Note this diagrammatic illustration shows flat-lying rocks 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 Figures 3 and 4 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 3 are geologic formations, or homogeneous regions of bedrock that have been subdivided and named by geologists. According to US Geological Survey mapping the rocks that underlie the project footprints are the karst-forming Conococheague (O€c) Limestone (Specialized Engineering 2017) although Stonehenge (Os) Limestone may also underlie areas of the site (The Thrasher Group, Inc. 2017). An important aspect of understanding the geology of Jefferson County (Figures 3 and 4) 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 (Meloy and Carter, 2012), and a more generalized geologic map (Figure 4) shows three relatively homogeneous hydrogeologic regions of the county. Lumping together the major carbonate rock formations shows a region covering much of the county called the Folded Carbonate Central Unit, where karst landscapes and aquifers dominate. Both the Western Faulted Unit and the Eastern Metamorphic Unit also include 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 and the Western Faulted Unit have different intensities of karst development, expressed in how dissolution has modified the permeability of the underlying bedrock and made it easier for water to flow underground, but carbonate rocks throughout the state have 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, and indeed into the groundwater aquifer 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.

Figure 3. Geologic map of Jefferson County as described in the text, with approximate location of the RAN 5 project. The Conococheague (designated as OЄc) and perhaps Stonehenge (Os) Limestones, both of which are karst-forming rocks, underlie the facility. The linear trend of the geologic formation reflects the folded geometry of the Appalachian Mountains. This map has been modified (approximate location of facility added) from Meloy and Carter (2012).

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 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 RAN 5 Project is almost wholly lacking. This is where karst is especially well developed with a relatively high level of rock dissolution in the subsurface and so

