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KARST-WATER ENVIRONMENT SYMPOSIUM

October 30-31, 1997
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Leonard A. Shabman
Director

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FOREWORD

Karst terrane is a geological phenomenon where the landscape is formed due to the long term dissolution and erosion of carbonate rocks. The karst terrane is distinguished by the existence of caves, sinkholes, and sinking streams, and direct interaction between surface and groundwater systems. Several major groundwater aquifers in the U.S. are located within the karst formations. Karst aquifers provide about 40 percent of the total groundwater used as drinking water.

In recent years, problems associated with groundwater development and pollution have become a major concern to water managers, scientists, engineers, and citizen groups due to the detection of several contaminants in groundwater systems. Because of the unique karst features, water source protection in karst terrane is a major challenge to scientists, engineers, land use managers, and regulatory agencies. There is a critical need for better understanding of water and pollutant movement in karst-water systems and improved strategies for water and land use management, and water source protection in the karst terrane.

The major goal of the karst-water symposium, held on October 30-31, 1997 in Roanoke, Virginia was to provide an opportunity for a multidisciplinary forum of scientists, engineers, water and land use managers, and other interested groups to discuss research and technology transfer programs, and regulatory problems and experiences associated with karst-water environments. This publication is a compilation of many excellent papers submitted for presentation at the karst-water environment symposium.

It is expected that these proceedings serve as a comprehensive and updated reference for water quantity and quality assessment in karst areas and set the direction for future research, technology transfer, and educational programs on topics related to karst-water environments.

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Finally, the symposium and these proceedings would have not been possible without the participation of national and international speakers. Their contributions were responsible for the success of the symposium and publishing of these proceedings.

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AUTHOR INDEX

Keynote Address

DYES DON'T LIE: PRACTICAL KARST HYDROLOGY

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Abstract

Tracer dyes are a fundamental tool for understanding and characterizing subsurface water movement in karst settings. Unfortunately, this tool is under-utilized because of four identified constraints. These constraints are fear of the resulting data, misperceptions, regulatory concerns, and a common lack of familiarity with modern techniques and approaches. These con-straints must be overcome; avoidance or inadequate use of a fundamental groundwater tool with tremendous utility in karst hydrology is not compatible with quality professional work.

Introduction

Let's start with a quote from literature:

Their's is not to reason why;
Their's is but to do and die;
—Alfred, Lord Tennyson; "The Charge of the Light Brigade".

We can revise this a bit to make it appropriate for karst hydrology:

If we are to reason why;
Better use some tracer dye.

The fluorescent tracer dyes represent a fundamental groundwater hydrology tool for determining groundwater flow directions, groundwater travel rates, and other groundwater characteristics. The utility of the fluorescent tracer dyes is especially great in karst areas where much of the groundwater flow is along preferential flow routes. Four of the more commonly used groundwater tracing dyes are fluorescein (Acid Yellow 73, CI 45350); eosine (Acid Red 87, CI 45380); rhodamine WT (Acid Red 388, no assigned CI number); and sulforhodamine B (Acid Red 52, CI 45100). Fluorescent dyes are extremely valuable as groundwater tracing agents because of a number of favorable characteristics, which include high detectability, safe for man and the environment,

and reasonably priced. Of particular importance is the fact that these four dyes (and a few others) can be adsorbed onto samplers containing activated coconut carbon. These samplers permit continuous, cumulative sampling.

Tracer dyes are a fundamental tool for understanding and characterizing subsurface water movement in karst settings. As is the case with any tool, the use of tracer dyes is not a universal answer to all issues. However, avoid-ance or inadequate use of such a fundamental tool is not compatible with quality professional work. Unfortunately, the appropriate and proper use of tracer dyes in groundwater hydrology work is often constrained by four factors:

1) fear of the resulting data,
2) incorrect perceptions,
3) regulatory concerns, and

4) a general lack of familiarity with modern tracing techniques and analytical approaches.

The following sections of this paper discuss each of the four constraining factors and make suggestions for overcoming the constraints.

Fear of the Resulting Data

An axiom for a trial attorney is to not ask the question unless you already know the answer. In science, you ask the question to learn the answer or to test a hypothesis. We often fail to ade-quately appreciate these diametrically opposite strategies. Furthermore, there is sometimes a tendency to falsely cloak concerns in the fabric of science while using strategies more appropriate for trial attorneys. Commonly, those who fear the answer are likely to take refuge in a host of minor issues and specious concerns. Properly designed groundwater tracing studies can adequately address the credible issues. Enhanced pro-fessional and public understanding of groundwater tracing with the tracer dyes is the ultimate solution to specious concerns raised by those who are fearful of what the resulting data may show.

The author has conducted hundreds of groundwater traces associated with waste sites. Those responsible for the wastes, often regulatory entities, are commonly convinced (or are at least fearful) that a groundwater tracing study will yield positive dye recoveries at numerous sites over a large area. While this may be the case, and there are examples in the technical literature, this is not the typical result. In most cases, a well designed groundwater tracing study will dramatically reduce the size of the area of potential impacts, and will identify areas and locations where monitoring and other activities should be focused.

Some may fear the data from a groundwater tracing study because they are aware of a poorly designed or conducted tracing effort at some other site. Just as in any other poorly designed scientific study, poorly designed traces routinely leave important questions unanswered, and in some cases lead to incorrect conclusions. A common study design flaw is inadequate background sampling to identify and quantify background fluorescence in urban or industrial settings. In the final analysis, groundwater tracing investigations using fluorescent dyes are neither so complex nor so difficult that incorrect conclusions are likely.

Groundwater tracing studies should be under the technical direction of persons who have success-fully conducted similar investigations. Pre-paration of a detailed study plan, and appro-priate review of the plan, will help insure that groundwater tracing studies are coherently designed and will be appropriately conducted. Field personnel should carry copies of the study plan during their field work; this helps insure that the work will be conducted as planned by the study designer.

Incorrect Perceptions

The first common misperception is that groundwater tracing with fluorescent dyes has limited utility and works well only where there are major cave streams and other well developed karst features. Groundwater tracing does rou-tinely work well in such settings, but it also works well in almost any setting where at least some of the groundwater movement is along preferential flow routes.

The following examples from the author's experience show the range of utility of the groundwater tracer dyes in karst and non-karst settings. Fluorescent tracer dyes have been traced:

1) From septic systems into seeps and bulkhead drains that contribute to marine shell-fish beds in Thurston County, Washington. Dye was introduced into 992 on-site sewage systems serving waterfront homes. The dye was subsequently detected from 23 percent of these (1).
2) From monitoring wells to pumping wells during pump tests. The dyes indicate travel rates along preferential flow routes; in contrast, pump test data characterize mean flow rates.
3) From points on the surface where water sinks to springs where it discharges. In the southern Missouri karst the longest groundwater traces were 39.5 miles straight-line distance. Travel time for the first dye arrival was 16 days for the first trace and 13 days for the replication.
4) Through basaltic lava flows; dye transport has apparently occurred both through fractures and though paleosoil zones.
5) Through fractured ryolite and granitic rocks.
6) Through landslide debris and through waste rock from mining.
7) Through clay-rich residuum up to 100 feet or more thick underlain by dolomite or limestone.
8) Through coal beds and abandoned mines.
9) Through alluvium.
10) From industrial waste sewers to stormwater line; from sanitary sewer lines to springs and wells.
11) From service station tank pits to wells.
12) From numerous locations into monitoring wells.

The second common misperception is that groundwater tracing tests have a high likelihood of failure. The primary reason for failures of dye tracer tests is faulty study design. The most common study design problems are:

1) Inadequate background sampling.
2) Inadequate sampling stations; points to which the dye moved were not included in the sampling network.
3) Failure to adequately monitor surface streams for dye discharges. Various biological and chemical processes destroy or remove tracer dyes from surface waters.
4) Reliance on grab samples of water or visual observations rather than on continuous and accumulating samplers.
5) Poor choice of dye for the setting and/or use of too little dye or water.
6) Poor selection of dye introduction point or points.
7) Sampling intervals that are too long and/or study durations that are too short.
8) Inadequate dye analysis instruments and/or inadequate analysis protocol.

The third common misperception is that groundwater traces are prone to yielding strongly colored water at some location where it will interfere with the use of the water or anger residents. In most cases there is little or no risk of such problems. The author has conducted a number of groundwater traces to aid in wellhead delineation of municipal wells; these have not resulted in any problems. Informing residents, police and other officials, and other relevant entities prior to introducing dyes prevents most problems. Furthermore, the public supports the approach of using harmless dyes to understand groundwater systems and thereby provide adequate water quality protection.

The fourth common misperception is that groundwater tracing is not necessary because other methods (such as potentiometric mapping or computer modeling) will provide the needed data. This simply is not true. The single most distinguishing feature of groundwater circulation in karst systems when contrasted with other types of systems is that the voids in soluble rocks are predominantly created by the flow regime. As a result, the permeability structure is a consequence of the imposed circulation system, and the permeability structure is organized to facilitate the circulation of water in the downgradient direction (2). Potentiometric maps do not permit one to interpret the location and structure of the local karst groundwater circulation system. Furthermore, while the con-duits within the system have a hierarchical organization similar to surface streams, numerous interconnections are possible between conduits of any order, and just which conduits are utilized can be highly stage dependent (2). Many areas share their recharge waters between two or more springs, and very complex multidirectional groundwater flow has been documented in some areas (3).

Groundwater tracing also provides data on travel times. While one can estimate travel times from various modeling approaches, the credibility of calculations is unverified unless tracing studies are conducted. The author once worked on a site where groundwater movement was through fractured rock. One model estimated travel time from an injection well to a recovery well at 28 days; another model yielded an estimated time of about 20 days. A groundwater trace was designed to determine which was the better model; travel time for the dye was 20 minutes (no, this is not a typographical error).

Regulatory Concerns

Do we know that the use of the tracer dyes constitutes a safe practice? The simple answer is yes, and this applies to all of the dyes commonly used in groundwater tracing work. Extensive assessments of the toxicity and adverse properties of the tracer dyes have been published (4, 5). Anyone considering or reviewing a ground-water tracing study should have copies of these important papers. Should you have difficulty obtaining such copies, please feel free to contact the author for a copy.

Field *et al.*, (4) recommend that the use of tracer dyes in the environment should not exceed concentrations of one to two milligrams per liter persisting for a period in excess of 24 hours in the groundwater at the point of groundwater withdrawl or discharge. This concentration limit is two to three orders of magnitude greater than the detection limit of the most commonly used dyes in water samples, and groundwater tracing using appropriate dyes and activated carbon samplers can be reliably done with even smaller dye concentrations.

Some states have approached water quality regulations with an inherent assumption that nothing unnatural should be intentionally added to the water, and that everything unnatural is a waste or is, for regulatory purposes, analogous to a waste. Tracer dyes are sometimes caught in this regulatory trap; they are not wastes, and they are not added to the water for purposes of disposal. The number of state agencies which have resisted the use of tracer dyes because of this regulatory trap is steadily declining as the utility (and indeed the necessity) of conducting dye tracing studies has become more widely understood and accepted. Reference (4) in a refereed toxicological journal has also been of great help, as have analytical approaches which minimize the amounts of dye necessary for credible tracing work.

Unfamiliarity with Modern Tracing Approaches

Modern groundwater tracing approaches are vastly improved over those that were "state-of-the-art" only a few years ago. Ten or fifteen years ago even most experienced karst hydrologists assumed that water introduced at a particular point would discharge from only one spring. While the concept that dye might discharge from several nearby springs was not that difficult to accept, there were those who believed that dye discharges to springs in different topographic basins somehow violated some law of physics. The fallacy of the assumption that dye could only discharge from one spring, or perhaps only from nearby springs, was demonstrated by well-conceived groundwater tracing studies that clearly showed dye recoveries at multiple groundwater discharge points. These findings resulted in the recognition by experienced practitioners that groundwater tracing studies should not be ended just because the introduced dye had been recovered at one spring.

Some karst hydrologists who conduct groundwater tracing studies have suffered failed traces because they failed to monitor the crucial spring. Not only can one miss springs, but some flow only during storm events, and others discharge to streams from beneath gravel deposits. Well designed groundwater traces routinely include sampling stations on streams to insure that all discharging groundwater is monitored for dyes. As a general rule, such sampling stations should be located no further than about a mile apart along a stream. This guidance must be strongly tempered with a number of site-specific considerations, and listing these is beyond the scope of this paper. However, a groundwater tracing program where sampling stations are routinely located at greater intervals than about one mile will routinely fail to detect most dye discharges unless the dye concentrations are particularly large.

There are some compounds which produce fluorescence peaks in or near the wavelength range characteristic of some of the tracer dyes. Additionally, small concentrations of some of the same dyes used in groundwater tracing are sometimes present, especially in urban and industrial areas. Background sampling to detect and quantify the presence of fluorescent compounds at sampling stations prior to any dye introduction is a standard component of modern groundwater tracing work. With adequate background sampling, one can work with most of the tracer dyes in almost all settings. The author has never encountered a site where background fluorescence conditions precluded the use of all of the fluorescent tracer dyes. However, background fluorescence presents much greater problems for filter fluorometers than for spectrofluoro-photometers which can synchronously scan excitation and emission fluorescence and then print out a graph of emission fluorescence intensity. Most professional grade groundwater tracing work now relies on laboratory dye analysis work which utilizes synchronous scanning protocols on spectrofluorophotomers.

The use of spectrofluorophotometer and synchronous scanning protocols for dye analysis has greatly reduced interference between background fluorescence and fluorescent tracer dyes used in groundwater tracing studies. Additionally, these instruments, as compared with filter fluorometers, have decreased the dye concentrations needed for credible dye detections by one to two orders of magnitude. The ability to conduct groundwater traces using relatively small amounts of dye also enhances the utility of modern groundwater tracing techniques. However, there is an important caveat; credible groundwater tracing requires the use of adequate quantities of dyes. There is no equation which is universally usable for determining the amount of dye necessary; the amount varies dramatically with the hydrogeologic setting. For example, Aley (6) reported the following:

"...the existing literature could lead one to conclude that 20 to 50 percent of the introduced dyes should be expected to discharge from dye recovery sites, and that a number of different dyes can be successfully used. Based upon our experience in epikarstic tracing work, dye recovery rates are commonly 0.1 to 1 percent for the permanently saturated epikarstic zones, and from 1 to 10 percent for the seasonally saturated zones."

One of the great advantages of the spectrofluorophotometers and synchronous scan protocols is that they yield quantitative data. Not only can dye concentrations be calculated, but detection limits can be determined for each of the dyes and for each of the matrixes in which they are typically present. Additionally, statistical analysis of field results can be used to calculate acceptable emission fluorescence wavelength ranges which are specific for each dye, each dye matrix, and for each analytical instrument. Table 1 summarizes such data for a Shimadzu RF-5000U in use at the Ozark Underground Laboratory. Mean emission fluorescence wavelength peaks resulting from several hundred positive groundwater traces were calculated; the acceptable wavelength range for each of the entries in Table 1 represents the mean wavelength range minus and plus two standard deviations.

Dyes Don't Lie

One of the greatest benefits of groundwater tracing studies using fluorescent dyes is that they provide direct data about the direction of groundwater movement and about groundwater travel rates. In contrast, potentiometric maps provide data from which inferences (which may or may not be correct) are drawn. Potentiometric maps, pumping tests, and models may be used to estimate travel rates; and again, they provide data from which inferences are drawn. Dyes don't lie. They clearly identify points to which the dyed water moves and can identify times of first arrival, peak concentration arrival, or the complete dye breakthrough curve if this is desired.

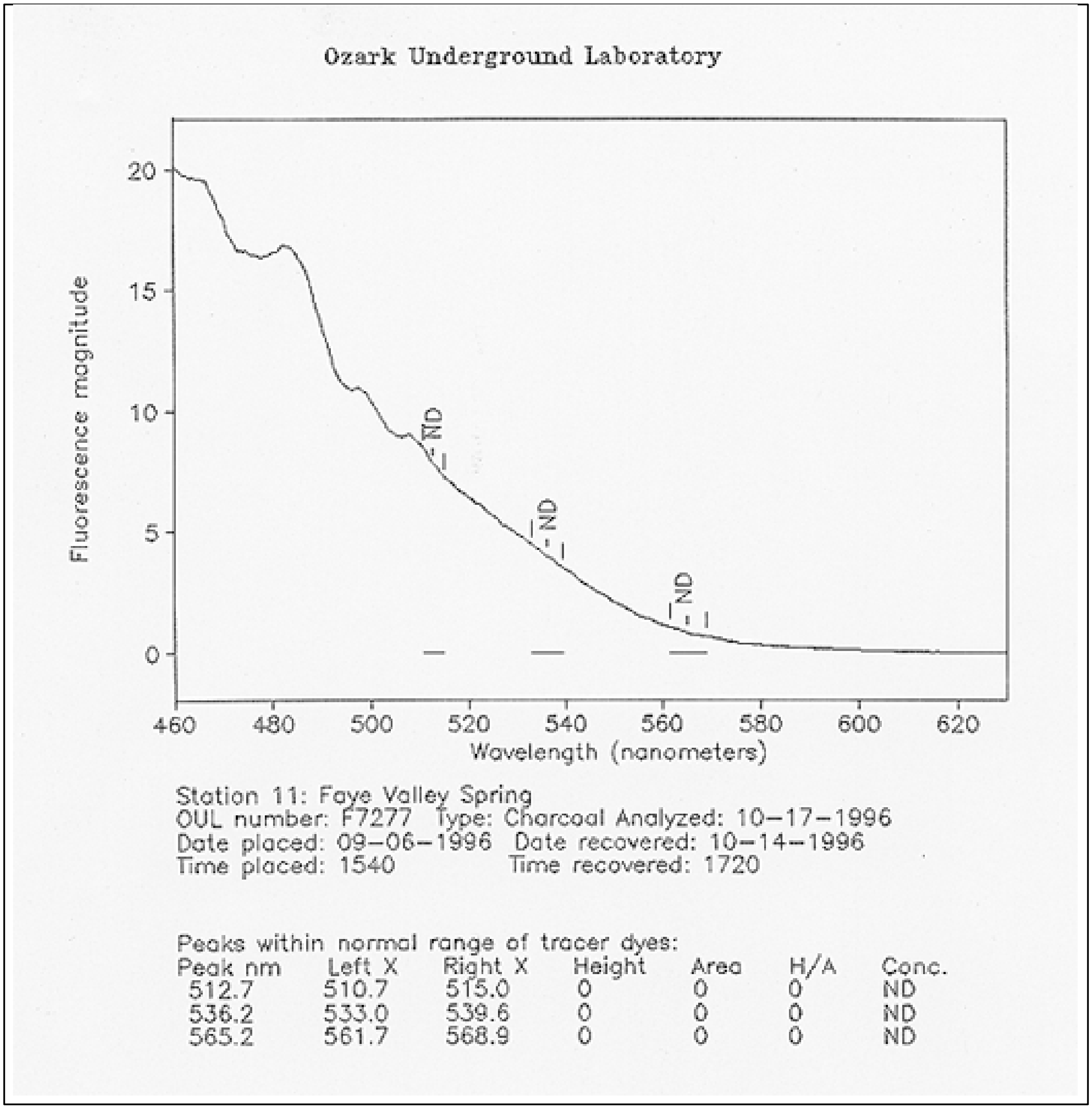
Figure 1 shows a typical dye analysis graph for an activated carbon sampler in place at a sampling station where no tracer dyes were detected during the sampling period. Figure 2 shows a dye analysis graph for an activated carbon sampler in place at the same station when both fluorescein and rhodamine WT dyes were present. The fluorescence peak in Figure 2 reflective of fluorescein is at 512.6 nm; the dye concentration is 11.4 micrograms per liter. The fluorescence peak in Figure 2 reflective of rhodamine WT is at 563.3 nm; the dye concentration is 148 micrograms per liter. Fluorescein dye is more fluorescent than is rhodamine WT. This is the primary reason that the fluorescein peak in Figure 2 is larger than the peak for rhodamine WT.

Figures 1 and 2 clearly show that dye tracing results are readily understandable; in the first graph there are no dyes detected, then in the second graph there are two dyes present. With good study designs and good project work, the results of dye tracing studies are fundamentally credible. Dyes don't lie.

Table 1. Normal emission wavelength ranges and detection limits for fluorescein, eosine, rhodamine WT, and sulforhodamine B dyes in water and elutant samples.

Dye and Medium	Normal Acceptable Emission Wavelength Range (nm)	Detection Limit (micrograms/L)
Fluorescein in Elutant	510.7 to 515.0	0.0100
Fluorescein in Water	505.6 to 510.5	0.0005
Eosine in Elutant	533.9 to 539.6	0.0200
Eosine in Water	529.6 to 538.4	0.0010
Rhodamine WT in Elutant	561.7 to 568.9	0.1550
Rhodamine WT in Water	569.4 to 574.8	0.0070
Sulforhodamine B in Elutant	567.5 to 577.5	0.1150
Sulforhodamine B in Water	576.2 to 579.7	0.0090

Note: The normal acceptable wavelength range equals the mean plus and minus two standard deviations; these values are from actual groundwater tracing studies previously conducted by the OUL. Detection limits are based upon the as-sold weight of the dye normally used by the OUL.



Peak nm	Left X	Right X	Height	Area	H/A	Conc.
512.7	510.7	515.0	0	0	0	ND
536.2	533.0	539.6	0	0	0	ND
565.2	561.7	568.9	0	0	0	ND

Figure 1. Dye analysis graph for an activated carbon sampler in place at a station where no tracer dyes were detected during the sampling period.

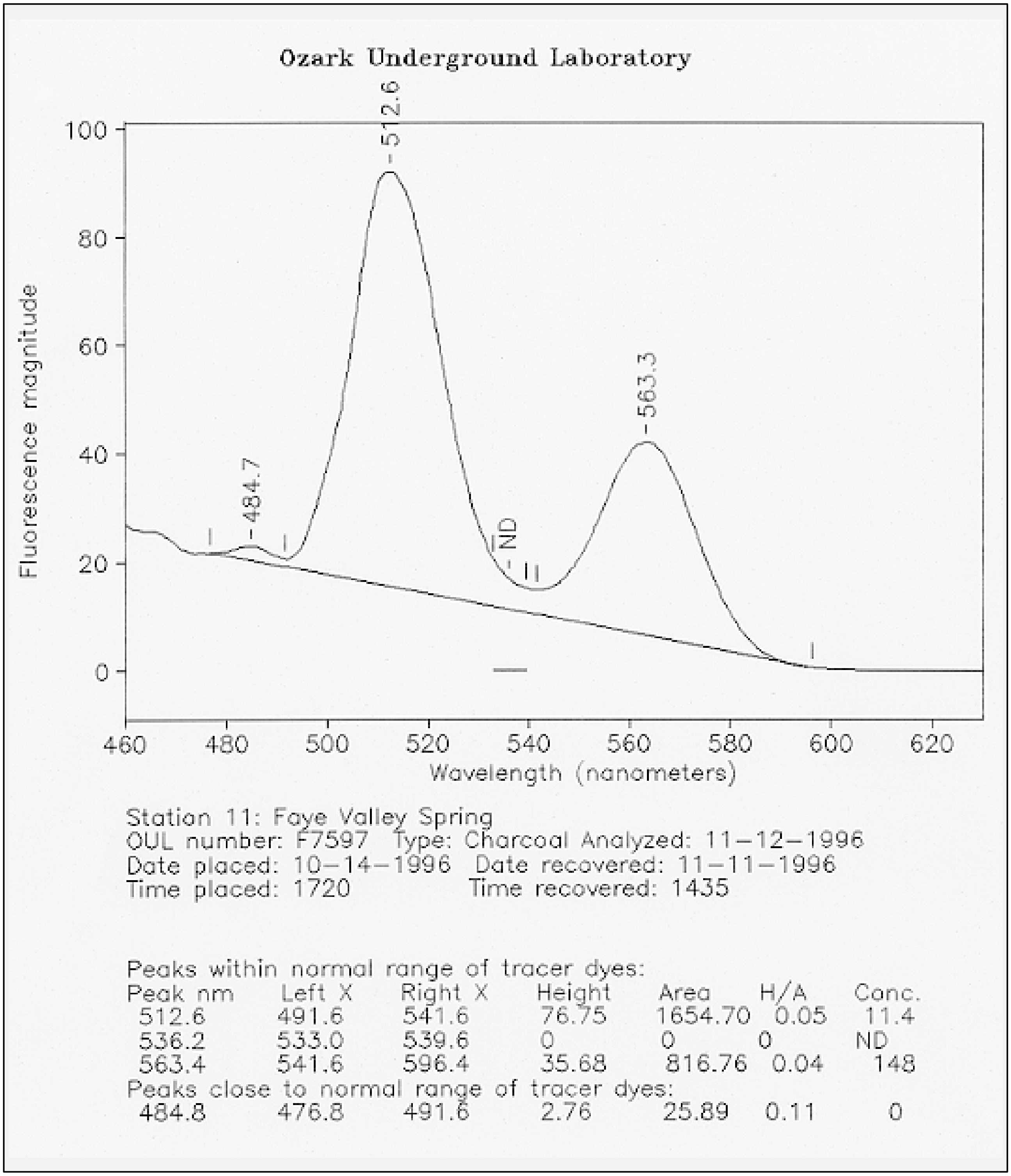


Figure 2. Dye analysis graph for an activated carbon sampler in place at a station where both fluorescein and rhodamine WT dyes were detected during the sampling period. The fluorescein peak is at 512.6 nm; the dye concentration is 11.4 micrograms per liter. The rhodamine WT peak is at 563.3 nm; the dye concentration is 148 micrograms per liter.

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GROUNDWATER TRACING FOR SPRING BASIN DELINEATION IN A FLOOD-PRONE AREA OF RUTHERFORD COUNTY, TENNESSEE

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ABSTRACT

Groundwater tracing was utilized in three spring drainage basins of Rutherford County, Tennessee, to determine how sinkholes, karst windows, and the springs are interconnected for the purpose of understanding present sinkhole flooding problems and planning for future growth. Ten successful dye traces were conducted. Seven of the traces went to Bushman Spring enabling the calculation of a drainage basin size of 10.2 mi.2 One tracer traveled a distance of over five miles in approximately three days. Double Springs was found to be a sub-basin within the larger Bushman Spring Basin. Two dye traces were conducted to Nice Mill Springs yielding a basin size of approximately 6.7 mi.2 The tenth trace was to Compton Spring. More tracing is needed to this large spring to determine the recharge area. In all of the spring basins, groundwater moves through the Ridley Limestone perched above the Pierce Formation. Rapid movement of the tracing agents suggests that the subsurface cavities have not been clogged by human activities. Constructed geologic and topographic cross-sections combined with two-foot contour map information, shows that the karst water table is very close to the surface. As a result, natural constrictions associated with changes in cave passage size cause stormwater entering the subsurface to backup behind the constrictions resulting in flooding of upgradient sinkholes. The orientation of joints, photo-lineaments, sinkholes, and straight cave passages in Snail Shell Cave show average similar trends of N500W and N400E. This information, along with the dye tracing results, demonstrates that a variety of tools are available to help predict the direction of groundwater flow or contaminant movement in Rutherford County.

INTRODUCTION

Rutherford County is the fastest growing county in Tennessee. According to the 1990 U.S. census, the county exhibited a 41 percent growth rate since the last census. Most of the county is underlain by soluble limestones that have developed a karst topography with numerous sinkholes, sinking and losing streams, karst windows, springs, and caves. Since much of the area is relatively flat, shallow sinkholes are not easily discernible, particularly at the 10 or 20-foot contour intervals of the USGS topographic maps. As a result, development has occurred in and around many sinkholes. With development has come increased paving and areas covered by roofs, and often the runoff is diverted to sinkholes. Stormwaters that once slowly percolated through the soil now rapidly enter the caves that comprise the underground karst drainage network. Caves, unlike storm sewers, naturally change in size. Increased runoff into the sinkholes thus back up behind the natural con-strictions. In addition, increased sedimentation and flow rates into sinkholes associated with development can clog sinkholes and portions of the subterranean drainage. Sinkholes are not solitary entities. Therefore, development around one sinkhole will likely have a pronounced impact on all others downgradient within the sub-terranean basin that leads to the spring discharge point.

The first step in understanding sinkhole flooding in a karst terrane is to determine how the caves, springs, and sinkholes are interconnected so that future growth can be planned. This is done through groundwater tracing using fluorescent dyes. This paper presents the results of 12 dye traces that were conducted. In addition, the paper will address the issue of the "openness" of the subterranean pathways and will present geologic cross-sections that show elevations of the karst water table with respect to select sinkhole bottoms, the surrounding terrain, and the springs.

STUDY AREAS

Dye tracing was conducted in three spring water basins (Figure 1). Bushman Spring is probably the largest spring in the county and is located on the Dillton Quadrangle forming the head of Bushman Creek. The results of the dye tracing performed for this report show the spring's drainage basin to be 10.2 mi.2 Nice Mill Spring is located along the bank of the West Fork of the Stones River on the Walterhill Quadrangle. The discharge range of the spring is unknown, but it appeared during the study to be quite large. The dye tracing results estimate the spring's drainage basin to be 6.7 mi.2 The third spring studied was Compton Spring which is located on the Lascassas Quadrangle near the community of Compton. Only one dye trace was conducted to this spring so no estimate of the drainage basin size can be made. Spring discharge was not measured, but it was quite large throughout the study suggesting a large drainage basin area.

HYDROGEOLOGIC SETTING

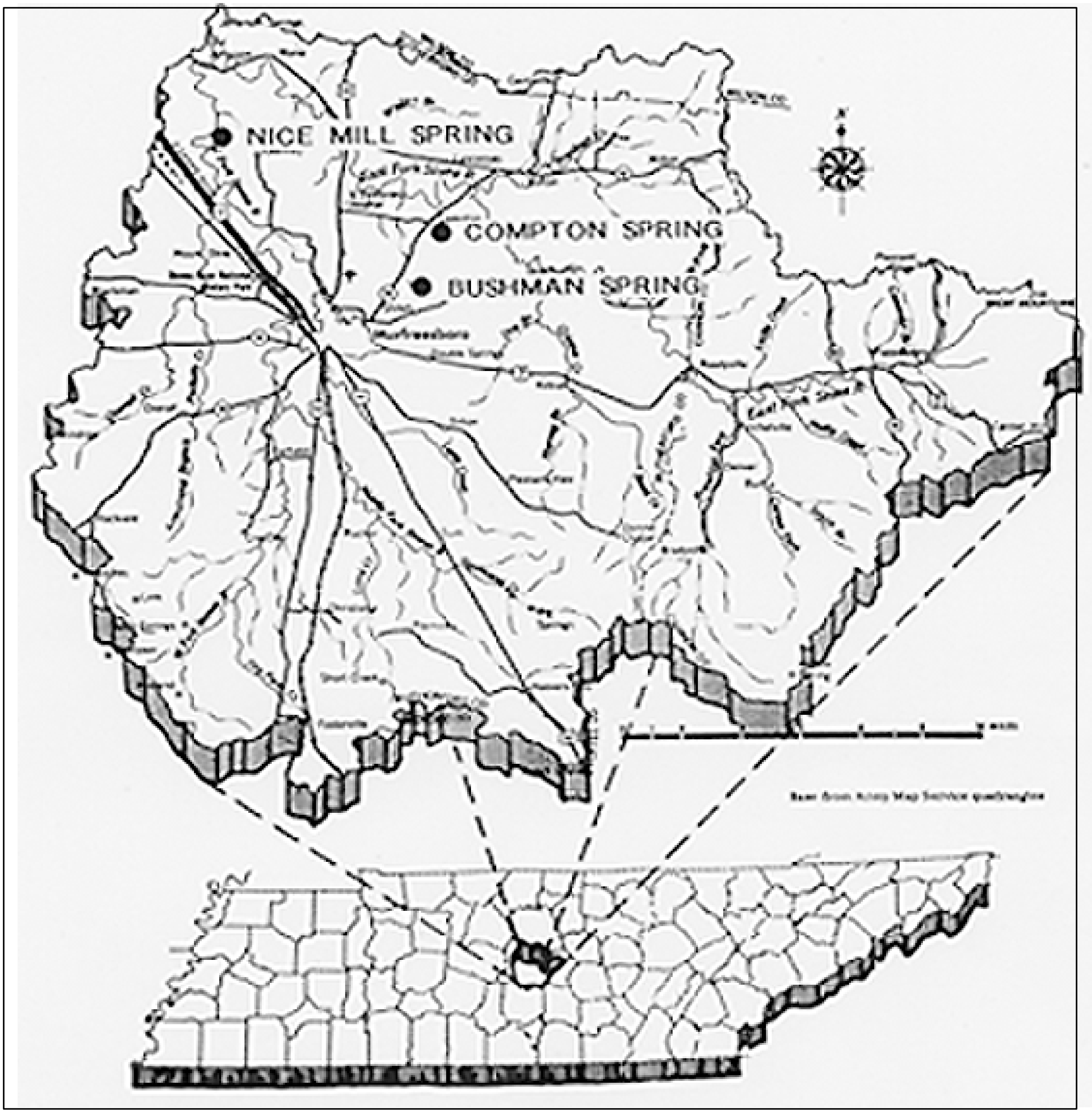
Rutherford County is located in the Central Basin physiographic province which is underlain by limestones of Ordovician age that have been gently upwarped to form the Nashville Dome. The first detailed geologic study of Rutherford County was conducted by Galloway in 1919 (1). Now, detailed geologic topographic maps exist for all of the county. The oldest rocks exposed in the study area are those of the Murfreesboro Limestone which are approximately 400 feet thick. Above the Murfreesboro Limestone is the Pierce Formation which is a shaly, thinbedded limestone that confines water beneath it in the Murfreesboro Aquifer and perches water above it in the Ridley Limestone. All of the springs involved in the study emerge at the contact between the Pierce Formation and the overlying Ridley Limestone. The Ridley Limestone is the most karstic limestone in Rutherford County. All of the dye tracing for this study was conducted in the Ridley Limestone. Above the Ridley Limestone in stratigraphic order within the Central Basin are the Lebanon Limestone, Carters Limestone, Hermitage Formation, Bigby-Cannon Limestone, Catheys-Leipers Limestone, and the Chattanooga Shale. The Ft. Payne Chert which overlies the Chattanooga Shale is the resistant formation that comprises most of the Eastern and Western Highland Rim physiographic provinces that surround the Central Basin. About 600 feet of stratigraphic section exists in the study area between the top of the Murfreesboro Limestone and the bottom of the Fort Payne Chert.

The first detailed surface and groundwater studies that were more specific to Rutherford County were conducted by Moore *et al.*, (2), Burchett and Moore (3), and Rima *et al.*, (4). Proprietary files of the Tennessee Cave Survey show that 124 caves have been discovered and explored in the county. Snail Shell Cave near Rockvale is the largest with over nine miles of passage. The first documented dye tracing in the county was conducted by Crawford (5) in the area of Snail Shell Cave as part of the state's proposal for the Superconducting Super Collider. More recently, the City of Murfreesboro contracted the U.S. Geologic Survey in Nashville to investigate flooding problems primarily within the city limits. One of the reports by Outlaw *et al.*, (6) is an extensive tabular compilation of data, but without interpretations. Much of the water level data collected involves sinkholes and creeks outside of the city limits. A study of sinkhole density comparing the various geologic formations of the Central Basin was performed by Burleyson and Ogden (7). Finally, a compilation of water levels reported by drillers for Rutherford County wells has been made by Ogden and Kaufman (8). General water table maps were made for topographic quadrangles throughout the county as part of this study.

METHODS

Orientation Data

Groundwater in karst areas flows primarily along solution-enlarged joints and caves that have developed along the joint trends. Therefore, to help predict which way groundwater flows in the study area, 118 joint measurements were made at outcrops using a Brunton compass. Two indirect methods of measuring fracture orientations are to map photo-interpreted fractures from aerial photographs and to delineate the orientation of the long axes of sinkholes. Two hundred and sixty photo-lineaments were delineated from black and white, stereo aerial photographs (1:20,000), and their orientations measured with a protractor. The long axes of 318 sinkholes were drawn on USGS topographic maps (1:24,000), and the orientations measured with a protractor, as well. Since caves represent existing or "fossilized" directions in which groundwater has moved, the orientations of passages in the county's largest cave, Snail Shell, were also measured. A straight cave segment was defined for the purpose of this


NICE MILL SPRING
COMPTON SPRING
BUSHMAN SPRING

study as a straight passage of 50-foot length. The orientations of joints, sinkhole axes, photo-lineaments, and Snail Shell Cave passages were then placed in 10° classes and plotted as rosette diagrams.

Groundwater Tracing

Groundwater tracing was conducted using the following fluorescent dyes: eosine, rhodamine WT, and fluorescein. Prior to conducting each trace, the Tennessee Underground Injection Control Program was notified for their voluntary dye registration program. The injected dyes were detected by using activated charcoal packets suspended on gumdrops that absorb and concentrate the level of dyes in the water. Prior to dye injection, the traps were placed in the waters for approximately a week to test for background concentrations. After injection of the dyes, the packets were usually changed at week intervals and sent to the laboratory for analysis.

RESULTS

Orientation Data

Figures 2 through 5 present the orientation measurements. In general, most of the joint, photo-lineament, sinkhole, and Snail Shell Cave passage data is scattered around N500W and N400E. This evidence strongly suggests that groundwater in the study areas moves along these general trends in a down-gradient direction. Another important control on the movement of groundwater is the location of the troughs of synclines. Subtle bends in the rock layers called synclines and anticlines occur "superimposed" on the Nashville Dome. These folds have been beautifully exposed for view by the recent opening of the new Interstate 840. Moore *et al.,* (2), attempted to delineate some of these folds by constructing a structural contour map of the Upper Stones River Basin with the top of Ridley Limestone as a datum. A portion of this map is shown in Figure 6. They found that the anticlines are generally dome-shaped and are found in the interstream areas. They also discovered that the synclines are elongated and that the troughs follow the trends of the streams and forks of the streams. Figure 7 shows the orientations of joints measured on the dry stream bed of Cripple Creek near Kittrell which is located on a synclinal trough. The northern orientations of the joints are essentially the same as the trough. Comparing the location of the synclinal troughs to the results of the dye tracing demonstrates some control by the troughs on groundwater flow in the study areas.

Groundwater Tracing

A total of 12 groundwater traces were conducted in three spring drainage basins. The dye was never located for two of the traces suggesting that the wrong spring was monitored or there was insufficient dye used. One trace was repeated to establish more points believed to be connected to Bushman Spring. In most cases, karst windows were monitored for dye, as well. The interconnection of injection points, karst windows, and springs of the two main basins are shown in Figure 8 (Bushman Spring) and Figure 9 (Nice Mill Spring).

Bushman Spring Basin

Most of the dye tracing was conducted in the Bushman Spring Basin. On December 20, 1996, three tracers were injected. The first was at the sink point of Double Springs stream just north of Fair Oak Court where several houses have experienced repeated flooding. This trace was detected at Bushman Spring. The tracer traveled a distance of approximately 2.5 miles in three days or less. The second dye injection occurred at the downstream end of Foreign Car Cave located next to the new Woodbury Highway. This cave contains a large stream and has approximately 400 feet of air-filled passage. A charcoal detector was placed in the upstream section of the cave in preparation for the third dye trace. The eosine dye injected into the cave stream was detected at Double Springs, the Messick karst windows, and Bushman Spring. The third tracer was injected into a sinkhole just north of Mt. Herman Church. The fluorescein dye was detected at Double Springs, the Messick karst windows, and Bushman Spring. The dye moved a minimum distance of 5 miles in three days or less.

On January 30, 1997, two dye traces were conducted to better understand the interconnection of karst windows and a sinking stream along Flat Rock Road. Rhodamine WT was injected into Flat Rock Sinking Stream which has a significant surface catchment area. Surprisingly, the dye did not go directly north to Bushman Spring but went nearly due west to the Messick karst windows (where the underground drainage then joins with the Double Springs Sinking

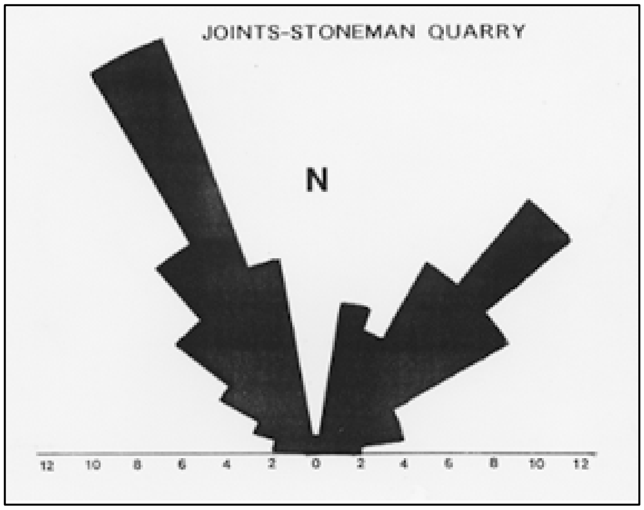


Figure 2. Orientations of joints in the Ridley Limestone.