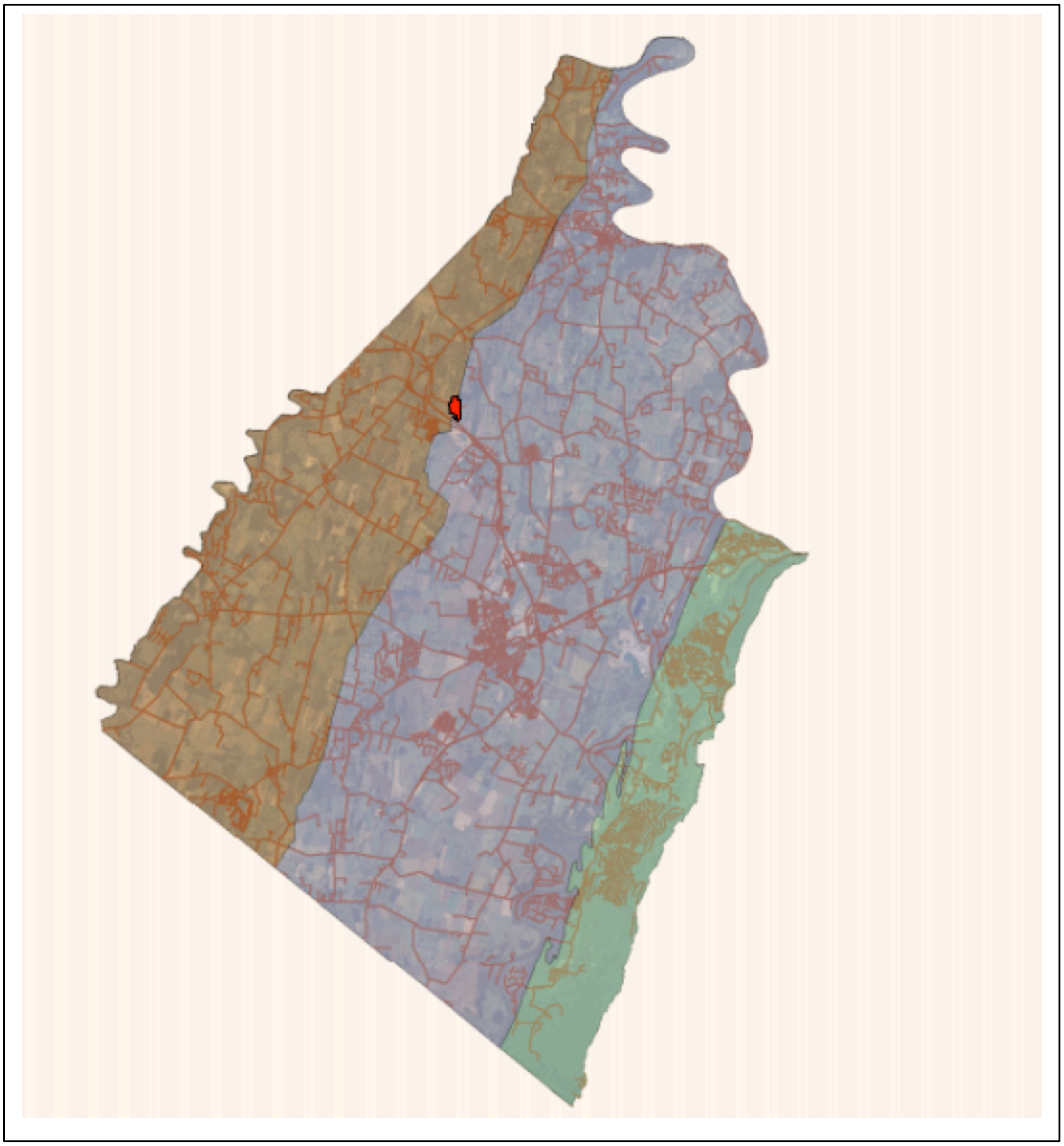

Figure 4. More generalized geologic map showing the central (purple) homogeneous region of carbonate rocks where extensive karst landscapes have formed, and with the eastern and western parts of the county underlain by various karst and non-karst forming rocks. This map has been modified (approximate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

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 are a complex interplay 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 RAN 5 Project. This means that rainfall that lands here infiltrates into the ground, rather than flowing across the surface. As it sinks underground, so can contaminants that may be present.

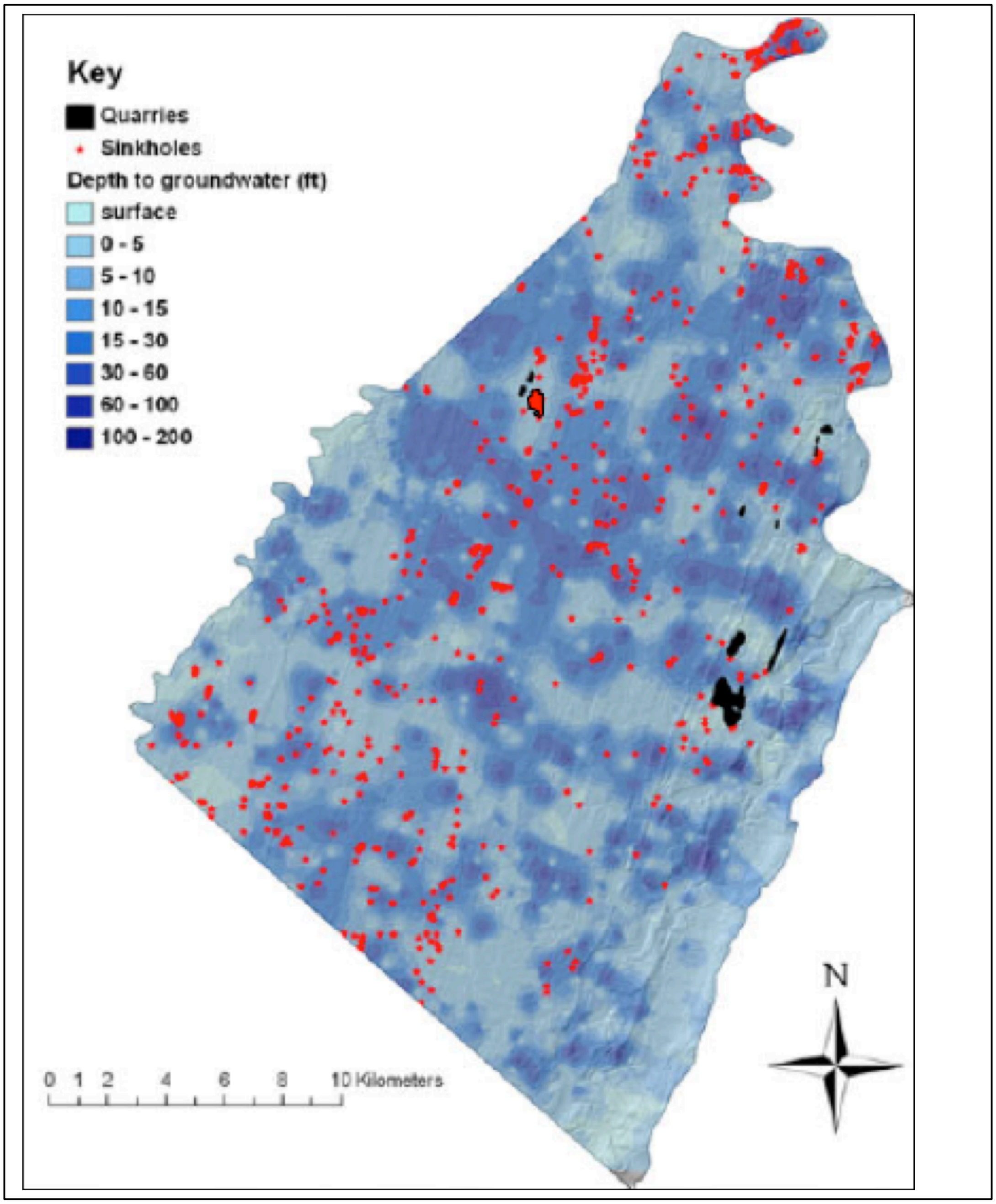

Figure 5. Sinkhole distribution for Jefferson County. Modified (approximate facility location added) from Doctor and Doctor, 2012. Sinkhole formation requires void space in the subsurface which has resulted from carbonate rock dissolution, and so the majority of sinkholes in closely match the location of the Central Folded Carbonate Unit hydrogeologic region (Figure 4). This indicates very well-developed conditions of karst landscape development.

4. Karst-Related Hazard Risks in the RAN 5 Project Area

4.1 Karst Hydrogeology of the RAN 5 Project Area

Taken together, each of these observations confirms that the area of the RAN 5 Project lies in the area of a well-developed karst landscape and aquifer. Hazards associated with construction and

Figure 6. Closed depression or sinkhole in the RAN 5 facility Basin 1 (WVDEP 2018a). All of the rock and soil where the depression is now has moved down through fractures into solutionally-enlarged voids in the bedrock, and aquifer, beneath. This sediment is a contaminant in groundwater (photographer not named).

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, 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 RAN 5 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 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. Once these contaminants reach the groundwater, they can travel quickly.

Describing Virginia's Great Valley, in which the carbonate rocks of Jefferson County, including the RAN 5 Project Site, are located, 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

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 RAN Project is almost wholly lacking. This map has been modified (approximate facility added) from Meloy and Carter (2012).

> 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.*

(emphasis added).

Describing more specifically 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.*

(emphasis added).

A 2017 analysis of the geology at the site, defined at the time as the "New Industrial Site at the former Jefferson Orchard" (Specialized Engineering 2017), concluded

> *The project site is located in an area with the potential for sinkhole formation.*
>
> a) Sinkholes are formed in karst by either slow, downward solutioning *or rapid collapse of the land surface*. Sinkholes can occur naturally or can be induced by activities of man.
>
> b) *The stability of the residual soils that overlie limestone is a concern for long term stability and maintenance of structures located in karst terrain.* Voids or domes often form in the residual soil above rock cavities, and unless the thickness of the residual soil is sufficient to carry the imposed loads and for development of arching, the soil may collapse and sinkholes may form. The dimension of a potential sinkhole is likely a function of the thickness of soil cover, the thickness of epikarst (the zone of soft soil and above the bedrock surface and in deeper slots between pinnacles formed by dissolution of the rock), and the presence and severity of bedrock discontinuities in the epikarst.
>
> c) Some sinkholes [*sic*] failures can be induced by construction activities

> and are of significance because the *sinkholes can directly affect the site being developed, either immediately or some years later.* Construction activities that can trigger sinkholes include 1) diversion or impoundment of drainage or dewatering activities, 2) removal of overburden cover, 3) shock vibrations, such as blasting, and 4) increased loading.
>
> d) *Prediction of sinkhole location or occurrence is difficult, if not impossible, and there is always a significant degree of uncertainty associated with the occurrence of future sinkholes*. Structures built within the area of influence of a sinkhole can also be affected by sinkhole collapse or subsidence. By virtue of the underlying geologic formation, the Owner must acknowledge *there is an inherent risk of potential ground subsidence or collapse associated with construction of structures in karst terrain. All sites in karst terrain have the potential for sinkhole formation.*

(emphasis added).

4.2 Sinkholes and the RAN 5 Facility

Generally, sinkholes refer to bowl-shaped, closed depressions common in karst landscapes, and while there are a variety of types and modes of how they form, they all share in common that water carries solid material, either soil or rock or both, and potentially other contaminants, directly downward into the aquifer under the influence of gravity. Sinkholes can form slowly or rapidly but they all exist because a principal feature of karst terrain is that there are voids or spaces in the rock beneath the surface that provide the room for surface materials to move downwards into.

The area of Jefferson County in which the RAN 5 Project site is located is an area of prolific sinkhole development (Kozar et al. 1991; Doctor and Doctor 2012; WVDEP 2018a; 2018b; 2018c; 2018d, 2019, 2020a, 2020b, 2020c; Connelly, 2018) (Figures 5, 8, 9, 10, 11). These have formed regularly during construction at the RAN 5 Project, at least in the Reuse Pond, Sediment Basin #1, and Sediment Basin #2. There are not only relatively large ones (Figure 6) but smaller ones that are just as important for providing direct pathways for contamination to infiltrate groundwater. Evidence for the recurring development of sinkholes at the site was clear in the permit inspection report of October 2, 2018, during which the visiting team "Inspected 8 potential sinkholes that have been discovered" (WVDEP 2018a, p. 1). The previous inspection visit had been only three weeks earlier.

A critical consideration is that while there are obviously direct consequences from sudden sinkhole formation (called <u>sinkhole collapse</u>), including the potential for loss of structural support for buildings, roads, pond liners and other infrastructure, in this setting a closely related, but more serious environmental threat comes from the potential for groundwater contamination. A spill of contaminants through a breached pond liner, for example, resulting from loss of support could result in catastrophic release to groundwater. And as Jones (1997, p. 2) explained,

> Karst waters and their accompanying ecosystems are especially vulnerable to man's activities - every sinkhole can act as an injection well to transmit

Figure 8. Four sinkholes in the RAN 5 Project Reuse Pond. (WVDEP 2018a) (photographer not named).