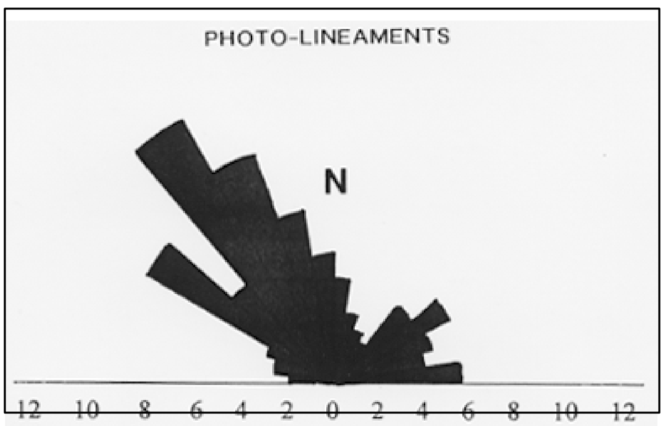


Figure 3. Orientations of photo-lineaments (photo-interpreted fractures).

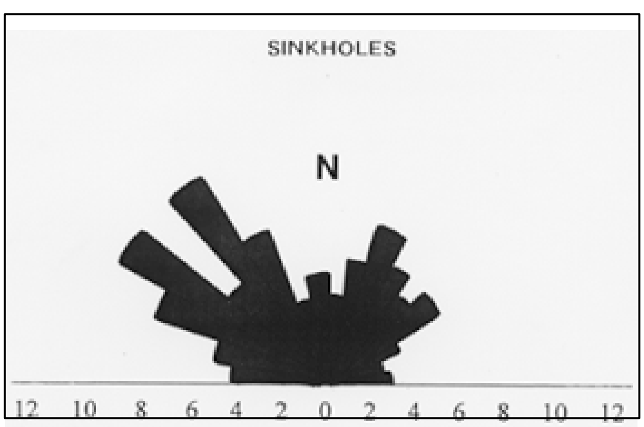


Figure 4. Orientations of the long axes of sinkholes.

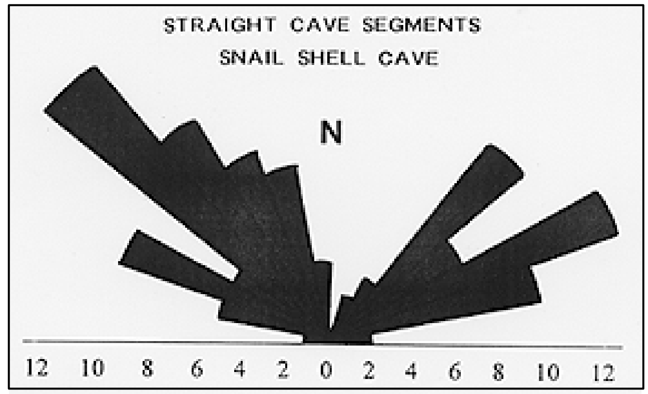


Figure 5. Orientation of straight passages in Snail Shell Cave.

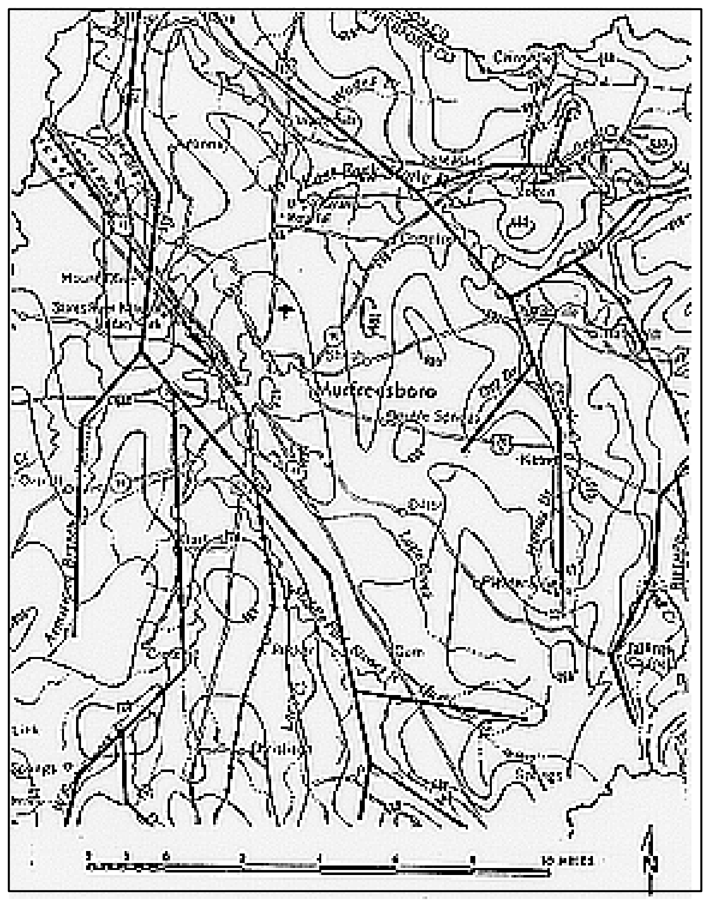


Figure 6. Location of synclinal troughs (adapted from Moore et. al., 1969).

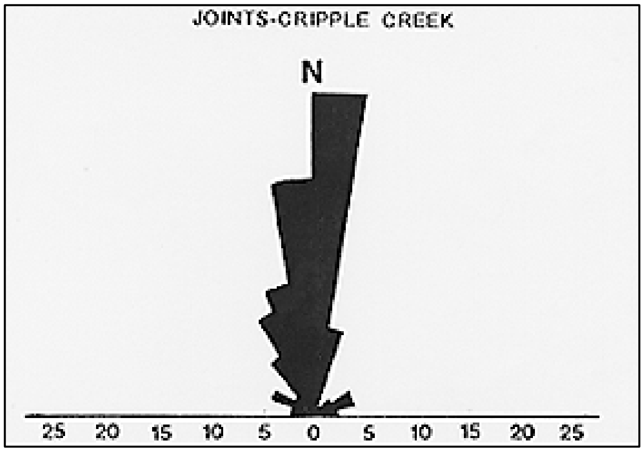


Figure 7. Orientations of joints at Cripple Creek.

Stream) where the waters continue through the subsurface to Bushman Spring. The second tracer was injected into Flat Rock Karst Window. The fluorescein dye was detected at Blue Hole (a karst window), the lower cave pool in Walker Karst Window, the Messick karst windows, Woods Edge (subdivision) Karst Window, and Bushman Spring. The concentration of dye in the Woods Edge Karst Window was low compared to the other sites suggesting a less direct hydraulic connection.

The first tracing results indicating the connection of Foreign Car Cave to Double Springs were unexpected so one more dye trace was then conducted from the cave. Selected karst windows were monitored along Flat Rock Road, as well as, Double and Bushman springs. A definite connection was determined between the Flat Rock and Blue Hole karst windows to Bushman Spring, but no dye was found at Double Springs. This strongly suggests that there is a complex subterranean connection between the stream in Foreign Car Cave, Double Springs, and the sinkholes located to the south. It is hypothesized that under low to moderate flow conditions, the recharge areas to Double Springs and the Foreign Car Cave stream are separate, but under high flow conditions some of the water in the cave splits and moves to Double Springs. This scenario is not uncommon in karst terranes, and a similar circumstance has been previously documented in the Snail Shell Cave drainage by Crawford (5).

The last dye trace conducted within the suspected drainage basin of Bushman Spring was from the Roose Well located in the Lilard Farm Estates Subdivision. Fluorescein was injected into an abandoned well on April 19, 1997 but was never detected at the spring. It is likely that the well is not connected to a solution-enlarged fracture or cavity. In such cases, travel time is very slow, and much more dye and monitoring time are required to achieve a positive detection. Topographic and geologic evidence suggest that this area is connected to Bushman Spring so it was included in calculating the spring's drainage basin size.

The trend of the dye tracing results, the fracture trend data, and topographic evidence suggests that a sizable area southeast of Mt. Herman Church is also connected to Bushman Spring. Therefore, this area has been included in the delineation of the basin area. The size of the Bushman Spring drainage basin is therefore calculated as 10.2 square miles with the Double Springs catchment area representing a sub-basin within that total.

Nice Mill Spring Basin

Two dye traces were successfully completed in the Nice Mill Spring Basin on February 22, 1997. The first trace was from a karst window located below the Bethel Church. Dye packets were placed in the upstream sections of the Sulphur Springs, Shacklett, and Buckeye karst windows. The dye was detected in all three indicating dye movement at a rate of approximately 2 miles in three or less days. The three karst windows in the basin show that most of the water flows through a well-integrated cavern system to its discharge point near Nice Mill on the West Fork of the Stones River. The large flow of the stream in Buckeye Karst Window strongly suggests a recharge area much larger than the two traces indicate. Therefore, additional area was added to the delineated drainage basin based on other geologic evidence. The size of the Nice Mill Springs drainage basin is thus speculated to be 6.7 square miles.

Compton Spring Basin

Only one dye trace was successfully completed in the Compton Spring Basin. This trace occurred on February 22, 1997 and was from a sinking stream located in the Two Hills Subdivision. The eosine dye traveled a distance of approximately one-half mile in three days or less. Another trace was conducted previously on January 30th from a sinkhole that was suspected to be connected to Compton Spring. This sinkhole, called Factory Road Sinkhole, is located near the intersection of

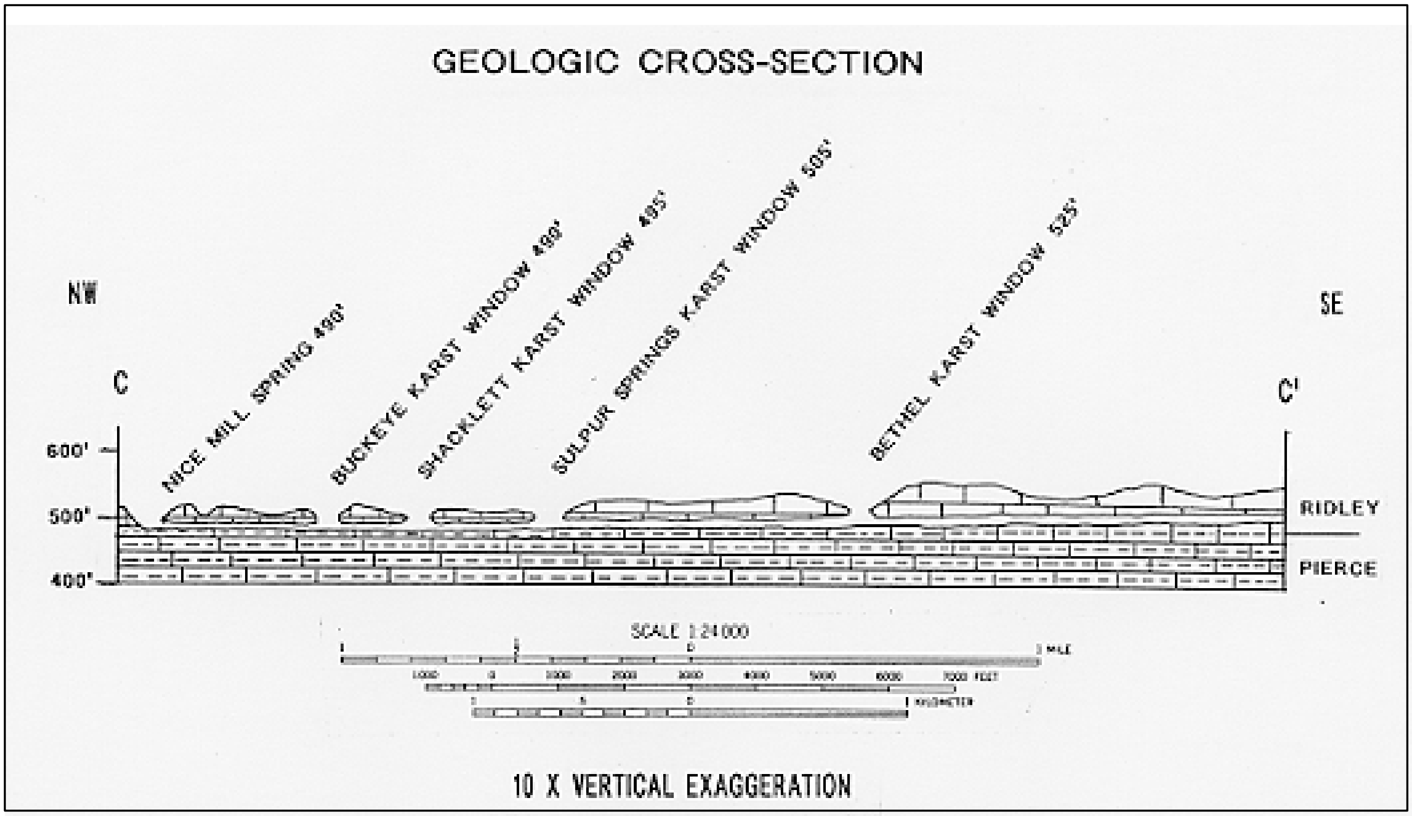


Figure 8. Geologic cross-section of the Bushman Spring Basin.

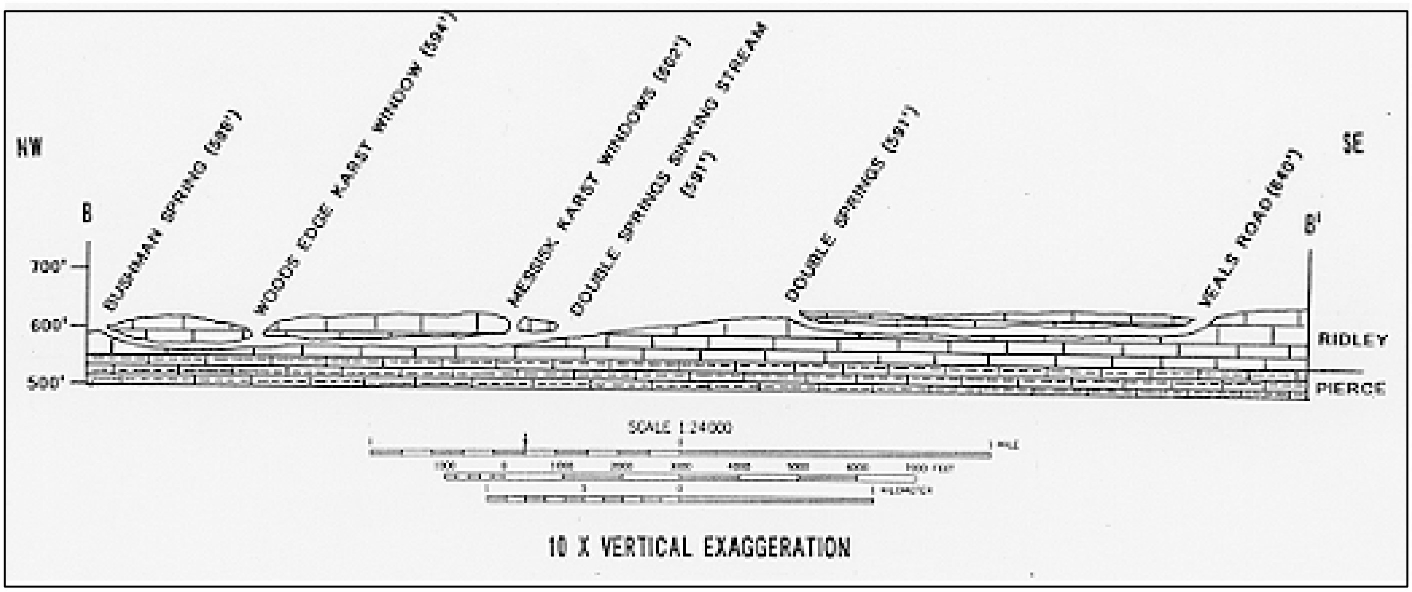


Figure 9. Geologic cross-section of the Nice Mill Spring Basin.

Factory Road and Halls Hill Pike. The injected eosine dye was never detected indicating that the site drains to another spring, or there was insufficient dye used. Visual observations of Compton Spring during the study show that the discharge is quite large suggesting a drainage basin of considerable size.

Implications of Results to Sinkhole Flooding Problems

Figures 8 and 9 show generalized geologic and topographic cross-sections of the Bushman Spring and Nice Mill Spring drainage basins, respectively, and are useful for interpreting sinkhole flooding in different locations. More precise elevations of selected areas involved with the tracing activities were obtained by two-foot contour interval maps on file at Murfreesboro and Smyrna city halls. The figures depict how groundwater moves through a thin section of Ridley Limestone perched on impermeable layers of the Pierce Formation. The springs emerge at the contact of these two formations. The elevations of the springs compared to the bottom of the sinkholes and karst windows show that the subterranean karst water table is quite flat and very close to the surface in many areas. Rapid movement of the tracing agents suggest that there are not artificial clogs in the subsurface, but natural changes in cave size that cause water to back up behind small passages during flooding. The dye tracing results show that sinkholes near the springs are well connected to sinkholes many miles away. Therefore, development that increases runoff into sinkholes located great distances apart can have an effect on each other.

CONCLUSIONS

Groundwater tracing was successful in delineating the watersheds of two major springs in Rutherford County and part of a third watershed. The tracing activities show that groundwater moves rapidly through the subsurface to the springs from distances in excess of five miles. The rapid movement of the dye tracers suggest that the caves are not clogged by human activities. Therefore, two reasons exit to explain sinkhole flooding in the spring basins. The first is that the karst water table is very close to the surface. Second, natural constrictions in the subsurface cavities cause stormwaters to backup behind the constrictions and fill the upgradient sinkholes. As a result, there are probably no cost-effective engineering solutions to prevent present sinkhole flooding problems within the studied basins. As a result, the information presented in this paper can best be used to plan for the future. It is now largely known within the Bushman and Nice Mill spring basins how the sinkholes are interconnected. Therefore, when development in or around a given sinkhole occurs, it can be predicted which areas down-gradient will likely be affected by the additional runoff to the subsurface.

The similarity of the joint, straight cave segment, photo-lineament, and sinkhole axes data shows that a variety of tools are available to help predict the direction of groundwater movement within Rutherford County. Therefore the direction of movement of any spilled or leaked contaminant within the studied basins can be predicted, as well as, the eventual emergence location. Close inspection of the cave passage orientation data shows that the main or "trunk" passages in some areas are developed along the troughs of the synclines while the tributary or "side" passages are developed along the joints. Within the synclinal troughs, sinkholes and joints are found to be aligned in a similar direction, although this is masked when all the orientations are combined on the rose diagrams. Therefore, much of the groundwater in the study area is believed to move through large conduits situated in the synclinal troughs, with inputs of subsurface waters moving downdip along solution-enlarged joints within the limbs of the synclines. These results should be quite helpful in developing monitoring programs at waste disposal sites and help in emergency response to spills, leaks, and pipeline breaks.

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DYE TRACINGS IN THE SPRING CREEK AREA, GREENBRIER COUNTY, WEST VIRGINIA

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Introduction

The three basins reported here are formed predominantly in the Mississippian Pocono, Greenbrier, and Mauch Chunk Groups. The Greenbrier is the large cave-forming limestone of West Virginia, and is the equivalent of the Saint Genevieve of Central Kentucky. The area is a part of the easternmost Dissected Appalachian Plateau Geomorphological Province. The strata are generally flat-lying with some gentle folding; however, some local folding has resulted in steeply dipping beds. Figure 1 shows the three basin location, and Figure 2 shows the geological column of the Greenbrier limestone.

The historical dye traces conducted by other investigators, prior to 1994, are documented in Table 1. This report is a summary of activities conducted by the authors between 1994 and1997. All tracings were conducted within three basins, Spring Creek, Buckeye Creek, and Culverson Creek, in the east-central Greenbrier County, West Virginia.

Basin Description

The three basins and location of trace studies are shown in Figure 3. The legends for Figure 3 are described in Table 2. Details of trace studies are documented in Appendix 1. Major features of the three basins are described below.

The Spring Creek Basin is the easternmost of the three basins. Spring Creek is approximately 24 miles long, and flows south from Droop Mountain to the Greenbrier River at Spring Creek Station. The basin's bottom, above the northern end of the Route 219 bridge, is formed almost entirely in the Union Limestone, a pure calcium-rich limestone. The basin crosses the underlying Taggard Formation at the bridge, and is developed on the Patton Limestone below the bridge. Spring Creek, in the area of the bridge, is about 15 to 20 feet wide and 2 to 4 feet deep. It is, however, a losing karst stream and contains many dry stretches above and below the bridge.

Major flow routes in the basin include: Friars Hole Cave (at 43.5 miles in length, it is the longest cave in West Virginia), Hill Creek (a prominent sinking stream), the Cannon Hole, Circulating Cenote, Grapevine Cenote, JJ Spring, and Spur Cave.

The Buckeye Creek Basin is located between Spring Creek and the Culverson Basin. This basin is about six-square miles in area and can be divided into several major segments. Turner Hollow, about one mile long, is located north and northwest of the Buckeye Creek Cave entrance. The Racetrack, an old pre-Civil war horse raceway, is almost exactly one mile in length, and extends south from the cave entrance. It has a flat bottom of alluvium, no surface stream, steep hillsides to each side, and is a polje.