Figure 9. Several sinkholes in the Reuse Pond (WVDEP 2019a) with temporary structures to minimize the transport of sediment into the karst aquifer (photographer not named).

Figure 10. Sinkhole in Sediment Basin #1 (WVDEP 2018d) (photographer not named).

Figure 11. Sinkhole in Sediment Basin #2 (WVDEP 2018a) (photographer not named).

> contaminants into the aquifer . . . Surface spills and contaminants can quickly infiltrate the land surface and be transmitted through a karst aquifer to spring or wells, *often several miles from the spill site.* Both the ground and surface water resource may be contaminated by a single spill in karst regions.

(emphasis added).

Because it lies on a well-developed karst landscape and aquifer, in a release of contamination from the RAN 5 Project facility not only could groundwater (and the ecosystem living within it, potentially including the federally threatened Madison Cave isopod) be impacted, but also the spring or springs where the groundwater emerges and the receiving streams and/or rivers downstream from there. In the case of the RAN 5 Project facility, where would that be? Unfortunately, without additional hydrologic evaluation of the site, we currently cannot say specifically where these receiving streams would be.

4.3. 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 the 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 base level stream or river. The three base level streams potentially relevant to the facility are the Shenandoah and Potomac Rivers, and Opequon Creek. But there is not a direct way from topographic maps to know what the directions of the underground flow will be, or indeed at which spring the flow will ultimately emerge.

There are several methods for determining this information, and the most powerful of these is called fluorescent dye tracing. In this work, certain types of environmentally safe dyes are injected into a sinkhole, sinking stream (swallet) (Figure 12), 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 it is generally not known in advance where the dye will go or 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* data sondes called field fluorometers, which are devices placed directly in the water flow that electronic measure and record dye concentrations.

Another commonly method involves placing activated charcoal dye receptors (Figure 13) into

Figure 12. 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).

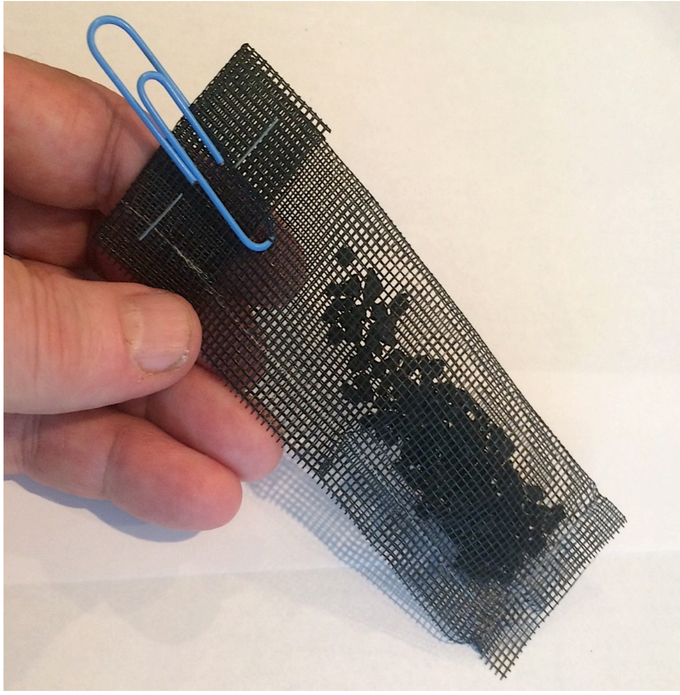

Figure 13. Activated charcoal dye receptor used in fluorescent dyes tracing of karst groundwater. The receptor is placed in the flow of a spring, and if the dye passes that location it adsorbs onto the charcoal. The charcoal is then analyzed in a laboratory for the presence of dye (Photo by Chris Groves).

the flow of any springs to which the dye might travel, and if the dye flows past that point it will adsorb onto the charcoal, which is collected and taken back to the laboratory. The methods 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 characteristics of 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 aquifers of Jefferson County (Jones, 1997), including in the vicinity of the RAN 5 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 dye showed cleared results (Figure 14). Two traces in the vicinity of The RAN5 Project facility, including an injection site about one mile from the facility (Trace D) and another about 4 miles away (Trace A) showed direct connections to numerous springs in a radial pattern. Trace A, with rhodamine WT dye injected to the south of the RAD Project facility, flowed to nine springs flowing in turn to the Shenandoah River, with estimated groundwater flow velocities ranging from 150 to 235 feet per day. Rhodamine dye from test D flowed north to six Springs which flow to the Potomac River or Opequon Creek. Estimated groundwater flow velocities for the traces to sites other than flow D7 (Figure 14) 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