The major flow route in the basin is Buckeye Creek, which flows through Buckey Creek Cave. With the exception of the upper Buckeye Hollow, the Buckeye Basin bottom land is all karst. The hills are developed in younger Mauch Chunk shale and sandstone sequences. This area is called the Knob Country, and this is a good description, as the countryside is much more rugged than the flatter Greenbrier karst plateau to the south.

The Culverson Creek Basin is the western-most of the three basins. It is about 60 square miles in area. It too is Knob Country, as its bottom land is developed principally in the Greenbrier imestone, whereas its ridges are composed of the Pocono, Mauch Chunk, and Pottsville formations. The Culverson Basin backs up against the mountains to the north. The highest of these is Cold Knob, the top of which has been bench stripped of the Pocahontas #6 coal seam, of the Pennsylvanian Pottsville Group.

Major flow routes in this basin include Culverson Creek Cave (at 21 miles length, the fourth longest cave in West Virginia), which resurges at Matts Black Cave, Midway Spring, McFerrin Breakdown Cave, and Lower McFerrin Spring. Nearby is The Hole, about 23 miles long, which is a Contact Cave and West Virginia's third longest cave. In West Virginia, a Contact Cave is defined as a cave developed near or at the contact between the Greenbrier Group and the underlying Maccrady Shale. Often dissolution begins in the bottom of the limestone, then the cave passage forms in the underlying shale by weathering and erosional processes typical to a surface stream.

Procedures

Four dyes were used for this project: Fluorescin (Sodium Fluorescein, # 15174 Uranine concentrate); Rhodamine (# 16972 Rhodamine WT); Direct Yellow (Solophenyl Flavine 7GFF); and Optical Brighter (Thinopal, Ciba Geigy # 340571-156-0).

The green Sodium Fluorescein and the red Rhodamine WT dyes were collected on activated-charcoal traps enclosed in wire mesh. The mesh was sealed using office staples, and the traps were tied with fishing line at the sample locations. On occasion, fishing weights were used to hold the trap in the water. Once the trap was retrieved and taken back to the laboratory, it was eluted with an alcohol solution. The resulting liquid was placed in a scanning spectrofluorometer and the standard fluorescein and rhodamine wave peaks searched for.

The yellow Direct Yellow and the white Optical Brighter dyes were captured on natural unbleached cotton, i.e., Swiss Beauty Pads. These were enclosed inside wire mesh and held in the water flow in a manner identical to that used with the charcoal traps. Once the cotton trap was retrieved and taken back to the laboratory, it was observed under an ultraviolet light. The direct yellow dye would show a bright yellow; the optical brighter would give a bright bluish-white fluorescence. This fluorescence was usually of much greater intensity than that of the background optical brighter found in the streams. The optical brighter was unusable in the Buckeye Creek Basin, as there was too much background brighter present.

Results

Dye traces (1994-1997) discussed in this report is documented in Appendix 1. As a result of this study several known flow paths were confirmed and several new flow paths were discovered. Major findings of the project are summarized below.

Spring Creek

Twelve dye traces have been completed to date from along the west side of Spring Creek in the Spring Creek Cenotes area. In this program, two streams were traced from the Portal and two from the Boarhole to the Cannon Hole and the Spring Creek Cenotes. A fifth trace, from the Sawpit Sinkhole, came out at the four Culverson Creek resurgences. The Portal and the Boarhole are six and four miles long, respectively, and located in the Esty area, which is about three miles north of the Cenotes.

Buckeye Creek

To date, 24 dye traces have been completed in the Buckeye Basin. It has been determined that, south of the raceway, a Locust Spring Hollow insurgence (Booth Cave) and four Pilgrims Rest Hollow insurgences (Tin Cave, Pilgrims Rest Cave, Double Stream Cave, and Seep Cave #2) all flow to the four Culverson resurgences. This indicates that *all* of the sinking streams in the southern Buckeye Basin, minus the southern-most sink, are flowing into the Culverson stream.

It was found that the water flowing into southern-most and upper-most Pilgrims Rest Hollow sink (the Reynolds Swallowhole) does not flow into Culverson or Buckeye Creeks, but rather to The Boggs Bluehole, an overflow at the uppermost of The Hole's resurgences. This indicates the possibility of existence of a separate karst basin between the Buckeye, Culverson, and The Hole basins. It was also discovered that water in the lower Pilgrims Rest Hollow (which is seen in Hanna Water Cave, Spout Cave, and the McMillon Bluehole) flows into Upper Buckeye Creek Cave. In addition, a lower Locust Spring Hollow insurgence (Locust Spring Cave #2) flows to Upper Buckeye. The Locust Spring water does not travel to Upper Buckeye via Spout Cave.

West of Buckeye Creek Cave, it was determined that the Osborne Insurgence flows to Fuells Fruit Cave. The water in Fuells Fruit's Cave, located in Buckeye Creek Hollow, resurges not into the surface Buckeye Creek but rather in Cliff Spring in Turner Hollow. It was found that Southeast of Buckeye Creek Cave, the Baber Pit #2 and Sisslar Spring waters both resurge at Bill Callison's pond and then sink at Callisons Pond Cave; the Callisons Pond Cave water reappears at Rubble Spring; the Hughes Sink water enters Buckeye Creek Cave by way of the southern tributary in the Spencer Sump area; and the Old School Cave water enters the cave via Mud Avenue. Because Mud Avenue is a dry cave passage floored with alluvium, there must be an under-passage carrying water into Buckeye Creek.

North of Buckeye Creek Cave, in Turner Hollow, the Deer Insurgence and Clutetown-Pit waters were found to resurge at Rock Spring, the Beaver Insurgence water reappeared at Cliff Spring, and the waters entering Short Stuff Cave, Turner Pit #2, and a small sink above the Deer Insurgence all resurged at Apple Spring. The Turner Pit trace was very disappointing, as this cave contains a very short, very large trunk passage, which was hoped would lead into the Buckeye Creek Cave mountain and to a large cave system.

Culverson Creek

To date, 20 dye traces have been completed in this basin. Previous studies had established that: Keese Sink flows to Marshall Spring; Charley Run flows to Bransford and Casteret Caves and then to DePriest Cave #2, DePriest Cave, DePriest Insurgence, and DePriest Spring; Roaring Creek flows to the Windmill Cenote and then to Marshall Spring; and Culverson Creek flows to its four resurgences on Spring Creek.

More recently, it was determined that Stove Cave water resurges at Briar Patch Spring, Plastic Bag Cave at Picnic Cave, and Poorfarm Cave at the Scout Camp North Spring. All three of these traces moved south-southwest in a parallel direction along strike. It was also determined that: the impressive-looking Knights Spring Cave, with its large flow of water, is nothing but a cut-around resurgence for Beaver Run Cave and the surface at Culverson Creek; the two Millers Caves and Junkpile Sink all resurge at the Longs Bluehole (Round Alluvium Spring); and Limestone Wall Sink and Longs Insurgence both resurge at Calf Spring. The Long Insurgence water did not flow through the Limestone Wall Spring and Sink to reach Calf Spring.

It was determined that Bob Gee Cave, located southeast of Trout, contains in the three basins' the only bifurcating stream discovered to date. During low flow, Bob Gee water flows southeast to Marshall Spring. During high flow, the water flows both to Marshall Spring and east to Carr Branch Cave.

An unreported north-flowing surface stream was discovered northeast of Williamsburg. The stream, hidden by folds of surrounding terrain, flows through a series of karst windows. The stream sinks at Piper Cub Sink, resurges at Locust Ridge Spring, sinks at Locust Ridge Sink, rises at Simmons Spring, and then sinks at Vanishing Lake Water Sinks. It then resurges at DePriest Box Spring on Charley Run. This trace was very interesting because the water's origin is west and on the Sinking Creek side of the Williamsburg anticline. The water flow was north and around the northern end of the clastics brought to the surface by this anticline, and then east into Culverson Creek. The Vanishing Lake Water Sink is located about one mile north of Williamsburg. This sink often backs up, forming a lake several hundred yards in diameter, and it gives the impression that the water is flowing south and into Simmons Spring. In fact, the water flow is to the north and into the Water Sink, which is incorrectly shown as a spring on the Williamsburg 7.5-minute USGS topographical map.

The last dye tracers found that three streams west of Vanishing Lake Sinkhole, Pembroke Road Sink North, Middle, and South, all flow into Sinking Creek, which is the stream basin directly west of Culverson Creek.

Remaining Work

Further investigation is needed to complete the project. It is not known where the water resurging at Hanna Caverns and Spout Cave, Packs Spring Cave, and Leona's Cave originates. In addition, a dye trace could not be completed at McFerrin Saltpeter Cave because of landowner con-siderations.

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Contributors through personal communication include: B. Balfour, J. Brown, D. Cowan, R. Handley, W.K. Jones, J. Lake, R. Rusty, G. Schindel, J. Schweyen, R. Simmons, and G. Turner.

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Table 1. Historical Dye Traces Conducted Prior to 1994.

Table 2. Map Legends for Figure 2.

Appendix 1. Documentation of Dye Traces (1994-1997)

tion of the Three Basins

Figure 2. Geological Column of the Greenbrier Limestone.

Figure 3. Three Basins and Dye Traces

A PARSIMONIOUS TANK MODEL FOR SIMULATING FLOW AND TRANSPORT IN A KARST AQUIFER

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Abstract

The long-term protection of the Barton Springs portion of the Edwards aquifer is widely considered by residents of central Texas to be a top environmental priority. Urban development is beginning to occur in the watersheds contributing flows to Barton Springs and there are indications that it may have negatively affected the pristine character of the Springs. This paper describes the hydrologic system associated with the Barton Springs portion of the Edwards aquifer and presents a lumped parameter model capable of reproducing general historical trends for measured water levels, spring discharge, and water quality.

Recharge to the aquifer was calculated based on flow loss studies of the creeks crossing the recharge zone and on estimates of the rate of diffuse infiltration of rainfall. Flow measurements on each creek above and below the recharge zone were used to develop a relationship between flow above the recharge zone and the rate of recharge. A five-cell groundwater model, each cell corresponding to one of the watersheds of the five main creeks crossing the recharge zone, was developed to support the management objectives of the city of Austin, Texas.

The model differs from previous models in that aquifer properties within cells are allowed to vary vertically. Each cell was treated as a tank with an apparent area, and the water level of a single well in each cell was used to characterize the conditions in that cell. The model simulates the transport of groundwater constituents by treating each cell as a completely mixed tank. The model was used to predict the movement of nitrogen in the aquifer. This required the identification of nitrogen loads contributed by creeks during baseflow and storm conditions, and by diffuse sources such as septic systems. This simple representation of the hydrologic system produced results comparable to traditional groundwater models with fewer data requirements and calibration parameters.

Introduction

The Edwards aquifer is a complex karst system which lies in a broad arc across central Texas, USA. The portion of the aquifer located just south of the city of Austin is a hydrologically separate system (the darkly shaded area in Figure 1) which discharges primarily at Barton Springs. This portion of the aquifer provides drinking water to about 35,000 residents in areas without access to the city's drinking water system and provides recreational amenities at Barton Springs Pool, a municipal swimming pool formed by a dam just downstream from the spring. The Barton Springs salamander, which exists only in the vicinity of the springs, is also dependent on spring discharge for its survival. The general geology of the aquifer has been described in numerous reports including those by Brune et al. (1), Garner and Young (2), and Slade et al., (3). Figure 2 shows the extent of the aquifer in the study area and a typical potentiometric surface.

The increase of impervious cover associated with urban growth will likely result in changes in the hydrology of creeks contributing to the recharge of the aquifer. To estimate the impacts of changes in surface water quality on the Barton Springs portion of the Edwards aquifer, The city of Austin entered into an agreement with the Center for Research in Water Resources at The University of Texas at Austin to develop a model which links the surface water and groundwater systems. One of the goals of this research effort is the development of a computer model of the aquifer capable of predicting changes in water quality in the aquifer and discharge at Barton Springs resulting from changes in the surface-water systems. This paper describes the development and calibration of a parsimonious hydrologic model for the Barton Springs portion of the Edwards aquifer.

Figure 1. Location of the Edwards Aquifer and study area (dark shaded region) described in this report.

Figure 2. Project Study Area (after Slade et al. (3)) represented as dark shaded area in Figure 1. Arrows indicate the general direction of groundwater flow. Contours indicate lines of equal potential, in meters.

Model Selection

Numerous types of models have been developed and used to predict water levels and spring discharge from karst aquifers. Deterministic models, which are commonly used in karst aquifers to predict groundwater flow and transport, are physically based and may have either distributed or lumped parameters. Lumped parameter models lack the spatial dimension in the equations describing flow and transport; consequently, only ordinary linear differential equations must be solved. These models offer the opportunity to simulate a given system with fewer data requirements for parameterization and calibration than their distributed counterparts. Lumped parameter models in groundwater applications generally have been single cell, linear reservoir models whose parameters are determined from spring discharge recession analysis. However, a multi-cell lumped parameter model was developed by Wanakule and Anaya (4) for the San Antonio portion of the Edwards aquifer.

The goal of the current modeling effort is the prediction of the regional impacts of nonpoint source pollution arising from urban development in the Barton Springs contributing and recharge zones. The impacts are expected to be widespread and lack the local expression which would be characteristic of chemical spills, leaking landfills, or other point sources of pollution. Spatially detailed water quality data are not available at this time, suggesting that a lumped parameter model with a relatively large cell size is adequate and, indeed, an appropriate choice for modeling the Barton Springs portion of the Edwards aquifer.

The model developed in this study is similar to that developed by Wanakule and Anaya (4) in that relatively few cells are used to describe the aquifer (only five cells to describe an aquifer covering about 400 km^2) which simplifies calibration of the model. The location of the cells and the key wells used in the study are shown in Figure 3. The shaded area in the figure shows the extent of the Barton Springs portion of the Edwards aquifer. The contributing zone is the area of the watersheds of the creeks contributing recharge to the aquifer.

The model calculates aquifer state based on a daily mass balance for each cell. For the purposes of calculating diffuse recharge volumes, the surface area of each cell is assumed to conform to the boundaries of the surface watershed of the creek supplying recharge to that portion of the aquifer. A single well was chosen in each cell to represent the conditions in that area of the aquifer (Figure 3). Each cell is treated as a hollow tank which is assigned an effective area (equivalent to specific yield).

Constituent transport processes were incorporated into the model by treating each of the cells as a completely mixed tank. As such, any constituent input to the aquifer is assumed to be instantaneously mixed with the entire cell volume. The constituent is assumed to be conservative and soluble. No retardation was assumed because of the expected small organic carbon content of this limestone aquifer. A daily mass balance was computed based on the mass entering and leaving each cell during each time step. In this formulation, the model predicts an average concentration in the cell based on the mass of constituent and the volume of water in the cell. This concentration represents an average over a relatively large area and is most useful for estimating relative changes in concentration rather than an exact concentration at a particular time and place, and thus is more appropriate for nonpoint vs. point sources of contamination.

Simulation of transport in the aquifer requires the identification of a suitable constituent which exhibits variation in concentration, is conservative, and whose sources can be quantified. Analysis of water quality data from Barton Springs indicated that nitrogen (as nitrate in the aquifer) might be such a constituent. This was the only conservative constituent which exhibited any long term variation in concentration at Barton Springs. In addition, the increasing use of septic tanks has lead to concerns about potential increases in nitrogen concentration in the aquifer.

There are a number of significant differences between this model and previous karst models that have been developed. Rather than increasing the number of cells to obtain better simulated results, model predictions are improved by allowing aquifer properties to vary vertically. In particular, specific yield and hydraulic conductivity of the cells are functions of elevation. A daily time step was used in the model which facilitated the calculation of recharge, increased the accuracy of the model, and allowed the governing equations to be solved explicitly, thus reducing the computer resources required for running the model. In addition, a simple method of calculating recharge from creek flow upstream of the recharge zone was developed which allowed more accurate estimates of recharge than many of the other Edwards' models which used monthly time steps.

Aquifer Recharge

Water balance studies indicate that the flow losses in the five main creeks crossing the Edwards outcrop are sufficient to supply all the known discharge at springs and well fields. The watersheds of the five creeks (Onion, Bear and Little Bear, Slaughter, Williamson, and Barton Creeks) are shown in Figure 3. Flow loss studies include manual gauging of the stream segments in the recharge zone (3) and comparison of hourly flow records of gauging stations located upstream and downstream of the recharge zone on each creek. Based on these data, the model calculates the amount of recharge from daily flow measurements recorded upstream of the recharge zone.

The constituent load entering each cell from recharge to the creeks is calculated from the daily average flow rate in the creek and an average daily concentration. A mean concentration for the baseflow and the storm flow data of each creek was calculated for all nitrogen species.

Diffuse recharge was assumed to occur at a constant rate. This is a reasonable assumption when the thickness of the vadose zone is large. Throughout most of the Edwards recharge zone the water table lies 30 m or more below the land surface. The average rate of rainfall infiltration was estimated with the Groundwater Loading Effects of Agricultural Management Practices (GLEAMS) model developed by the U.S. Department of Agriculture (5). Using historical rainfall data from the period 1979-1993 and descriptions of the soil and vegetation types on the recharge zone, average infiltration was estimated to be about 50 mm/year, which is about 6 percent of the average annual precipitation. The daily infiltration was multiplied by the approximate surface area of each cell to calculate the daily volume of infiltration.

The constituent mass entering each cell from diffuse recharge was calculated based on the surface area of the cell over the recharge zone, the average daily rate of infiltration, and the average concentration in the diffuse recharge. The GLEAMS model was used to estimate the input of nitrogen to the Barton Springs portion of the Edwards aquifer from septic systems and rainfall.

Aquifer Discharge

Discharge from the Barton Springs portion of the Edwards aquifer occurs mainly from a series of springs in and around Barton Springs Pool, which is located on Barton Creek near its confluence with the Colorado River. These springs account for approximately 90 percent of the known discharge from this portion of the aquifer. The well chosen to represent the water level in the Barton Creek cell is located near Barton Springs and is used by the USGS to estimate spring discharge. Spring discharge in the model was calculated from a rating curve developed by the USGS.

Slade et al., (3) concluded that subsurface flow between the Edwards and other aquifers is not significant. Some of the recharge from Onion Creek apparently flows south to the San Antonio portion of the Edwards aquifer (6); however, the volume of water and flow rates are unknown and were assumed to be insignificant. All recharge from Onion Creek was directed to the Barton Springs portion of the aquifer.

Pumping data collected by the Barton Springs/Edwards Aquifer Conservation District were analyzed to determine the location and volumes of the water-supply wells. The data from 1994 were the most complete and were used for each year of the simulation. The average rate of pumping was equal to about 0.14 m^3/s, which is 10 percent of the long term average discharge from Barton Springs and equivalent to about 375 L/d per capita.

Discharge from the aquifer also occurs in the segment of Barton Creek between Loop 360 and Barton Springs during periods of high aquifer water levels. The volume and rates of discharge are unknown. Discharge to the creek was used as a calibration parameter to improve the spring flow prediction.

Constituent mass leaves the aquifer via pumping wells, discharges to Barton Springs, and as baseflow to Barton Creek during periods of high water levels in the aquifer. The amount of mass leaving a cell was calculated based on the average concentration in the cell and the volume of water discharged.

Model Calibration

Numerous variations in the model configuration were tested in order to obtain the best possible match between observed and predicted water levels and spring discharge rates. Variations included increasing the number of cells, varying specific yield with elevation, allowing discharge to occur across the southern boundary of the model, and using a dual porosity formulation for selected cells. The simple configuration of five cells with no flow external boundaries provided predictions which were essentially as accurate those produced by more complicated models.

Flow between the cells is described by Darcy's Law. Even though flow in the Barton Springs portion of the Edwards aquifer occurs primarily in caves and cavities, and secondarily through porous media, Darcy's law produced better agreement between measured and predicted water levels than a model based on the Chezy-Manning equation. Significant improvement of the model predictions was achieved by allowing the properties of the Onion and Barton cells to vary vertically. Water-level predictions for the Onion Creek cell were significantly better when using a higher hydraulic conductivity and the water level in the cell was allowed to exceed 180 m above mean sea level. Improvements in spring discharge prediction resulted from a layered configuration of the Barton cell, with the effective area increasing upwards. A schematic diagram of the calibrated model is shown in Figure 4.

The measured and predicted discharge from Barton Springs for the calibration period is shown in Figure 5. Since the prediction of Barton Springs discharge is based on the water level in the well used by the USGS for flow estimation, the figure also indicates the accuracy with which water level in that portion of the aquifer is predicted.