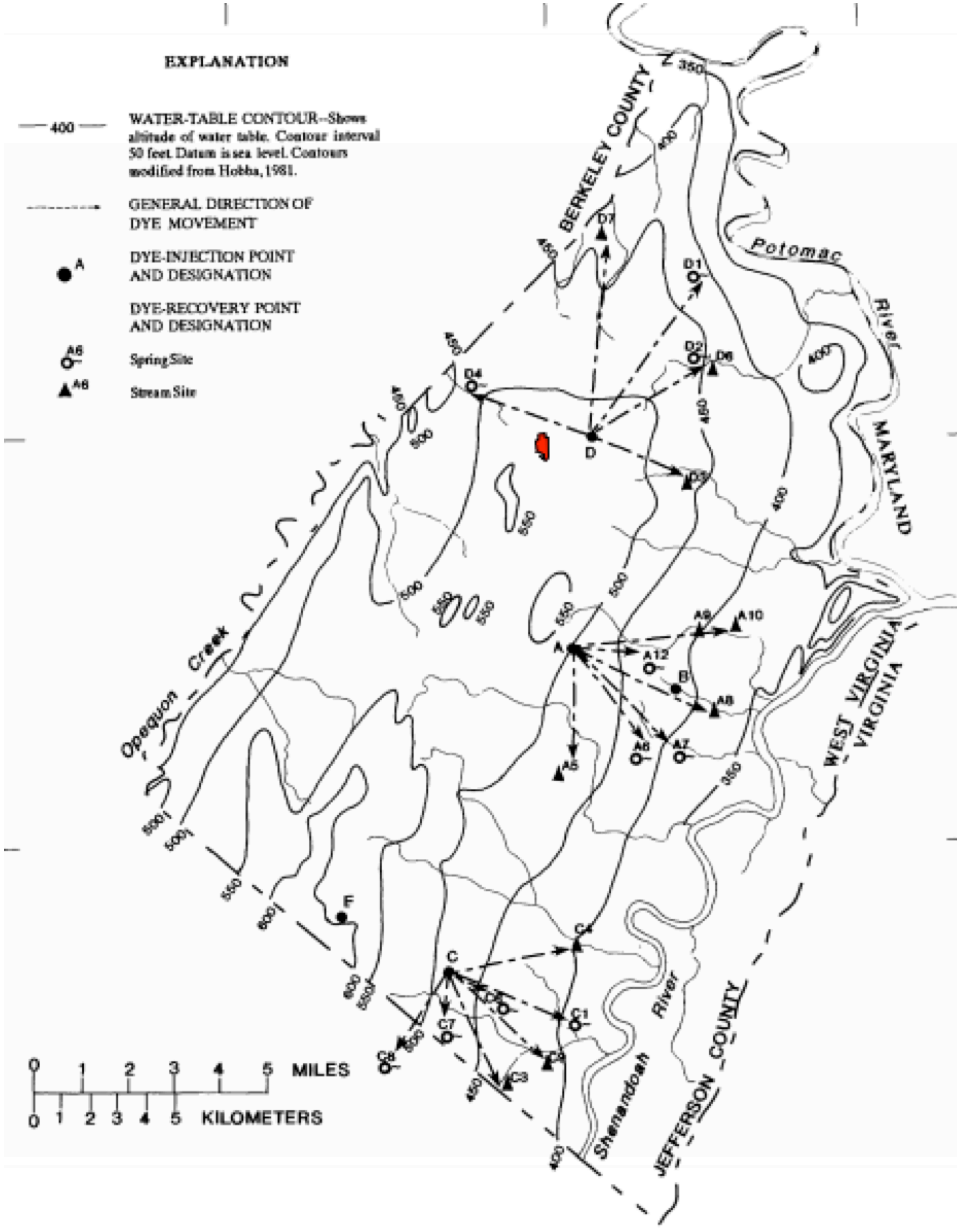

Figure 14. Results from three dye traces conducted from 1987-89 by Kozar et al. (1991) with approximate Location of facility shown. Traces in the vicinity of the facillity showed direct connections to numerous springs in a radial pattern. Trace A, with rhodamine WT dye injected near the southern end 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.

Such conduits exist within the karst aquifers of Jefferson County. Indeed, Davies (1965) described maps of 16 caves of explorable size in the county.

The radial flow pattern emanating out from the vicinity of the RAN 5 Project facility indicates 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 or Opequon Creek —somewhere between the injection points for Trace A and Trace D. This means that sediment or other contamination entering the aquifer either from construction, or potentially a leak, 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. While due to proximity it seems more likely that groundwater flow from the RAN 5 Project facility would flow towards the springs associated with Trace D than those in Trace A, it is not possible to know for certain without 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 (Figures 15 and 16) including traces from the southwest of the RAN 5 Project facility (Jones and Deike 1981). Dye for one of these traces was injected into Leetown Sinkhole about two miles southwest of the RAN 5 Project facility, and flowed to four springs including Balch Spring at the US Geological Survey Leetown Science Center (LSC). Subsequent hydrologic work (Kozar et al. 2007) (Figure 17), 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 Leetown Sinkhole to Balch Spring at the LSC (Jones 1997). Since the RAN 5 Project facility is not shown at the scale of Figure 17, blue circles are shown in Figures 15-17 showing the location of Leetown Sinkhole to correlate the maps.

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 farther from the facility and 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 southwest of the RAN 5 Project (Figures 15-17) reveal a similar but more complex situation where depending on the exact location of the injection, dye can flow to the north or west, or less likely to the south, due to a radial flow pattern. The RAN 5 Project facility lies to the northern end of this area of radial flow. Due to the close proximity to previous dye tracing work, the facility likely lies close to the groundwater divide between the Potomac River and Opequon Creek and could go either way depending on the exact position that water or contaminants enter the ground. Without additional detailed tracing work, there is uncertainty about which of these directions contamination introduced into the aquifer from the facility would travel, although 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. Such tracing directly from the facility is highly recommended.

Figure 15. Dye traces were summarized by Jones (1991), including those shown in Figure 14 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 approximate location of the RAN 5 facility is shown. Blue circle shows Leetown Sinkhole.

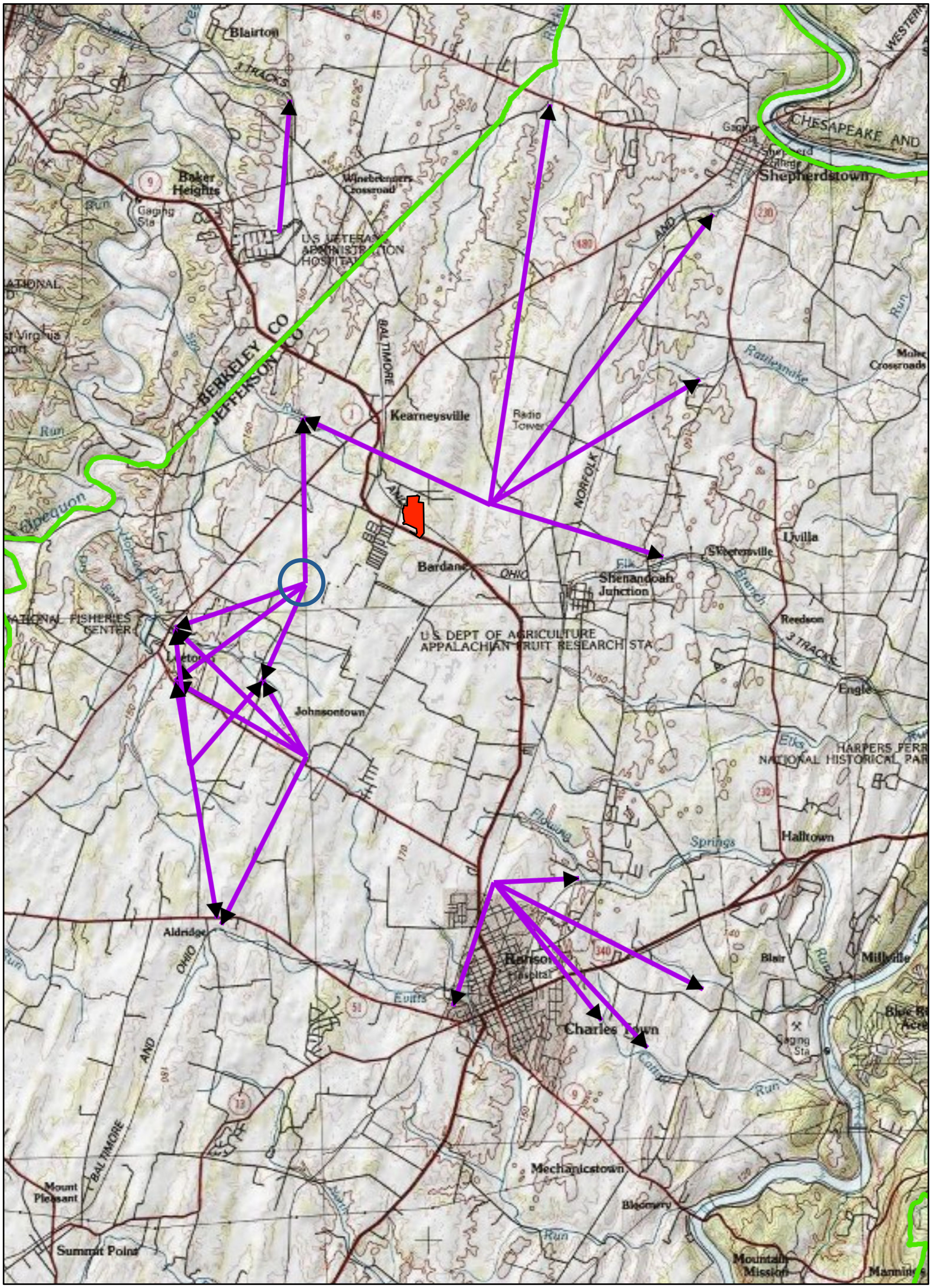

Figure 16. Dye traces summarized by Jones (1997). This is the map shown in Figure 15, for clarity redrawn for this report. The approximate location of the RAN 5 facility is shown. Blue circle shows Leetown Sinkhole.