The model predictions for nitrogen concentration were compared to those measured at Barton Springs and in each cell. A comparison of model predictions with measured values at Barton Springs for the period of January 1989 - October 1995 is shown in Figure 6. The average concentration predicted by the model for this period was 1.46 mg/L compared to the average concentration of the measured values during this period of 1.48 mg/L. This agreement indicates that all the major sources of nitrogen have been identified. The measured values show a greater variability which is likely the result of two factors: laboratory and sampling errors may result in reported values which differ from the actual values by 10 percent at this concentration level, and recharge occurring in Barton Creek near the springs can result in rapid changes in discharge quality, which are not representative of average conditions in that portion of the aquifer.

Conclusions

A simple five-cell model was developed for the Barton Springs portion of the Edwards aquifer which can predict regional water levels and spring discharge from flows in the creeks contributing recharge to the aquifer. A comparison of model predictions with historical data for the period August 1979 - October 1995 demonstrates the accuracy of the model. This simple representation of the hydrologic system produced accurate results with fewer data requirements and calibration parameters than traditional groundwater models.

This groundwater model, when used in conjunction with a surface water model, will allow a prediction of the hydrologic impact of the increase in the runoff coefficient resulting from changes in land-use patterns. The effect of potential stormwater runoff control structures on recharge and water levels also can be evaluated.

When faced with the task of modeling an extremely complex flow system, the natural tendency is to develop a more complex model. This research shows that a very simple model can provide useful information about the behavior of such a system. In addition, the model explicitly acknowledges the lack of detailed information about the location of conduits and other flow paths by predicting only regional effects. Predictions made by more complex models are often given more validity by persons unfamiliar with their use or development than might be warranted. This is especially true when the values of physical parameters such as specific yield or hydraulic conductivity may have been estimated from a sparse data set.

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Figure 3. Location of Aquifer Cells and Key Wells.

Figure 4. Schematic Diagram of Tank Model.

Figure 5. Comparison of Measured and Predicted Discharge for Calibration Period.

Figure 6. Comparison of Measured with Predicted Nitrogen Concentration at Barton Springs.

SIMULATING RAINFALL INFILTRATION INTO A KARST AQUIFER USING A GROUNGWATER MODELING APPROACH

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Abstract

This study is part of a comprehensive investigation of the mountain Kucaj limestone in eastern Serbia where the development of a regional water supply system is planned. The regional plan is based on the surface water impoundment and construction of a dam on the Black Timok River. However, before building the dam, as a temporary measure, the development of the groundwater source of the main karst aquifer Mrljis which is located at lower part of the Balck Timok River is planned.

The objective of this report is to discuss a comprehensive mathematical model developed for the karst aquifer. The groundwater flow zone is divided into big blocks of relatively homogeneous flow characteristics which are separated by the linear zones of intensive karstification. The discrete two-dimensional model which simulates the rainfall infiltration into the groundwater system is based on Darcy's law. Results show monthly representative values of total infiltration expressed as a percentage of the daily rainfall for daily rainfalls greater than 2 mm/day. Depending on the month, the infiltration estimation obtained was between 8 to 32 percent and on average about 20 percent. In addition, the infiltration distribution for a singular rainfall which extended over three days was obtained (70, 20, and 10 percent of the rainfall for three days, respectively).

Introduction

The fluid flow laws in general, and groundwater flow in particular, can be descibed adequately by partial differential equations. These equations enable hydrodynamics engineers to simulate all forms of groundwater flow with a great degree of precision if physical properties of porous media, boundary conditions of the aquifer, and temporal variations of flow are known. Determination of parameters which are the basis for a groundwater model development requires intensive and long term investigations by a number of specialized experts with considerations for costs involved. This is particularly important for simulation of flow in karst aquifers.

Karst-Aquifer Mathematical Model

Mathematical modeling is based on the solution of partial differential equations which describe groundwater flow under steady and unsteady flow conditions. In this study, a finite difference method was used to solve the partial differential equations. The model formulation is based on application of Darcy's law to confined and unconfined systems. Two values of permeability coefficient were used in the model; one toward x-axis and the other toward y-axis. This procedure allowed permeability simulation only in one direction. A lack of necessary input data and costs involved in gathering the needed data required the simplification of the model.

The following data were needed to develop the mathematical model:

1. The areal extent of the aquifer with defined boundary conditions in a hydraulic sense.

2. The contour line map of the underlying bed as a bottom boundary condition for the flow zone.

3. Topographic map for terrain surface. In general, the groundwater flow is unconfined in the area of study and the height of the piezometric level is limited by the terrain surface elevation. The confined flow condition is limited to the Mrljis zone which is the main drainage zone for the karst aquifer.

4. A map for distribution of flow parameters (transmisivity or permeability coefficients, depending on the flow conditions). Based on the terrain's geology, hydrogeology, and laboratory investigations the presence of distinctive zones of groundwater flow and flow directions were established. These distinctive zones are fissured systems and underground channels that are common in karst aquifers and are the result of lithologic and tectonic constitution of the limestone sediments and non-uniform karstification.

5. A map for distribution of the storage coefficient. In limestone, karstification results in heterogeneous distribution of porosity, and therefore, the storage coefficient is not a constant.

6. Periodic stream boundary conditions. Besides permanent streams which represent the fundamental boundary conditions, it was important to define other periodic stream conditions. The hydrologic properties of the Black Timok river is defined by two parameters: water level and hydraulic loss at the river bottom. The hydraulic loss at the river bottom is represented by a leakage factor. For this study site, the leakage factor value was based on a hydraulic loss of 1-2m between the river and the groundwater measured at the base of the terrain. Black Timok River serves as the groundwater drainage zone at the central part of the river and the river is the infiltration zone downstream of the source Mrljis. Water is infiltrated into the underground in the areas upstream of the estuary of the Radovanska and Mirovsa Rivers (Figure 1).

7. Infiltration from the periodic streams. There is periodic river inflow from the north-west boundary, the portion of the river-basin which is not a part of limestone but provides

the largest volume of water that infiltrates into the underground through the river bottom: Big river and its tributary, Bogovina river and its tributary, and the Dry river with its tributary. Rarely, except for periods of high rainfalls and snow-melting, does any portion of the water from these rivers reach through surface flow to the Black Timok River. On the basis of long-term analysis (37 years) of hydrometeorological data, it was concluded that volume of the inflow water (within the model) depends on the time of the year (month) and total amount of monthly rainfall. The model described in this paper simulates the water infiltration from the periodic surface streams described above. Their location is described by a single matrix, from the river inflow location to the karst area and to their termination at the terrain surface. The amount of the water infiltration and the length of the periodic stream is a function of the rainfall. The larger water volume thus infiltrates at the upstream portions of the river as compared to the downstream portion.

8. Periodic sources. Effects of Bogovina Cave and Fundonji Spring as periodic sources of water are simulated in the model by inputting outflow levels from these sources. Periodic sources occur during the large and intensive rainfalls especially at spring time.

9. Groundwater outflow through the sandstone. This outflow, which occurs along the eastern boundary of the karst aquifer, provides the groundwater database for the eastern domain of the area of study.

10. Infiltration due to rainfall. The infiltration process is assumed as homogeneous in the flow plane and is considered a function of rainfall intensity and period (month of the year.

The following data were collected for model calibration and verification:

1. Recorded piezometric water levels.

2. Recorded flow capacity for permanent or periodic sources.

3. Water infiltration and drainage into the river.

Mathematical Model Calibration

Calibration of the model was performed for unsteady flow condition for the period of six months (April 1 to October 31, 1992). Under the assumption that infiltration due to rainfall is the dominant parameter of the groundwater regime, model calibration was conducted for the six-month period with consideration for two distinguished phases: 1) period of groundwater recharge upon occurrence of intensive infiltration due to rainfall and through the river bed; and 2) period of groundwater discharge during the recession period.

The calibration process enabled us to develop a mathematical model that represents the part of the basin's karstic aquifer that gravitates toward the source Mrljis and to the Black Timok River. The recorded discharge data for the Mrljis, Bogovinska Cave and Fundonj Spring were used to verify the model.

The general characteristics of the model are defined by distribution of the flow parameters. At the start, assumed distribution (and amount) of the transmisivity coefficient values for the porous medium were used to obtain the finite and verified distribution parameter by the calibration process. Figure 2 shows the grid map of the mathematical model, along with the distribution of the transmisivity coefficient for the aquifer and the simulated distinctive groundwater flow direction.

Basic Parameters for the Groundwater Regime of the Karst Aquifer

The groundwater regime of the karst aquifer is a consequence of the hydrometeorological parameters within the river-basin. The selection of the dominant groundwater regime parameters was accomplished by using the results of previous analysis of the recorded long-term meteorological and hydrological data.

Several facts and assumptions were built into the model and verified during the calibration process. Based on the previous analysis of data and confirmation by the mathematical model, it was ascertained that the groundwater recharge within the model domain occurred as follows: 1) by the infiltration due to rainfall; and 2) by the infiltration of the permanent and periodic water sources through the river bed. Groundwater recharge within the model domain occurred as follows: 1) a part of the Black Timok River in the central zone of the terrain; 2) the permanent sources (Mrljis, Groznicevac); 3) periodic sources (Bogovinska Cave, Fundonj Spring); 4) sandstone layer along the east contour of the model; 5) outflow profile of the Black Timok River as underground outflow; and 6) outflow profiles of the periodic rivers (Bogovinska and Big) during the large rainfall events.

The Functionality of Rainfall Infiltration

The definition of the amount and distribution of the rainfall infiltration is one of the most important, comprehensive and delicate task of the hydrometeorological analysis of the area under consideration. Especially important is the temporal quantification of the rainfall infiltration.

Similar to the storage coefficient, rainfall infiltration is variable in space and time. It is obvious that adopting a homogeneous infiltration process for the massive limestone area is not appropriate. However, because of the lack of data for terrain measurements, rainfall infiltration is simulated as a homogeneous system that varies with period of year (month) and daily rainfall. Estimation of temporal infiltration and its dependence on rainfall was realized during the model calibration, with the assumption that, as a dominant parameter, changes in the groundwater balance are a function of the rainfall (or infiltration). This assumption was based on the results of the sensitivity analysis for the model parameters.

To define the functionality of the daily rainfall, rainfalls less than 1 mm/day were eliminated from consideration based on the assumption that rainfall amounts less than 1 mm/day is without practical importance to the groundwater system.

Two parameters were used to define infiltration. The first parameter is the month's characteristics in terms of the percentage of the month's rainfall versus the sum of the rainfall. The second parameter is temporal infiltration distribution of the daily rainfall. By testing several time intervals, a representative three-day time interval was obtained. All rainfalls are accounted for if the rainfall is greater than 1 mm/day and occur on few successive days.

On the basis of a large number of analysis, the percentage of rainfall which enters the ground through infiltration was determined for each month of the year (Figure 3). Figure 4 shows the percentage of infiltrated water distribution over a 3 day period for rainfalls greater than 1 mm/day. Evaporation and evapotranspiration were not considered in calculations as it was indirectly incorporated within the given relationships.

Conclusion

The given example in this paper is an attempt to develop a mathematical model for groundwater flow in a karst aquifer. The results of this study must be perceived valid for the parameters of the given terrain with the assumptions discussed in this paper. However, model results could not be completely confirmed due to the lack of data for terrain investigation.

Figure 2. The filtration parameter distribution as the blocks and privileged ways.

Figure 3. Infiltration in percent of rainfall, by the months.

Figure 4. A rainfall infiltration distribution, by the days.

SIMULATION OF GROUNDWATER FLOW IN A SLIGHTLY KARSTIFIED CARBONATE AQUIFER USING A CONTINUUM EQUIVALENT AND INVERSE MODELING APPROACH

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Abstract

Simulation of groundwater flow in a karst aquifer is a difficult task, primarily because of highly heterogeneous aquifer characteristics. When the karst is not highly developed, the aquifer occasionally behaves globally as a fractured aquifer. The purpose of this work was to test, in this case, if regional parameter identification can be accomplished using inverse modeling techniques and if hydrodynamic simulation can be performed using a distributed continuum equivalent model. This approach is applied to a slightly karstified carbonate aquifer with high flow velocities and important storage (Charente, France). Inverse modeling was performed using a downscaling technique, a least squares approach, and the adjoint state method. The calibration criteria included measured heads, flow rates at the springs, and exchanged water volumes between the rivers and the aquifer. Inverse modeling was used to calibrate parameters and simulate flow during two steady-state periods (during high and low water). The automatic calibration procedure provided simulated parameters for the two periods: transmissivity distribution, imposed fluxes, and river-aquifer exchanges. This work has shown that in a slightly karstified carbonate aquifer, the use of a continuum equivalent combined with inverse modeling provides an acceptable approximation of regional groundwater flow characteristics during both the high and low water periods.

Introduction

Groundwater modeling in a karst aquifer is challenging, primarily because of the highly heterogeneous characteristics common in limestone terranes. The most adapted modeling approach depends on the nature of the karstified rock and on the objective of the simulation. When the carbonate rock has not suffered much dissolution and when the purpose of the modeling is to represent regional groundwater flow for management purposes, a continuum equivalent can be a reasonable approximation (1). This approach is especially useful when little or no information is available concerning the presence and localization of conductive drains. However, it does not accurately describe the flow in the individual major conduits and assumes that the flow is darcian everywhere in the aquifer. This approach is also based on the hypothesis of the existence of a representative elementary volume (REV) over which the hydrodynamic properties of the rock are assumed to be constant.

The preliminary field characterization required for a distributed groundwater model is especially difficult in a karst aquifer because of the presence of important highly variable local heterogeneities. Therefore, alternative parameterization techniques are required. Inverse modeling is widely used to complement the available information and is recognized as a necessary tool in all types of groundwater modeling (2). Inverse modeling has been used repeatedly in so-called homogeneous aquifers (having few heterogeneities). Only a few studies have used this technique for the identification of flow parameters in a karstic environment; and when used, it is mostly with simple input-output models (3).

Highly heterogeneous aquifers are especially difficult to calibrate because the variability in the measured heads represents features that are not included in the continuum equivalent model. However, on a larger scale, inverse modeling with this approach gives a global view of the heterogeneities and provides the parameters of a heterogeneous continuum equivalent. The purpose of this study was to test if inverse modeling can be used to calibrate the required parameters for groundwater flow modeling in a slightly karstified aquifer using a continuum equivalent. This approach is used on a carbonate aquifer located near the city of Angouleme (Charente, France) to calibrate parameters and simulate steady state flow for the high and low water periods. The purpose of the modeling exercise is to acquire a better understanding of the regional flow regime and to identify the hydrodynamic characteristics of the aquifer.

Study Area and Model Description

The La Rochefoucauld karst covers an area of over 600 km^2 and is located in middle and upper Jurassic rocks, east of the city of Angouleme (Charente, France). This aquifer is very important for the region because its main spring is used by the city of Angouleme (population 55,000) for its water supply. In terms of flow rates, this spring is the second largest spring in France, after the Fontaine de Vaucluse (southern France). Because of the high vulnerability of this karst aquifer to contamination, the local authorities have demanded a modeling study aimed at developing a better understanding of how to protect and manage this resource.

The aquifer's eastern limit occurs where the crystalline bedrock plunges westward under the carbonate rocks (Figure 1). Semi-pervious Quaternary deposits located in this area are hydraulically connected with the underlying karst aquifer during periods of recharge, and are disconnected when the water table drops below the Quaternary deposits. The aquifer is limited on the western side of the study area as the carbonate rocks are buried under more recent marlous carbonates and impervious Cretaceous formations. The aquifer is banded on the western side of the study area by a thick series of low-permeable marls and marlous carbonates located along faults and flexures.

Exposed since the end of the Cretaceous period, the highly fractured carbonate rocks have been subject to karstification to depths of over 100 m. The results from spectral and correlation analyses using piezometric heads and spring flow rates have shown that this aquifer has large flow velocities and large storage capacities (4). Although a rapid component of the flow has been observed with tracer tests (5), the flow velocities of this slightly karstified aquifer justifies the darcian hypothesis and the use of a continuum approach.

The model used in this work is based on a finite element program, HPP-GMS (6). The aquifer is discretized into 335 triangular cells with a maximum length of each adjoining cell boundary of 2500 m (Figure 1). The aquifer is limited at the contact with the crystalline bedrock with an imposed flux boundary during the high water period and a no-flow boundary during the low water period representing the temporary influence of the semi-pervious deposits on the interface. The north and south limits are located on groundwater divides and are therefore set as no-flow boundaries. During the high water period, the true northern limit of the aquifer is located along a groundwater divide south of the Bonnieure River. To represent the temporary drainage effect of the karst network located in this area, hydraulic heads were imposed at the same altitude as the Bonnieure River during the high water period. In the southwest area, the limit is set on a steady-state flow line (representing a no-flow region perpendicular to the flaw line), according to piezometric data in the region. The western limit is also set on a flow line coinciding in part with the faults closing the aquifer around the springs. The aquifer is underlain by the impervious Toarcian formation which results in variable thicknesses of between 20 m on the eastern boundary to 550 m near the springs along the western boundary. Although the aquifer is locally overlain by Cretaceous formations and marlous carbonates, it is considered to be globally unconfined.

The primary discharge from the aquifer is via the perennial Bouillant spring. A secondary discharge is the Leche spring, located 500 m uphill from the Bouillant spring. Together, these springs have an average flow rate of 12.8 m^3/s, but can vary from 2.4 m^3/s to 40 m^3/s. Both springs are represented together in the model using a constant head boundary condition. The Bandiat and Tardoire rivers are sinking ephemeral streams that dry out every summer as they recharge the underlying carbonate rocks, thus providing an important year-round component of flow to the springs. The Bonnieure River is perennial and flows along the northern part of the study area. During the low water period, part of the Bonnieure River contributes to the flow at the springs, but during the high water period it drains part of the aquifer outside the study area. The Tardoire, Bandiat and Bonnieure rivers are represented in the model using leakage objects as follows:

$$Q = C\left(h_r - \max\left(h_b, h\right)\right) \quad (1)$$

where Q is the volumetric flow rate, C represents an exchange coefficient, h_r is the water level in the river, h_b is the level of the bottom of the river, and h is the piezometric head in the cell.

The exchanged water volumes, Q, are calculated using exchange coefficients, C, which are a function of the hydraulic conductivity and cross-sectional area of the flow. These coefficients were adjusted for the Bandiat and Tardoire rivers based on differential flow rates on both rivers. No adjustment was done for the Bonnieure River because of the absence of an uphill hydrometric station. For this river, small values of the exchange coefficients were used to represent a stronger link with the aquifer. The exchange coefficients are set to zero for the Bandiat and Tardoire rivers when and where these rivers do not flow.

Short term water budgets have shown that this aquifer has a very dynamic behavior and steady state is probably rarely observed. Nevertheless, under the hypothesis that over one month a temporary steady state can be reached, the calibration was performed for two distinct periods: the high water period of March 1994 and the low water period of September 1995.

Recharge to the aquifer was calculated on a monthly basis using a simple water budget in a superficial layer of one meter of soil having a readily available water supply of 0.1 m (7). The calculated recharge for the high water period is 110 mm. No recharge to the aquifer occurred during the low water period.

Pumping wells for potable use operate year round to draw water from the aquifer with total pumpage equal to 1.6×10^6 m^3/year. Other pumping wells (totaling 8.9×10^6 m^3/year) are used only during the irrigation period, from June to August.

The Calibration Procedure

The inverse modeling was performed using the approach developed by Chardigny et al., (8), which uses the finite-element program HPP-GMS to simulate groundwater flow. Applications of this approach have been reported by Chardigny et al., (8), and by Siegel et al., (9).

In inverse modeling, the parameterization step consists of reducing the number of parameters to be estimated. Zonation and interpolation are the most used parameterization techniques (10), but have the disadvantage of requiring some prior knowledge of the spatial distribution of the calibrated parameters. The parameterization technique used in the selected inverse modeling approach, the downscaling technique (11), avoids this constraint. Hydraulic conductivities are described at different scales, independently from the computation mesh. The aquifer is first discretized using four elements (the initial parameter mesh) large enough to include the entire system. As a first approximation, hydraulic conductivities are identified by calibrating the parameters at the nodes of the initial parameter mesh. The hydraulic conductivities required at the nodes of the computation mesh are interpolated linearly. When the calibration procedure cannot proceed any further (which happens rapidly with the initial mesh), each parameter element is divided into four elements and the calibration resumes on the newly defined nodes. The downscaling procedure continues until the calibration criterion is met or until the size of the parameter mesh equals the size of the computation mesh. This multi-scale parameterization scheme adapts the discretization of the aquifer to the known information contained in the element (such as known head variables) and ensures a uniform set of parameters for a given mesh.

The objective function, $J(p)$, used in this work is composed of two terms, the squared difference between measured heads, h_i, and simulated heads, $\hat{h}_i$, and a regularizing term which reduces the calibrated parameter, p_k, oscillations using a weighing term, λ.

$$J(p) = \sum_{i=1}^{n} \left(h_i - \hat{h}_i\right)^2 + \lambda \sum_{k=1}^{m} \left[\left(\frac{\partial p_k}{\partial x} \right)^2 + \left(\frac{\partial p_k}{\partial y} \right)^2 \right] \quad (2)$$

Minimization of $J(p)$ is accomplished by using a Quasi-Newton iterative scheme. The gradient of the objective function is calculated using the adjoint state method. With this mathematical scheme, a number of parameters larger than the number of measured heads can be estimated. This method has the advantage of being rapid and reliable.

The hydraulic conductivities (or transmissivities) and imposed fluxes (during the high water period) are calibrated automatically using measured piezometric heads. The water table is assumed to be continuous, which is not always observed in highly karstic aquifers. However, when the carbonate rock has experienced little dissolution, the likelihood of a regionally continuous water table is more common.

The hydraulic heads were measured during the high water period of March 1994 and during the low water period of September 1995. In the present case study, most of these heads were measured from old unused wells whose elevations were estimated from topographic maps (the error on the measured levels can be as great as 2.5 m). Moreover, it is assumed that all the measured heads represent the average water level over a vertically homogeneous aquifer. This is probably not true in all cases because of the important vertical heterogeneity of the carbonate rocks. A total of 131 and 80 measured heads were available for the calibration process of the high water periods and the low water, respectively. Where numerous head measurements were available for a small cell, these were combined as a geometric mean value and was assigned to the nearest node. The measured heads vary from 150 m on the eastern boundary to 47 m at the springs (western boundary, representing the lowest head value in the study area).

Results

High water period

The calibration of the high water period provided good correlation with measured values. The determination coefficient between simulated and measured heads is close to one (Figure 2). The mean error is smaller than the estimated measurement error. The simulated spring flow rate is close to the measured flow rate (Table 1). Globally, the exchanges between the Bandiat and Tardoire rivers and the aquifer are adequately represented, confirming the adjustment of the exchange coefficients. These calibrated coefficients vary from one to ten. The highest values are located in the regions where water losses are the most prevalent (downstream) and where there is almost no hydraulic connection between the rivers and the aquifer. Because of the absence of an uphill hydrometric station, no precise estimate of the exchanged fluxes between the Bonnieure River and the aquifer could be made to adequately calibrate the exchange coefficients. However, the simulated heads show that the river drains part of the aquifer outside the domain, which corresponds to the measured piezometric data in this area. The local draining influence of the karst network appears to be adequately represented with the two constant heads.

Table 1. Calibration results for the high water period.

	Calibration results	Measurements
Mean error (m)	0.57	
Spring flow rates (m^3/s)	21.79	22.15
River aquifer exchanges (m^3/d)	604 726	571 937
Bonnieure River / aquifer exchanges (m^3/d)	-37 022	

Imposed fluxes (m^3/d)	9 122

Figure 1. Model of the La Rochefoucauld Karst Aquifer.

The implementation of imposed fluxes on the eastern boundary of the study area are necessary for simulated heads to adequately match measured heads along the perimeter of the study area. The highest simulated values were located in the southeast and northeast regions. These simulated values could not be verified with field observations.

The calibrated transmissivities were found to be highly variable over the areal extent of the aquifer. Figure 3 illustrates the calibrated transmissivities, along the x and y directions (the origin is located on the southwest corner). In the x direction, the smallest simulated values are found near the eastern boundary and the largest simulated transmissivities are located in the vicinity of the springs on the western boundary (x=0). This result can be explained by the greater thickness of carbonate rock near the springs. The higher simulated transmissivity in this area is also likely due to the presence of more karstified rocks in the vininity of aquifer discharge. In the y direction, high transmissivities are found in the vicinity of the springs (y=17,000). The northern area of the aquifer has the lowest simulated transmissivities. Locally, the automatic calibration has identified very high transmissivities in some cells, indicating the presence of potentially large contrasts in the field. This is due to the presence of head discontinuities which create important local gradients requiring high conductivity contrasts. It is possible that these discontinuities originate from the most karstified fractures or conduits. However, the high transmissivity contrasts do not form any linear patterns that could be physically associated with karstified conduits.

The recharge to the aquifer, although estimated very simply, seems to be adequate. There was no need to make any adjustments to this parameter.

Table 2. Calibration results for the low water period

Low water period

In general, the upper part of karst aquifers experiences the most active solution (the epikarst) because it is more readily exposed to the eroding capacity of groundwater flow. Therefore, the hydraulic conductivity is not uniformly dis-tributed over the depth of the aquifer. When the water level drops, there is a desaturation of the highly transmissive upper layer and the remaining saturated rock is globally less transmissive resulting in varying hydrodynamic characteristics of the aquifer during the year. A second calibration was performed for the low water period under the hypothesis that the aquifer is at steady state and without recharge or imposed boundary fluxes. The exchange coefficients for the Bandiat and Tardoire rivers and the aquifer were calibrated manually and the hydraulic conductivities of each cell were calibrated automatically as before.

The simulation results are presented in Table 2. In general, the low water period simulation yielded relatively good results relative to observed heads, although not as good as for the high water period (Figure 4). There is a systematic underestimation of the simulated heads on the eastern boundary. This could be explained by a discontinuity between the heads measured in the carbonate rock and those influenced by the semi-pervious Quaternary deposits located at the boundary between the bedrock and the carbonate rock. During the high water period, there was no simulated discontinuity because the water levels in the carbonate rock were high. The mean error is larger than for the high water period and higher than the measurement error.

	Calibration results	Measurements
Mean error (m)	3.58	
Spring flow rates (m^3/s)	1.11	6.98 (2.38*)
Bandiat River / aquifer exchanges (m^3/d)	42 994	21 667
Tardoire River / aquifer exchanges (m^3/d)	76 469	87 938
Bonnieure River / aquifer exchanges (m^3/d)	49 545	

* Lowest flow rate observed in October 1990.

Figure 3. Calibrated transmissivities for x and y directions.

Figure 4. Measured (circles) and simulated (line) heads for the low water period.

The simulated flow rates at the springs were low and similar to the lowest observed flow rates of 2.4 m^3/s (October 1990). The low water period used in this study is apparently not indicative of steady state as the aquifer was still discharging at the time the piezometric heads were measured. In September 1995, small river/aquifer exchange water volumes were observed and a large part of the spring flow rate came from aquifer storage. In the steady-state simulation, no storage release was represented and the only input in the model was through river losses, leading to low simulated flow rates at the springs.

The water volumes exchanged between the Tardoire River and the aquifer are adequately simulated, but those between the Bandiat River and the aquifer are too large. The exchange coefficients lowered to a value of one (the smallest value used during the high water period) and further adjustment of these parameters did not yield more comparable exchanged flows. The necessity to vary the exchange coefficients during the year is justified by the fact that during the dry season, the river flow rates are much smaller. Hence, the water covers a smaller area within the river bed. Consequently, the rivers lose less water to the aquifer. According to simulation results, the net exchange of water to the aquifer is from the Bonnieur River. This corresponds to the observed piezometric data for the dry period. The simulated exchanged flow rate between the Bonnieure River and the aquifer is 0.57 m^3/s. This value is smaller than a previously estimated value of 1.1 m^3/s, based on limited piezometric data. To adjust the exchanged fluxes between the Bonnieure River and the aquifer, it would be necessary to have additional information on the total volume of water exchanged. However, this would require an additional hydrometric station upgradient on the river.

The calibrated transmissivities for the low water period (Figure 3) are much more homogeneous than those during the high water period, although a more conductive area is again observed in the vicinity of the springs. The transmissivities are globally lower for the low water period than for the high water period, and the large hydraulic transmissivity contrasts simulated for the high water period are not visible during the dry period. These observations reflect the fact that during the high water period, there is a temporal activation of superficial large karstified fractures which become dry when the water level drops, verifying the hypothesis stated earlier. For some cells however, the calibrated transmissivities are higher for the low water period than for the high water period. This could be caused by the location of the measured heads. Because the measured heads used for the two calibration periods are not exactly the same, the scant information available for one of the two periods could have a significant impact during the other period, inducing apparently contradictory simulated transmissivities. Another explanation could come from the fact that the low water period is not really in steady state. That is, during a recession period, there can be discontinuities in the water levels as some important karstified fractures may have drained while the adjacent smaller fractures are still draining. This transient state creates a less continuous water table, which departs from the model hypothesis.

Conclusions

In the case study presented, two distinct steady-state periods were used in the parameter identification scheme to represent varying hydrodynamic characteristics of the karst aquifer. Considering the approximations inherent to the equivalent continuum approach in a heterogeneous karstified carbonate formation, the errors in measured heads and the fact that the low-water period is not really in steady state, the simulation results closely matched observed values for both periods. These results provide a better understanding of the regional flow of the aquifer. Transmissivities were estimated for the high and low water periods and a highly conductive area in the vicinity of the springs was identified. The imposed fluxes on the eastern boundary were identified for the high water period and the differences in rivers/aquifer exchanges between the recharge and the dry periods were estimated. The values obtained from the two calibrated and simulated steady-state periods can be considered as extreme and the parameters are expected to vary between the adjusted values for the two periods. This work shows that a continuum equivalent and inverse modeling can be used to simulate groundwater flow in a slightly karstified carbonate aquifer. Simulation provided an acceptable approximation of groundwater flow for the study area. However, this approach should be used only in slightly karstified aquifers where the underlying hypotheses are observed. Future work on this aquifer will focus on validating the calibrated parameters on other data sets in steady-state and transient-state simulations.

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OUTLINING OF PROTECTION AREAS IN KARSTIC ENVIRONMENT, A NEW APPROACH

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Abstract

The EPIK method is a general method used for the assessment of the vulnerability of karstic aquifers to contamination. The method can be used as a basis for the outlining of protection zones in karstic aquifers. The purpose of the method is to produce maps of vulnerable zones for springs or wells and water catchment basins in karst terrain.

After the water catchment basin is determined, one can proceed in the following four steps: (1) characterization of the global karstic network development, (2) cartography of the infiltration conditions, (3) cartography of the protective cover and (4) cartography of the epikarst. Four attributes are thus considered, the assessment of the vulnerability results of the overlaying and weighting of the mapped attributes.

The EPIK method is in a developing phase. It has been fully tested on one site. Further tests are in progress.

Introduction

Karstic aquifers are usually considered more vulnerable to contamination than normal aquifers. This can be explained particularly by their highly heterogeneous structure. It is characterized by very high permeability within the underground channels which are surrounded by slightly permeable blocks, and as well as by diffuse or concentrated surface recharge. This double duality has a typical hydrodynamic behavior: the floods caused by high infiltration concentrated within very permeable areas are swift and violent, and the filtration or the auto-purification processes do not have time to develop as they do in the porous aquifers.

Because of their specific functioning the karstic aquifers require very particular protection. Only a few karstic springs exist which are absolutely secure from pollution. The pollution may have various origins: natural (turbidity and organic matter) or anthropogeneous (fecal bacteria,

industrial or domestic pollution). The level of pollution varies with time and are highest during floods.

Present situation

The Swiss legislation for the protection of the waters - 1993 Federal Law (1) requires the outlining of three protection zones (S1, S2, and S3) for any important water catchment (spring or well) that is used for water supply. The regulation applies to the areas that are affected by land-use.

The protection zone must achieve the following objectives:

Zone S1: No pollution must reach the water catchment from this area.

Zone S2: The purpose of this area is to keep as many germs and viruses as far away as possible from the water catchment. The substances that degrade with difficulty must not reach the underground waters. In case of an accident within this area (serious danger), a sufficiently long period of time has to be available to proceed with a drainage.

Zone S3: This is a buffer area between zone S2 and the contiguous water protection sector. The most important restrictions inside this area are the limitation or forbidding of industrial construction and of material extraction.

The criteria of the protection zones in karstic and fissured environment vary from those applied in interstice porosity environment (2). Further, the three areas are not always contiguous. Generally speaking, the physical properties of these protection zones may be summarized as shown in Figure 1.

In karstic environment the three protection zones are delimited mostly by the observation of characteristic geomorphologic phenomenon.

Zone S1: It encompasses the water catchment zone, properly speaking, as well as all the preferential water infiltration points (dolines, sinkholes, fissured zones, etc.).

Zone S2: It corresponds to all the parts of the catchment basin from which the surface water infiltrates swiftly and reaches the water catchment in a short period of time (a few days).

Zone S3: It may be delimited following the same criteria as for the S2 zone; in many cases it encompasses the entire water catchment basin.

Today, the delimitation of the protection zones for all the water catchments in Switzerland is almost completed. But sadly, despite this important effort, one has to admit that the protection of the water catchments in karstic environment still remains insufficient.

Very often the protection zones are only partly effective. Zones 1 and 2 usually do not extend over a wide enough area, and zone 3, on the other hand, is too extended (almost over all the water catchment basin). Water quality problems arise frequently (agricultural or industrial pollution).

Therefore, the preponderant criteria taken into account for delimiting the S zones, i.e., mostly geomorphologic characteristics and a few transit velocities established by means of tracing tests, are often not quite representative.

Vulnerability of the springs or karstic water catchments

Definition

Vulnerability is an intrinsic property of aquifers that depends on the sensitivity to natural and anthropogeneous impacts (3). It is a general property that is used for characterizing, with the help of geological and hydrogeological information, the sensitivity of underground aquifer systems to either a punctual or diffuse anthropogeneous contamination. The sources of contamination such as dumping grounds, buried heating-oil tanks or the like, possible oil scattering resulting from traffic accidents, and natural or artificial manure scattering are globally taken into account.

Nevertheless, the vulnerability of karstic aquifers varies with the nature of the contaminant, the organization of the flows, the organization of the infiltration of the waters, and the specific turbidity of the pollutants transported towards the aquifer (4). It is tightly bound to the hydrodynamic behavior of the karstic aquifers.

Functioning of the karst

Karstic aquifers are characterized by geomorphologic specificities and by hydraulic phenomenon such as the existence of important springs, of water sinks, the absence of a surface drainage network, the existence of karstic networks resulting from dissolution, the typical hydrogramme of the springs (fast and violent floods, fast water recession, slow drying up) variations of the water level which can be fast or slow inside the near and remote boreholes, and of course, variations of the chemism with regard to the flow. On the basis of these general characteristics the following representation of a karstic aquifer is proposed (5). It is a network of connected channels (karstic network) reaching outlets which drain or recharge a volume of weakly permeable fissured or fractured rock.

Studies of hydraulic evaluation at the scale of a basin of the Swiss Jura karst show that an average of 50 percent of the effective rainfalls recharge the weakly permeable blocks ensuring the outflow of the springs during the drying up periods. The remaining 50 percent recharge the drains which have a fast circulation. Since fast infiltrations do not pass through weakly permeable rocks, it presupposes, on the one hand, the existence of concentrated infiltration points such as water sinks directly linked to the karstic network, and on the other hand, the presence of an epikarst. The epikarst is defined as a highly fissured absorption zone corresponding to the slackening of the surface grounds (6). This superior zone of the karst is not continuous; it may reach a thickness of a few decimeters, possibly a few meters, and many contain a perched aquifer that swiftly concentrates the infiltrated water towards the karstic network (7).

Figure 1. Irregular succession of the zones S1, S2, and S3 for a karstic spring (following H. Jäckli, (2).

Figure 2. Schematic representation of the functioning of a karstic aquifer.

Consequences of the karst functioning for vulnerability

The conceptual representation of the karstic aquifer shown in Figure 2 makes it possible to develop a coherent model of the hydrodynamic behavior and of the transported processes. It is on the basis of this representation that vulnerability is defined:

At low water level, the water of the weakly permeable blocks constitutes most of the flow of the springs. This water has spent a relatively long time inside the aquifer and has mostly flown through weakly permeable zones. Vulnerability during this period is thus relatively weak.

At high water level, more than half of the infiltration water induced by a rainy event runs swiftly through the aquifer by means of distinctive channels. Therefore, the filtration processes are weak although dilution is usually high. Vulnerability depends on the infiltration conditions of the aquifer (boundary conditions), on the spatial distribution of the hydraulic conductivity, and of the accumulation coefficient (field of the physical parameters) which are of prime importance for the flow and transport processes.

The boundary conditions have, following the infiltration conditions, three types of consequences for the vulnerability:

(1) Infiltration of the rainfall outspread over the entire water catchment basin. The vulnerability will mostly depend on the time the water will need to reach the karstic network via the epikarst or the weakly permeable blocks.

(2) Concentrated infiltration of rainfall in the form of water sinks. Vulnerability is very high where concentrated infiltration of runoff water happens, as well as over the whole catchment basin of these waters (Figure 3a).

(3) Infiltration through a detrital cover (covered karst). The vulnerability of these zones mainly depends on the permeability and the thickness of the cover. It is to be noted that the permeability of the cover varies according to its saturation state (Figure 3b).

In order to take into account the field of the physical parameters of the aquifer, one must distinguish the karstic network on the one hand and the epikarst on the other hand. The aquifer is very vulnerable if a karstic network exists in direct connection with a well developed epikarst (Figure 3c). The aquifer is less vulnerable if the epikarst is not directly linked to the karstic network. Lastly, the aquifer is only slightly vulnerable if it contains neither a karstic network nor an epikarst (it is then a fissured aquifer). It is obvious that the delimitation of protection zones cannot be established by means of a single criterion. On the contrary, it is necessary to use a multi-criteria method that will take into account the specific functioning of the karst.

EPIK method

The purpose of the new method proposed here is to evaluate the vulnerability of the water catchment basin of the springs or water catchments. It is a multi-criteria method called EPIK because it takes four criteria into consideration: Epikarst, Protective cover, Infiltration conditions, and Karstic network (8). These criteria correspond to four specific characteristics — such as those described above — of the organization of a karstic aquifer.

With this method one can evaluate the sensitivity of the underground waters in karstic areas in a comprehensive but still objective manner. The determination of the various classes of each criterion is performed with the help of several methods: direct or indirect, local or global - such as tracing tests, geophysics, geomorphologic studies, analyses of the hydrogrammes, auger or retro-showel probing, and interpretation of aerial photographs.

After determining the limits of the water catchment basin for the considered springs, one proceeds with the following four steps: (1) characterization of the karstic network development and attribution of a global factor to the water catchment basin, (2) cartography of the infiltration conditions, (3) cartography of the protective cover, and (4) cartography of the epikarst.

The various classes assigned to each criterion E, P, I, and K are the following:

Figure 3. Some examples of the preponderant factors for the vulerability of the karstic aquifers.

Criterion E: Epikarst

E1 epikarst connected to the karstic network (such as karrenfields, well drained dolines, and cuesta morphology according to the degree of the fracturation)

E2 epikarst connected to a fissured zone (intermediary zones in the alignment of the dolines, dry valleys)
E3 non-existent epikarst (covered zones P2 or P3)

Criterion P: Protective cover

P1 without a protective cover (less than 20 cm of plant cover)

P2 with a protective cover (between 20 to 100 cm of plant cover)

P3 with a middle protective cover (>100 cm of soil or 20 to 100 cm of soil and high permeable detrital cover such as lateral or frontal tills, ...)

P4 with a highly protective cover (>l00 cm of less permeable detrital cover such as see mud, loess, bottom glacial tills, ...).

Criterion I: Infiltration conditions

I1 concentrated infiltration (surface water that sinks infiltrates into the aquifer in a concentrated manner, the stream and its borders, artificial drained surface in the water catchment basin of the stream)

I2 intermediary infiltration (water catchment basin of the sinking stream)

I3 intermediary infiltration (surface of more than 25 percent slope and the foot of the slope)

I4 diffused infiltration (remainder of the water catchment basin).

Criterion K: Karstic network

K1 presence of a well developed karstic network (network with decimetric to metric channels that are scarcely choked up and well connected)

K2 presence of a poorly developed karstic network (drain network, or poorly connected or chocked up network, or network with a decimetric or inferior size)

K3 presence of a mixed karstic spring (outlet in porous environment) or fissured unkarstified aquifer

Evaluation of the vulnerability degree

The evaluation of the vulnerability degree requires the determination of appropriate weighting coefficients for the various classes of each criteria. For determining these coefficients, sensitivity tests were carried out using detailed maps of the pilot area (St-Imier), in order to obtain a satisfactory equivalence between the vulnerability classes and the protection zones S1, S2 and S3.

The weighting equation takes the following form:

$$F = a\,Ei + b\,Pj + c\,Ik + d\,Kl$$

where a, b, c and d are relative weighting coefficients and Ei, Pj, Ik, and Kl are linear coefficients corresponding to the class index.

The relative weighting coefficient emphasizes the strong influence of one criteria to another on the vulnerability; a and c are equal to 3, and b and d to 1. The epikarst and the infiltration conditions definitively strongly influence the sensitivity of the karstic groundwater.

Determination of the vulnerability classes

By combining the values of the four criteria, the vulnerability degree F is obtained. According to the values of the vulnerability degree, several classes of vulnerability can be established. By grouping them, one may define three major vulnerability classes corresponding to the protection zones.