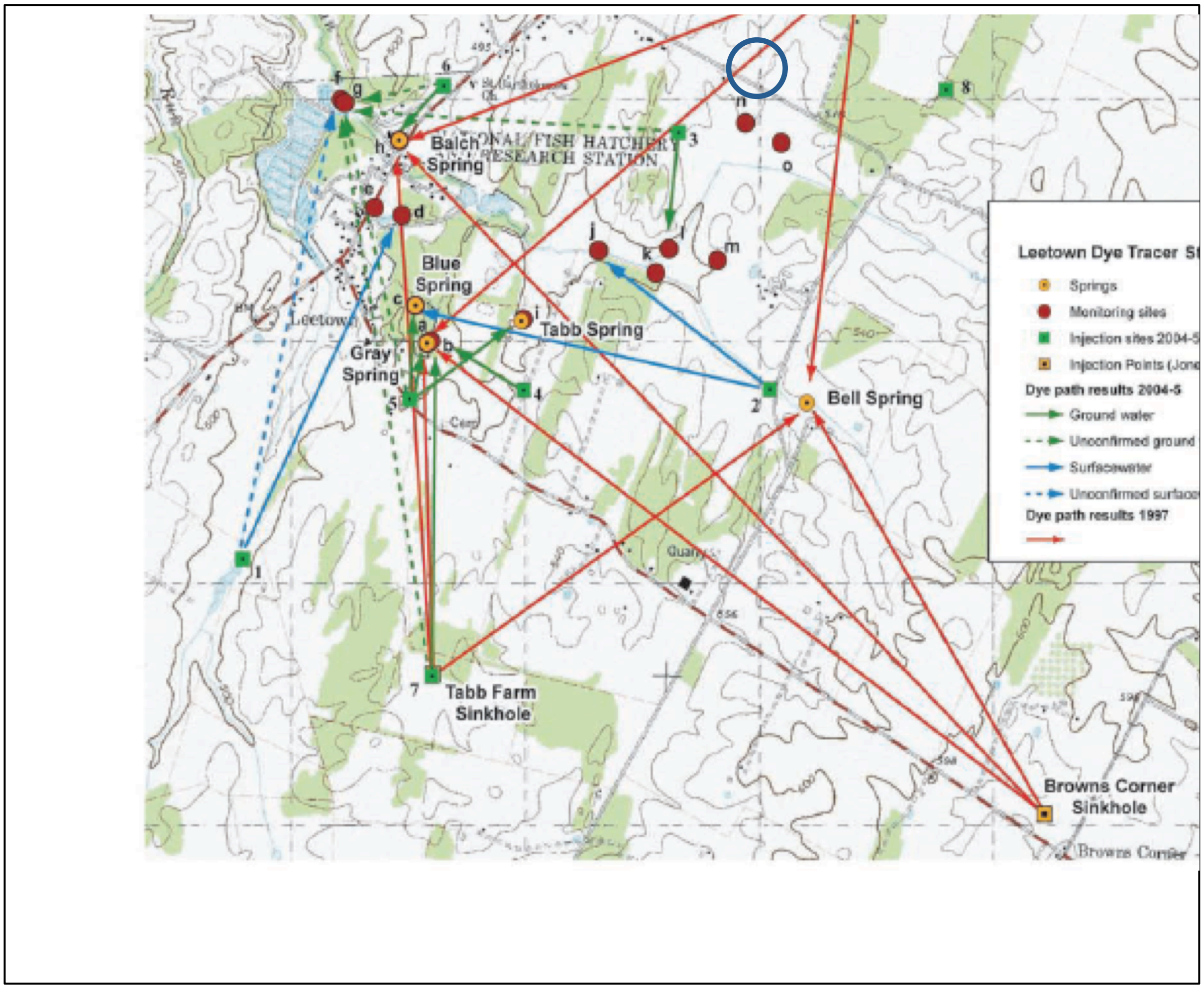

Figure 17. Dye tracing in the vicinity of the US Geological Survey Leetown Science Center (Kozar et al. 2008) with earlier traces (Jones 1997) shown. The blue circle shows the injection location at Leetown Sinkhole that flowed to Balch Spring at the LSC, also shown on Figures 15 and 16.

An additional source of information about groundwater flow that is often useful concerns the geometry of the 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 a 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 14) but because the complexity of the geologic structure and the 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. While due to this structural complexity it cannot be certain, the hydraulic gradients in the vicinity of the facility suggest flow towards springs of Kozar et al.'s (1991) Trace D.

5. Comment on the Pollution Prevention Analyses for the RAN 5 Project

The current analysis has established that the footprint of the project lies on carbonate rocks with well-developed karst landscapes and aquifers, that these landscapes are subject to inherent characteristics that present development challenges such as sinkhole collapse, and perhaps most importantly, that groundwater in these aquifers is extremely vulnerable to contamination. Indeed, in the area of the facility spills released to the groundwater system can travel relatively quickly through systems of fractures and conduits to emerge at springs which can then be polluted along with receiving streams into which they discharge. Understanding of details of the resulting hydrogeology--including the directions of groundwater flow and the springs and rivers that contamination would ultimately reach—is critical for considering how to protect these groundwater and surface water resources.