The notion of vulnerability zones is a bi-dimensional notion (2D plan) that does not explicitly include the third dimension since the flows run in a three-dimensional environment. The above four criteria do not specifically take into account the depth at which the surface of the water table lies. This criterion does not seem relevant for karstic aquifers because the fast and direct recharge induced by the runoff waters may happen locally through the intermediary of infiltrating water sinks (9).

Application example: springs used as drinking water in St-Imier

The springs used by the small town of St-Imier (Jura bernois, Switzerland) is an example among so many others which show the relative efficacy of the delineation of protection zones in karstic environment, according to the actual practical instructions (2).

The water catchment basin of the springs of La Raissette, La Grande Dou, and Torrent is located in the western part of Switzerland, on the territories of the canton of Bern and Neuchâtel. Its area is about 140 km^2. The springs provide domestic water to several towns, including St-Imier.

From a geological point of view, the study area (Figure 4) is part of the folded Jura. The aquifer water level is located in some limestone formation from the age Sequanian to Portlandian (Malm); its thickness is from 200 to 400 meters. The aquiclude is characterized by the marls (Argovian). From a structural point of view, the water catchment basin of the springs is build up with the northern side of the Gurnigel - Chasseral anticline and with the southern flank of the Montagne du Droit-Mont-Soleil-Mont-Crosin anticline. These two anticlines have a general SW-NE direction.

In the 1980s, the protection zones were extended only on the northern part of the water catchment basin (10). Their limits were based on the practical instructions edited for this purpose by the Federal office of Environment, Forests and Landscape (2). Box A of Figure 4 shows these. Zone S3 covers the totality of the area taken into account.

Despite the establishment of these protection areas, pollution problems, such as liquid manure, happen four times a year, when the snow melts or after violent thunderstorm rainfalls.

The method EPIK has been applied to this site to try to ameliorate this unsatisfactory situation. One would like to try to determine as clearly and objectively as possible some protection zones which are a reasonable size and compatible with the application rules.

The mapping of the different parameters allows us to obtain a vulnerability map that is characterized with the presence of three classes of vulnerability equivalent to the protection zones.

Box B of Figure 4 makes it possible to visualize our proposition for the limit of the protection zones Sl through S3 provided to the water catchment basin. The comparison between box A and box B shows that the protection zones S1 and S2 obtained by means of the EPIK method are clearly more abundant at the scale of the basin. This should allow the implementation of more effective restrictions with regard to land-use.

Conclusions and prospects

The use of criteria that take into account the functioning of the karst, such as the development of the karstic network, the infiltration conditions, the protective cover, and the presence of an epikarst, makes it possible to create new maps that are representative of the vulnerability of karstic springs. These maps constitute a new basis for instituting protection zones on karstic ground. Nevertheless, although the concept underlying these new maps is clear nowadays, well-tested applications are still needed to appreciate fully its pertinence.

Presently, we are testing in the field the efficiency of the new zones (tracings and observation of the impact of the regulated manure scattering) within the St-Imier area. The use of a geographic information system (GIS) for the example of St-Imier has also made it possible to test the sensitivity of the various weighting systems and to simplify the construction of the synthetic vulnerability map. Simultaneously, the EPIK method is being tested in other karstic contexts (e.g., karst of the Tabular Jura and karst of the Prealps).

In the future, it is planned to first use a digital topographic model (DTM) to establish directly a surface runoff value (characterization of the criterion of the infiltration condition), and in a second step, to establish specific methods for the instituting of vulnerability zones which are specific for different contaminant types.

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Figure 4. Representation of the protection zones with and without the EPIK method. Box A: "classical" protection zones. Box B: Proposition for the new zones with the EPIK method.

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EXPLORATORY DRILLING IN HIXSON, TENNESSEE DISCOVERS "NEW" AQUIFER OVERLYING THE KARSTIC KNOX DOLOMITE

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Abstract

Hixson Utilities is located a few miles north of Chattanooga, Tennessee in the folded Valley and Ridge Province. Until recently, Cave Springs was their sole water supply, but growth in the area dictated a search for additional supplies. An initial exploratory drilling program located a high producing "gravel zone" on top of the Knox Dolomite. Seven additional exploratory wells were then drilled spaced in such a manner to intersect the Copper Ridge Dolomite in one area of the wellfield and the Chepultepec Dolomite in another. These are the lower two formations of the Knox Group. A detailed logging of the boreholes and a hydrostratigraphic analysis discovered that the reported "gravel" zone is actually a clean, angular chert residuum that overlies the Copper Ridge Dolomite but not the Chepultepec. Specific capacity values of the wells range from 6.7 gpm/ft to 114.3 gpm/ft with transmissivities ranging from 4,076 ft^2/day to 27,283 ft^2/day with the wells overlying the Copper Ridge Dolomite expected to sustain yields in excess of 1000 gpm. There is over 100 feet of chert-rich clay overlying the rock, but a dye test was conducted from an ephemeral stream that crosses the wellfield to determine if surface-waters may be rapidly infiltrating and adversely influencing the groundwater quality. After two months of monitoring, no dye was detected. The conclusions of the investigation strongly suggest that there is a high-yielding, turbidity-free, chert-residuum aquifer above the Copper Ridge Dolomite free of surface water influences. Since the Knox Group is over 3000 feet thick and commonly wells intersect cavities that produce surface-influenced water, these results will be useful for choosing future wellfields throughout the Valley and Ridge Province of the southern Appalachians.

Introduction and Background

The Hixson Utility District, located a few miles north of Chattanooga, Tennessee, is one of the largest suppliers of groundwater in the state. The district has been using a recently installed water well to complement the groundwater supply known as Cave Springs. To prepare for future water demands, an exploratory drilling program was conducted at the 30-acre site that contains the present production well to place additional wells for maximum production with minimal well interference. This paper presents the results of the drilling program, implications of the constructed geologic cross-sections and potentiometric-surface map, and interpretations of groundwater occurrence and flow.

Location and Hydrogeologic Setting

The well field is located on the Daisy, USGS 7½-minute quadrangle near the intersection of Daisy Dallas Road and Middle Valley Road. A generalized geologic map showing the location of the site is presented in Figure 1 (adapted from Bradfield, (1)). The geologic cross-section shown in Figure 2 (adapted from Swingle and Floyd, (2)) shows that the site is underlain by the Cambrian-aged Copper Ridge Dolomite (Ccr) and the Ordovician-aged Chepultepec, Longview, and Newala formations within a broad syncline bounded by two thrust faults. The contact of the two lower formations of the Knox Group crosses the well field and provides important differences relevant to the interpretation of groundwater occurrence and flow. DeBuchananne and Richardson (3), discuss the stratigraphic makeup of these rocks in regard to groundwater flow. In these reports, the Copper Ridge Dolomite is stated to be about 1000 feet thick and the Chepultepec about 700 feet thick. Due to the approximate 20-degree dip of the rocks to the

Figure 1. Generalized geologic map of the Walker Well Field.

Figure 2. Geologic cross-section of the Daisy Quadrangle.

southeast and the thickness of the Chepultepec, the Longview and Newala formations do not occur beneath the well field. The upper Copper Ridge Dolomite contains massive beds of dolomitic sandstone, and the lower Chepultepec is composed of chert-rich, sandy dolomite and thin beds of sandstone and cherty limestone. Due to the abundance of sandstone and sandy dolostones, the process of dissolution has been less effective in enlarging fractures compared to traditional karstic limestones. Weathering of these units has produced a thick residual cover of angular pebble and gravel sized chert, sandstone, and dolostone pieces mixed with clay.

Drilling Results

A total of seven test wells, 6 inches in diameter, were drilled by Miller Drilling Company with depths ranging from 200 to 300 feet. Although the previous test wells did not show production in the bedrock, a photo-lineament analysis was performed in hopes of siting wells in fractured rock. This technique showed significant success because most of the new test holes encountered water-bearing fractures in the sandstones and sandy dolostones below the gravel. Drilling also encountered substantial estimated yields in the "gravels" overlying the bedrock. These gravels represent the water-bearing horizon at the present production well, and as mentioned previously, are composed of angular fragments of chert, sandstone, and dolostone that have been derived from weathering of the underlying bedrock and subsequent piping of the clay particles by vertically migrating groundwaters.

In addition to siting the test wells on photo-interpreted fractures, wells were drilled on both sides of the contact of the Copper Ridge Dolomite and Chepultepec Dolomite to determine the geologic character and water bearing properties of each. The geologic contact has been dashed on Figure 3 which shows the location and pump test results of each well. Test wells #1, 5, and 6 encountered water in fractured sandstone and sandy dolostones, but most of the yield was from the overlying gravels. At test well #2, there is a relatively thin and low water-bearing zone overlying the bedrock. Test well #3 did not intersect a clean gravel zone, and no water was encountered above the bedrock. Test well #4 encountered small quantities of water in a fractured dolomitic sandstone. A gravel-rich clay overlies the rock at this location, but it does not contain water. The driller estimated the yield to be too low to warrant a pumping test. At test well #7, no discrete, clean gravel zone was encountered. Water was not obtained until weathered and fractured limestone was intersected. This is the only test well that hit significant thicknesses of limestone indicating that drilling penetrated the mid-Chepultepec Dolomite formation.

The pump test results on Figure 3 show that the specific capacity values range from 6.7 gpm/ft to 114.3 gpm/ft. with a corresponding range in transmissivity of 4,076 ft^2/day to 27,283 ft^2/day. It should be noted that much of the production potential of TW5 was cased off prior to the pumping test so that yield from one discrete zone could be measured. Although one of the wells in the Chepultepec had the highest yield, it is likely that the well will show surface-water influences because production is from a solution-enlarged fracture in limestone. The expense of filtration will make this an unlikely candidate for future development.

Groundwater-Tracing Results

Two groundwater traces were conducted at the site. The first trace was performed to determine if water from an intermittent stream that crosses the wellfield loses water to the subsurface and possibly provides rapid surface-water influences on the groundwater. On August 20, 1996, approximately one-half pound of fluorescein and one-half pound of eosine dye were mixed with the water being pumped from well #1. The dye injection occurred approximately 25 feet south of the well, and the colored water ran slowly down the dry gully, filling small depressions in the streambed along its pathway. Prior to dye injection, passive, activated, charcoal dye-detection packets were lowered into the down-gradient exploratory wells. These packets were changed weekly for the first two weeks and then every two weeks for the next month. Neither of the dyes were detected during the six weeks of monitoring, demonstrating that there are no rapid surface-water influences from waters moving along the intermittent stream.

The second trace was conducted at test well #5 on August 22, 1996, to help establish groundwater-flow velocity and direction. Approximately one pound of rhodamine WT dye was mixed with 55 gallons of water and injected

Figure 3. Distribution of specific capacity and transmissivity values.

into well #5. An additional 55 gallons of water were then added to the well. Prior to dye injection, passive, activated, charcoal dye-detection packets were placed in the down-gradient wells. The packets were changed weekly for the first two weeks and then every two weeks for the next month. A very small concentration of rhodamine WT dye was detected in well #1 approximately 30 days after injection. This information verifies the flow direction predicted by the potentiometric map and establishes groundwater-flow velocity under summer water-table conditions as approximately 10 ft/day.

Hydrostratigraphic Interpretations

Two geologic cross-sections were drawn to help interpret the continuity of the gravel zone and present the stratigraphic framework of the bedrock water-bearing zones (Figure 4 and Figure 5). Figure 4 presents a cross-section through test wells 5,4, and 3, and Figure 5 is drawn through wells 5,1, and 7. There is no vertical exaggeration on either figure, but they are at different scales. Because the cross-section lines are not perpendicular to stratigraphic strike, the dip of the rocks is drawn as the apparent dip. To simplify the cross-sections, units were grouped together. For example, the thick clay nearly always contained some gravel, but it was distinctly different from the clean gravels below. Similarly, the limestones contained some sandy dolostone, and the dolomitic sandstones contained some sandy dolostones. Comparing the cross-sections to Figure 3 showing the geologic contact, it becomes apparent that the clean, water-producing gravel occurs above the Copper Ridge Dolomite and not the Chepultepec Dolomite. Also, thinning of the gravel in a down-dip (up-section) direction suggests that the gravel aquifer is of limited aerial extent. Significant water production did occur from sandstones, dolomitic sandstones, and/or sandy dolostones in test wells 4, 5, and 6 (and probably #2). These rocks units were not reported to have been encountered during drilling of the production well, thus demonstrating the existence of other significant water bearing horizons than the gravels. Although a cross-section was not drawn between the production well and test well #7, the data initially suggest that the lowest producing horizons of the production well may occur at a depth of between 315 feet to 340 feet below the surface at the test well #7 location. Because the clean gravel was not encountered at the test well and the well penetrated nearly 100 feet of rock, the gravel probably does not exist at that location.

Potentiometric Map Interpretations

Using the known elevations of previously drilled test wells around the production well, a survey was performed to plot the locations of the new test wells and determine ground elevations so a potentiometric map could be made (Figure 6). Water rose in each well from the point it was first encountered during drilling, indicating confinement of the aquifer by the overlying clay. Groundwater flow in all directions is essentially toward the production well suggesting relatively broad influence of groundwater removal. The amount of potentiometric surface reduction is significantly greater within a 300-foot radius of the production well with the amount of hydrostatic head reduction sharply decreasing outside of this radius. Comparison of this map with a more regional map produced by the USGS (Bradfield, 1992)[1] suggests that the production well has caused groundwater to reverse flow direction in the vicinity of the Walker Well Field. A further comparison indicates that groundwater levels at the well field may have dropped from 5 to 10 feet since August 1989 as a result of groundwater pumping. A review of water levels in an USGS-

Hixson Utility District observation well shows that nearly 15 feet of water-level change can occur in a year.

The newly mapped potentiometric surface strongly suggests that the groundwater in the gravels is in hydrologic continuity with the bedrock aquifer(s) beneath because the water levels throughout the well field so closely match. Therefore, pumping of groundwater from the bedrock will likely cause downward drainage from the overlying gravels as hydrostatic pressure is reduced. The geologic map, cross-sections of the well field, and former work by the USGS show that most of the recharge is from precipitation on the hills immediately west and north of the site and through the chert residuum covering the Copper Ridge Dolomite. The USGS (1) places the well field within the recharge area for Cave Springs. This interpretation may be incorrect, unless production from the well has indeed significantly altered the potentiometric surface. Observation of the rocks at the entrance to Cave Springs shows that thrust faulting has caused an anticlinal fold on the southeast side of the fault.

Figure 4. Stratigraphic cross-section.

Figure 5. Stratigraphic cross-section.

Figure 6. Potentiometric surface map (7/10/96).

It is unlikely, though not impossible, for groundwater to move from the Walker Well Field through both limbs of the anticline and emerge at Cave Springs. In similar structural settings in karst terranes, it is more common for groundwater to move within a narrow belt along the strike of the fault plane.

On Figure 6, a cross-section has been drawn depicting an asymmetrical cone of depression around the production well. Bradfield (1) noted a similar asymmetrical cone of depression during the 24-hour pumping test and attributed it to the shallower depth of observation well #1 and less hydraulic communication. This may be correct, but similar cones of depressions also are indicative of aquifer boundary conditions or significant horizontal differences in hydraulic conductivity. This interpretation may be credible now that it is known that the gravel production zone is not uniform and continuous throughout the property.

Conclusions and Recommendations

Drilling of the seven new test wells and mapping of the potentiometric surface have provided important new information about the occurrence and movement of groundwater beneath the Walker Well Field and also has caused new questions to be posed. Previously, groundwater was thought to occur only in the gravel zone overlying the bedrock. It is now known that the fractured sandstones, dolostones, and limestones are capable of producing significant yields. The gravel production zone was hoped to extend throughout the well field, but now appears to occur just over the Copper Ridge Dolomite. Groundwater occurrence beneath the site is, therefore, complex and cannot be assumed to occur in isotropic and homogeneous aquifers of infinite aerial extent.

Mapping of the potentiometric surface suggests that the gravel and bedrock aquifers are in hydraulic continuity, but differences in hydraulic conductivity likely exist vertically due to different aquifer materials and laterally due to changing lithologies perpendicular to stratigraphic strike. Groundwater flow in the gravels is through porous media and are governed by Darcy's Law, whereas flow in the bedrock is through fractures, solutionally enlarged fractures, and along the 20° dipping bedding planes. Comparison of the 1992 USGS potentiometric map and the well field map suggests that groundwater flow has reversed direction and that groundwater levels have decreased. Groundwater tracing has helped establish groundwater-flow direction and approximate groundwater-flow velocity, and has demonstrated that the groundwater is safe from rapid surface-water influences. As a result, filtration of the water supply will not be necessary.

The results of this work should have significant applications throughout the Valley and Ridge Province of the southeast. Knowledge of the clean chert residuum aquifer on top of the Copper Ridge Dolomite will eliminate much of the guess work with drilling on the extensive Knox Group and will enhance the chances of obtaining groundwater free of surface-water influences, unlike most of the karstic bedrock. Because the Copper Ridge Dolomite is the lowest formation of the Knox Group, it should be relatively easy to locate, even in areas where the Knox has not been mapped to the formational level.

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THE ELKTON AQUIFER OR WESTERN TOE AQUIFER OF THE BLUE RIDGE MOUNTAINS -- A REGIONAL PERSPECTIVE

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ABSTRACT

The Elkton aquifer (formerly "western toe" aquifer) is a discontinuous, karst-dolomite aquifer, less than 3 miles wide, that underlies colluvium, alluvium, and residuum at the toe of the north-western slope of the Blue Ridge Mountains. The colluvium is stony material shed from resistant, siliciclastic rock of the Blue Ridge Mountains. The combined thickness of colluvium, alluvium, and residuum may exceed several hundred feet. In Augusta, Rockbridge, and Rockingham Counties, Virginia, wells in the Elkton aquifer individually may produce more than 1,000 gallons of water per minute and together produce more than 20 million gallons of water per day from dissolution openings in the dolomite that underlies the thick regolith. A statistical analysis of the specific capacity of 28 Elkton aquifer wells and 16 other dolomite wells in Virginia and West Virginia showed that for both groups the ranges of the middle 90 percent of specific-capacity values spanned about three orders of magnitude. The median specific-capacity value for Elkton aquifer wells (26 gallons per minute per foot) was more than three times the median value for other dolomite wells (7.2 gallons per minute per foot). A Mann-Whitney test indicated a statistically significant difference between these median values where the p-value is 0.05. The geomorphic and lithologic controls that define the aquifer exist in discontinuous, isolated parts of 36 counties in the Valley and Ridge Physiographic Province from Harrisburg, Pennsylvania to Anniston, Alabama.

INTRODUCTION

In 1988, as part of the Regional Aquifer-System Analysis Program, the U.S. Geological Survey (USGS) began a 6-year study of the groundwater resources in parts of 11 states in the eastern and southeastern United States (1). The study was called the "Appalachian Valleys-Piedmont Regional Aquifer-System Analysis" (APRASA). The APRASA team investigated groundwater resources primarily in the unglaciated part of the Valley and Ridge, Blue Ridge, New England,

and Piedmont Physiographic Provinces (Figure 1). The Valley and Ridge subproject team of the APRASA study focused on regional analysis of the hydrogeology of carbonate and siliciclastic rocks in the Valley and Ridge Physiographic Province (2). Prior to this study, the Elkton aquifer (unnamed) had been recognized as a major, local source of water within only six counties in the Valley and Ridge Physiographic Province: Cumberland County, Pennsylvania; Augusta, Rockbridge, and Rockingham Counties, Virginia; Unicoi County, Tennessee; and Calhoun County, Alabama. The aquifer was not recognized elsewhere probably because it occupies less than 1 percent of the province and is geographically discontinuous.

The purposes of this article are to name the Elkton aquifer, to describe the geomorphic and lithologic controls on its occurrence, to demonstrate statistically that the aquifer is hydraulically distinct, and to show the regional extent of the aquifer along the southeastern edge of the Valley and Ridge Physiographic Province.

Figure 1. The Appalachian Valleys — Piedmont Regional Aquifer —System Analysis study area and physiographic provinces.

This article is an extension of part of a comprehensive report that (2) describes and maps hydrogeologic terranes in the Valley and Ridge Physiographic Province, tests these terranes for significant differences in water-yielding properties, and provides estimates of the quantity of water available to municipal and industrial wells in these terranes. A hydrogeologic terrane was defined as a regionally mappable area that is characterized by similar rock type and water-yielding properties.

King (3) described and mapped the geology of the Elkton area, Rockingham County, Virginia, and gave special emphasis to the occurrence of residual manganese deposits within the residuum of the Tomstown (or Shady) Dolomite at the northwestern foot of the Blue Ridge Mountains. Leonard (4) described and mapped the surficial and bedrock geology along the northwestern foot of the Blue Ridge Mountains within Augusta, Rockbridge, and Rockingham Counties, and gave special emphasis to the quantity and quality of groundwater being produced from wells and springs by industries and municipalities in the area. Hack (5) described the geomorphology and mapped the surficial deposits of the Shenandoah Valley, within the Valley and Ridge Physiographic Province in Virginia and West Virginia, and gave special emphasis to the residual manganese ore deposits. Hinkle and Sterrett (6, 7) updated Leonard's work, and emphasized the importance of large groundwater supplies along the western toe of the Blue Ridge Mountains within Rockingham and Augusta Counties, Virginia.