A series of evaluation and planning projects have been made for the site which pay varying attention to the impact of local karst hydrogeology on the potential environmental risks of site construction and operation (e.g. Specialized Engineering 2017; The Thrasher Group, Inc. 2017; 2019; Environmental Resources Management, Inc. 2019a, 2019b; 2020).

The landscape and hydrology of Jefferson County have been 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) and these data have formed much of the basis for the analysis in the current report.

However, there is a disconnect. Perhaps the most relevant analyses related to the facility and environmental impacts related to karst are the *RAN 5 PROJECT Storm Water Pollution Prevention Plan Roxul USA, Inc. Jefferson County, West Virginia* (The Thrasher Group, Inc. 2017, with amendments), the *RAN 5 Project Groundwater Protection Plan* (Environmental Resources Management, Inc. 2020), the *Integrated Environmental Plan Storm Water Pollution Prevention Plan and Groundwater Protection Plan RAN 5 Facility* (Environmental Resources Management, Inc. 2019a), and the *Spill Prevention and Response Plan RAN-5 Manufacturing Facility* (Environmental Resources Management, Inc. 2020). Considering the critical importance of karst hydrogeology in understanding and planning to minimize the impacts of site construction and operation on water resources, and indeed considering relatively extensive work that has been done in Jefferson County and the readily available literature describing those results, with the exception of the 2017 geotechnical report (Specialized Engineering 2017) discussion of karst hydrogeology in these reports seems to have been cursory. The single most basic and important method to understand ground water flow in these environments, even to investigate basic questions of which direction and to where groundwater is flowing, is fluorescent dye tracing. And although abundant results are readily available, these critical data were not considered in any of these evaluations.

6. Conclusions

An evaluation of risks associated with construction within the area impacted by the RAN 5 project, based on a review of existing literature, shows that the facility 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 the facility is for groundwater contamination. While an analysis of the efficacy of engineering plans to prevent introduction of potentially contaminated stormwater, sediment, and other chemicals associated with construction and the manufacturing process is beyond the scope of this report, in the case of a release of groundwater impacts could be catastrophic in ecological terms (a complex ecosystem that includes the federally threatened Madison Cave isopod lives within the karst aquifer of Jefferson County) and potentially creating human disruptions by polluting groundwater, springs, and the surface waters to which these springs flow. Indeed, with the current state of understanding it is not clear to which spring, or potentially wells, such contamination would flow, or put another way, what the receiving stream(s) for the facility even are. Although there has been considerable progress in understanding ground water flow through dye tracing in northern Jefferson County, tracer tests from the facility itself would be required to identify the particular springs and streams that would be impacted by a release of contamination.

This is a well-studied groundwater system, and dye tracing shows the RAN 5 Project overlies the northern part of an area of radial flow. Contaminants introduced along the route could potentially flow northward towards the Potomac River, or westward toward springs at the US Geological Leetown Science Center or elsewhere along Opequon Creek. Though less likely, flow towards springs reaching the Shenandoah River is also a possibility.

Although I have focused on an analysis of hydrogeological conditions that could lead to risk in the construction and operation of the RAN 5 Project, rather than any engineering solutions, there are strategies and practices that can help to mitigate these risks. This is an environment where spills into the groundwater could have enormous costs, and I encourage those responsible for project planning and implementation to take the strongest possible measures to prevent this from occurring in the first place. Because the site lies close to a groundwater divide between the Potomac River and Opequon Creek, groundwater dye tracing should be undertaken from several points at the facility to identify the spring(s) and stream(s) that would be impacted by a release of contamination.

7. References

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8. 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).

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.

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. In this case the area’s base level streams are the Shenandoah and Potomac Rivers, and Opequon Creek

carbonate aquifer: an aquifer developed with the carbonate rocks limestone or dolomite.

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.

data sonde: an instrument for electronically collecting water quality data and storing the information on a computer on real-time 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.

drainage basin: in karst settings an area of the landscape from which rainfall infiltrating the ground drains to a spring.

field fluorometer: an instrument used in fluorescent dye tracing that electronically records dye concentrations and records the data on a computer.

fluorescent dye tracing: mapping out the pathways of underground water using fluorescent dyes.

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.

groundwater: water in the saturated zone of an aquifer, below the water table.

hydraulic gradient: the direction and slope of the water table surface.

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.

permeable: permeability describes 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%.

recharge: rainwater or snowmelt that soaks into the ground and which in many places is the source of groundwater.

sinkhole: bowl-shaped closed depression found in karst areas.

sinkhole collapse: often sudden loss of soil and/or rock into the subsurface of a karst area leaving behind a closed depression.

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

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

topographic map: a map showing the three-dimensional shape of the land surface in an area.

water table: the surface that defines the top of the saturated zone of groundwater in an aquifer.