Becher and Root (8) described and mapped the geology and groundwater resources of Cumberland County, Pennsylvania, and described regolith up to several hundred feet thick and potentially large groundwater supplies along the northwestern flank of South Mountain, which borders the southeastern edge of the Valley and Ridge Physiographic Province. Knopman and Hollyday (9) applied statistical methods to well records in Pennsylvania to rank factors that influence the water-yielding potential of the dense, fractured, and dissolved rocks in the Piedmont and Valley and Ridge Physiographic Provinces. Hollyday and Hileman (2) used these statistical methods to help define hydrogeologic terranes throughout the Valley and Ridge Physiographic Province.

THE ELKTON AQUIFER

Adequate appreciation of the Elkton aquifer requires knowledge of the geomorphic and lithologic controls that determine the location of the aquifer, the hydraulic characteristics of the aquifer that distinguish it from other dolomite aquifers, and the regional extent of the aquifer throughout the Valley and Ridge and adjacent parts of the Blue Ridge Physiographic Provinces. Each of these subjects is discussed in the following sections.

Geomorphic And Lithologic Controls

The western toe of the Blue Ridge Mountains is an area characterized by an apron of colluvium and alluvium at the toe of the northwestern slope of the Blue Ridge Mountains (6, p. 50, 51). The colluvium consists of thin, stony material shed from outcrops of resistant, siliciclastic rock, principally the Antietam Quartzite and lithologically similar units within the Chilhowee Group that is associated with the Blue Ridge Mountains. The stony colluvium commonly grades down the slope into dissected alluvial terraces that contain cobble-size gravel, sand, and sandy loam. In many discontinuous places, this colluvial-alluvial apron overlies fine-grained residuum and cavernous dolomite bedrock within the southeastern margin of the Valley and Ridge Physiographic Province (Figure 2). In parts of the western toe, the combined thickness of colluvium, alluvium, and residuum exceeds several hundred feet (3, p. 55, 59). The name Elkton aquifer is herein given to the cavernous bedrock that is overlain by the colluvial-alluvial apron of the western toe. At the type locality (eastern Rockingham County, Virginia), the buried karst resides primarily in the dolomitic parts of the Tomstown (or Shady) Dolomite, Waynesboro (or Rome) Formation, Elbrook Dolomite, and Conococheague Limestone (3, p. 7) where they are overlain by the colluvial-alluvial apron of the western toe. Within Augusta, Rockbridge, and Rockingham Counties, Virginia, public and industrial supply wells in the Elkton aquifer individually may produce more than 1,000 gallons per minute and together produce more than 20 million gallons of water per day (4, 6, 7, 10, p. 431).

Hydraulic Distinction

A statistical analysis of well records was

Figure 2. Diagrammatic hydrogeologic section of the Elton aquifer in eastern Rockingham County, Virginia.

performed to determine if significant differences in the water-yielding properties between the Elkton aquifer and other areas of dolomite could be detected. To determine differences between the Elkton aquifer and remaining dolomite aquifers, a comparison was made using 44 records of the most productive wells from the Groundwater Site Inventory database of the USGS for Virginia and West Virginia. For the purpose of this comparison, a most productive well was defined as one with a casing diameter of greater than or equal to 7 inches, used for either public or industrial supply, and located in a valley. As an example of well production, the estimated interquartile range in potential yields to 195 of the most productive wells in dolomite in the entire Valley and Ridge Physiographic Province was 210 to 1,400 gallons per minute, assuming 30 feet of available drawdown (2). In addition, wells located within dolomite and within a band that was 3 miles wide along the southeastern border of the Valley and Ridge Physiographic Province in Virginia and West Virginia were classified as Elkton aquifer wells (28 total), and those within dolomite areas to the northwest were classified as other dolomite wells (16 total). For the two groups of wells, the ranges of the middle 90 percent of specific-capacity values overlapped and spanned about three orders of magnitude (Figure 3). The median specific-capacity value for Elkton aquifer wells (26 gallons per minute per foot) was more than three times the median value for other dolomite wells (7.2 gallons per minute per foot).

To further examine the apparent difference in specific-capacity values between Elkton aquifer and other dolomite wells, a nonparametric statistical procedure, the Mann-Whitney test (11, p. 281), was employed. The Mann-Whitney test was used to determine if the apparent difference in median values between Elkton aquifer and other dolomite wells was statistically significant. The Mann-Whitney test involves a null hypothesis that no real difference in median values of specific capacity exists between the two groups of wells. An alpha value, or level of probability, is used in the test to represent the maximum probability of rejecting the null hypothesis when it is actually true. The alpha value used in this analysis was 0.05. The p-value represents the attained level of significance determined from the data using the Mann-Whitney test. If a p-value is less than or equal to the alpha value, the null hypothesis is rejected, and significant differences are assumed to exist between the two groups.

The Mann-Whitney test indicated a statistically significant difference between the median values of specific capacity for Elkton aquifer wells and other dolomite wells in Virginia and West Virginia (p-value of 0.05). Therefore, public and industrial supply wells in the Elkton aquifer had significantly greater specific-capacity values than comparable wells in dolomite elsewhere in Virginia and West Virginia.

Regional Extent

The geomorphic and lithologic controls that define the Elkton aquifer, namely cavernous dolomite that is overlain by thick residuum, alluvium, and colluvium at the southeastern edge of the Valley and Ridge Physiographic Province, extend beyond Virginia and West Virginia and exist in parts of 36 counties in the province (Figure 4). As examples, Becher and Root (8) have mapped an area of thick colluvium and alluvium that overlies the Tomstown Dolomite in southeastern Cumberland County, Pennsylvania. This area of thick alluvium and colluvium is associated with springs of second magnitude. Bradfield (12) reported on seven test wells that were drilled for the city of Erwin, Unicoi County, Tennessee. Three of these wells penetrated gravel and weathered Honaker

Dolomite in the valley of Indian Creek at the toe of the Unaka Mountains. Of these three wells, two were tested at 500 and 690 gallons per minute (12, p. 26). In addition, an area of thick colluvium and residuum overlies the Shady Dolomite on the slopes of Coldwater Mountain in southern Calhoun County, Alabama. Scott and others (13) included this area in the recharge area of Colwater Spring. This spring has an average measured discharge of 22,000 gallons per minute and is estimated to be the largest spring in the Valley and Ridge Physiographic Province.

Within the Blue Ridge Physiographic Province, but also within a few miles of the western toe, are coves (not mapped herein) that are underlain by dolomite, or dolomitic limestone, that in some places are covered by coarse-grained colluvium and alluvium and fine-grained residuum. Examples in Tennessee are Cades Cove, Blount County; Limestone Cove, Unicoi County; and Shady Valley, Johnson County. The hydrogeologic setting is similar to the type locality in eastern Rockingham County, Virginia (Figure 2), and the

Figure 3. Variation of specific-capacity values for public and industrial supply wells in dolomite in and out of the Elkton aquifer in Virginia and West Virginia.

Figure 4. Approximate location of controls that define the Elkton aquifer in the Valley and Ridge Physiographic Province in the Eastern and Southeastern United States.

authors would consider these occurrences Elkton aquifer even though they are within the Blue Ridge Physiographic Province.

SUMMARY

Prior to the APRASA study, the Elkton aquifer (unnamed) had been recognized as a major, local source of water within only six counties in the Valley and Ridge Physiographic Province in Pennsylvania, Virginia, Tennessee, and Alabama. It was not recognized elsewhere probably because it occupies less than 1 percent of the province and is geographically discontinuous. The Valley and Ridge subproject team of the APRASA analyzed well records for the statistical significance of the Elkton aquifer and recognized the aquifer's regional extent. The purposes of this article were to name the aquifer, describe controls on its occurrence, demonstrate that it is hydraulically distinct, and show its regional extent. At least six prior reports described the geology of the western toe and the hydrology of the aquifer. Two prior reports placed the aquifer within a regional context.

The western toe of the Blue Ridge Mountains is an area characterized by an apron of colluvium and alluvium at the toe of the northwestern slope of the Blue Ridge Mountains. In many discontinuous places, this colluvial-alluvial apron overlies fine-grained residuum and cavernous dolomite bedrock within the southeastern margin of the Valley and Ridge Physiographic Province. The name Elkton aquifer is given to the cavernous bedrock that is overlain by the colluvial-alluvial apron of the western toe. Within Augusta, Rockbridge, and Rockingham Counties, Virginia, the Elkton aquifer has public and industrial supply wells that produce more than 20 million gallons of water per day.

A statistical analysis of well records was performed to determine if significant differences could be detected in the water-yielding properties between the Elkton aquifer (28 wells) and other areas of dolomite (16 wells). For the two groups of wells, the ranges of the middle 90 percent of specific-capacity values overlapped and each spanned about three orders of magnitude. The median specific-capacity value for Elkton aquifer wells (26 gallons per minute per foot) was more than three times the median value for other dolomite wells (7.2 gallons per minute per foot). A Mann-Whitney test indicated that public and industrial supply wells in the Elkton aquifer had significantly greater specific-capacity values than did comparable wells in dolomite elsewhere in Virginia and West Virginia.

The geomorphic and lithologic controls that define the Elkton aquifer, namely cavernous dolomite that is overlain by thick residuum, alluvium, and colluvium at the southeastern edge of the Valley and Ridge Physiographic Province, extend beyond Virginia and West Virginia. These same controls exist in parts of 36 counties in the Valley and Ridge Physiographic Province from Harrisburg near Cumberland County, Pennsylvania, to Anniston in Calhoun County, Alabama. In addition, these geomorphic and lithologic controls would appear to exist in several coves within the Blue Ridge Physiographic Province near the western toe.

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BUFFER ZONES IN KARST TERRANES

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Abstract

Environmental maintenance of karst resources necessitates proper delineation of drainage paths and other components of the hydrologic system, including both on the surface and in the subsurface. An integral component of karst is the sinkhole. It is both a product of karst-forming processes and an entry point for meteoric water entering the subsurface. Collectively, sinkholes are an indicator of discrete recharge to conduit-dominated aquifers formed in soluble rock. Additionally, sinkholes serve as funnels that concentrate and carry water to the subsurface.

Because groundwater in karst typically travels quickly through open conduits and exits at discrete points of discharge, such as springs or wells, maintenance of water quality in such aquifers requires special care. Sinkholes are all too often viewed simply as closed depressions as seen on topographic maps or on aerial imagery. However, each sinkhole has a contributing surficial drainage basin. Where grouped in close proximity to one another, sinkhole clusters share a larger drainage basin. Under such conditions the drainage-basin boundary encloses a much larger area than included within individual closed contours on a topographic map.

It is well established that keeping contaminants from entering sinkholes is a crucial step in the protection of groundwater in karst. Many environmental regulations specify minimum distances that must be maintained from the bottom point of a sinkhole, from its "drain hole," or from its outer contour on a topographic map. These distances are often used to delineate protective boundaries for development. The area within these boundaries constitutes a "buffer zone" that should be maintained in a natural, unobstructed state. However, in most cases, the buffer zone should be extended, in order to protect a greater part of the contributing basin. The funnel of a sinkhole does not simply extend to the outermost contour on a map. It extends to the basin divide, which in many cases is shared with an adjacent sinkhole. Where areal sinkhole density is high and recharge to an aquifer is collected through multiple points of input, the buffer zone must be carefully chosen and defined.

Introduction

Karst terranes are inherently very sensitive to environmental stresses. This is compounded in karst areas experiencing increased land use, paticularly through urbanization, an inevitable result of population growth and concomitant increases in residential, commercial, industrial, and agricultural activity. Increases in the numbers of buildings, parking lots, various transportation and utility corridors, and the like result in a progressive degradation of the natural environment (Kastning 1989b, 1995a, 1996). Environmental problems are numerous and typically include (1) instability and collapse of the ground surface, (2) erosion or sedimentation of sinkholes, (3) flooding of sinkholes, and (4) contamination of groundwater. Human intervention in karst terranes may impact the subsurface in various ways, particularly in caves. Examples include alteration of ecosystems or damage to the contents of caves, such as aesthetic deposits of minerals or archeological and historic materials. It is not the intent of this paper to review each of the hazards and environmental problems implicit in karst terranes. However, the reader may readily find information on these in many references (Aley 1972; Aley and others 1972; Dougherty 1983; Kastning and Kastning 1991, 1993; LeGrand 1973; Slifer and Erchul 1989; Zokaites 1997). A trend in recent years is to produce informative booklets, brochures, maps, and posters on environmental problems in karst for distribution to schools, libraries, museums, and similar institutions (Hubbard 1989; Kastning and Kastning 1990, 1992, 1995; Zokaites 1997). They are also being provided to landowners and governmental officials in communities underlain by karst.

Misconceptions about Karst

Unfortunately, there is a pervasive lack of understanding among people living in karst regions about the intrinsic nature of this type of terrane and the characteristic processes that have formed it and continue to operate. Nonfamiliarity also extends to many individuals who have the authority and mandate to address and alleviate environmental and engineering problems that arise from changes in land use. An essential first step in effective management of this terrane is to know the definition of karst.

Karst is a landscape that is principally formed by the dissolving of bedrock. It is characterized by sinkholes, caves, sinking streams, springs, and solution valleys. The study of karst is a relatively new science that draws largely on the principles of geology and geography. A thorough understanding of the processes that occur both at the surface and underground and an appreciation for the total hydrologic system necessitates a familiarity with scientific karst studies. The level and scope of modern karst studies are demonstrated by the recent proliferation of textbooks on the subject (Kastning 1994). Recent texts on karst include those of Ford and Williams (1989) and White (1988). Moreover, the number of scientific journal articles and graduate theses on karst is expanding at a phenomenal rate. Monroe (1970) presents a handy glossary of karst terminology.

There are several common misconceptions regarding karst (Kastning and Kastning 1994). We have found the following to be among the most significant:

Misconception No. 1: Bedrock is composed of homogeneous materials that are solid (without voids). Rocks are viewed as strong, unyielding, and relatively inert materials that provide a stable foundation at the surface of the Earth. Although this may be true of crystalline materials such as igneous and metamorphic rocks and hard, dense, insoluble sedimentary rocks, soluble rocks (such as limestone, dolostone, marble, and gypsum) potentially have been hollowed through dissolution by acidic groundwater. Cavities excavated in this manner will vary greatly in size and some may be quite sizable. Dissolutionally enlarged openings, in turn, may cause structural instability of the bedrock and provide avenues for the circulation of groundwater. *The presence of karst features on the surface is nearly always indicative of subsurficial openings and integrated groundwater flowpaths.*

Misconception No. 2: Water enters a sinkhole because it is there, rather than, sinkholes form where water enters the ground. Most people recognize that water enters sinkholes. After all, if a sinkhole is a closed depression on the surface, it will collect water from precipitation and runoff. This water has nowhere to go except into the ground. Sinkholes are all too often viewed as pre-existing funnels that happen to channel and concentrate water impinging on them. However, the relationship between surficial waters and sinkholes is generally the inverse: *sinkholes form and enlarge at places where surficial water can easily enter the ground,* such as along enlarged fractures in the soluble bedrock. Infiltrating water has formed the sinkholes, rather than pre-existing sinkholes merely providing convenient sites for recharge. Once established, sinkholes may then concentrate water flow and continue to enlarge.

Misconception No. 3: Pollution entering the ground is not a threat. That is, "Out of sight, Out of mind." When compared with most other types of rock (*e.g.,* sandstone, shale, and crystalline rocks, such as granite, gneiss, etc.), carbonate rocks and gypsum are highly porous and permeable. *Karsted rocks will not naturally filter contaminants to any appreciable extent.* Moreover, contaminants are easily and very rapidly transmitted to points of discharge, principally springs and wells. The residence time of chemical ingredients in karstic groundwater is relatively short and sources of water from the subsurface are easily polluted in karst. In karst, what goes into the ground soon comes out of the ground with little chemical change.

Misconception No. 4: Water issuing from springs in bedrock is pure and healthy to drink. The fallacy of this statement is obvious from the foregoing explanation. There are many people, including those living in karst areas, who routinely obtain "potable" water from springs and believe that groundwater is inherently pure.

Recognition of Surficial Karst

In most cases, karst features and landforms are readily obvious and could be easily recognized in the field, on topographic maps, and on aerial photography. This is particularly true where karst development is mature and subsurficial conduits of flow have become sufficiently enlarged and well integrated into networks that link discrete recharge zones (such as sinkholes and sinking streams) to discrete discharge zones (namely springs). Mappable surficial karst features are often useful in ascertaining information about subsurficial conditions, including geologic structure and likely directions and configurations of groundwater flow (Kastning 1989a). Sinkholes are perhaps the single landform most useful in mapping the extent and type of karst (Kastning 1989a,b).

The degree to which karst can be mapped from surficial information may be limited. Maps, aerial photographs, and other remotely sensed data have various degrees of resolution. Hubbard (1984, 1991) has shown that a large proportion of sinkholes recognizable on standard aerial photographs are not indicated on 7.5-minute topographic maps. This is primarily because sinkholes are not expressible on these maps unless their elevations intersect a contour value. For example, unless a contour elevation value lies between the elevations of the bottom and rim of a sinkhole, a sinkhole twelve feet in depth will not be indicated on a topographic map having a contour interval of 20 feet, regardless of the areal size of the depression. Additionally, many sinkholes that are identifiable on soil maps are not visible on aerial photographs (Hubbard 1991). The only truly reliable method of mapping all sinkholes in an area is through fieldwork, especially if smaller ones need to be documented.

There are many areas of karst where the surficial expression of sinkholes and other diagnostic features are absent or highly subdued. Sinkholes may be very broad or of shallow depth and escape detection. A casual investigation may easily miss these. There are many documented areas in the world having extensive and well-integrated groundwater flow systems through caves, yet the surface overlying them is nearly devoid of karst features. At first glance one might judge the area, based on surficial observations alone, as non-karstic or of minimal karstic significance.

Environmentally sound planning often dictates that areas of karst be delineated. This is especially true where recharge zones must be protected from contaminants introduced at the surface that may be readily conveyed into underlying aquifers through infiltration at sinkholes or along dissolutionally widened fractures. Assessments for planning and construction purposes and enforcement strategies for karst protection typically rely on published maps (generally U.S. Geological Survey topographic quadrangles) and, in some cases, aerial photography. Small sinkholes are often missed or simply ignored as inconsequential. If shallow, poorly defined sinkholes are overlooked, delineation of recharge zones, where karstification has enhanced vertical infiltration and percolation, will be inadequate and this may lead to future problems with groundwater quality. For example, this has recently been the case for mapping of karst terranes within proposed corridors for highways and powerlines in Virginia. Large areas of karst where surficial features are subdued were left out of the initial feasibility and environmental impact studies (Kastning 1995a, 1996). The environmental sensitivity of a large area of karst was overlooked simply because surficial features did not "jump out" at the investigators. This should not have been the case, as it is well known that the Appalachian region of Virginia has extensive areas of karst and thousands of documented caves (Davies 1970; Douglas 1964; Herak and Stringfield 1972; Holsinger 1975, 1985; Hubbard 1983, 1984, 1988, in preparation; Kastning 1986, 1988, 1989b, 1990, 1995b; Kastning and Kastning 1995; Miller and Hubbard 1986).

Stipulations in Environmental Regulations and Guidelines

Fortunately, many environmental agencies and other governmental bodies now specify sinkholes as sensitive features and often as natural hazards. Developers are advised to avoid sinkholes for most land-use applications. This is to minimize the danger of land instability near or under structures, to prevent erosion, sedimentation, and flooding of sinkholes, and to protect the recharge zones that sinkholes represent.

On the negative side, many guidelines merely stipulate a minimum horizontal distance that something can be placed or constructed with respect to (1) the center of a sinkhole, (2) the lip of a sinkhole, (3) the bottommost point in a sinkhole, or (4) the drainhole in a sinkhole. For example, it may be required that a septic tank be at least 50 or 100 feet from the bottom point in a sinkhole. What if the developer abided by the letter of the wording and placed a septic tank 55 feet from the bottom of a circular sinkhole with a radius of 150 feet? At the bare minimum, the structure should be placed outside of the lip of the sinkhole. However, in the case of multiple sinkholes occupying a small area, being beyond the lip of one sinkhole may only mean that the location is now within the bowl of an adjacent sinkhole. Clearly, even though placement of the structure may be outside of the stated minimum limit and the developer would be in compliance, the intent of the guidelines would not be met. Expediency, avoidance of extra costs, or prevention of the abandonment of the project often dictate the eventual outcome. The solution to the problem is a rethinking of what is meant by a "buffer zone."

Buffer zones and the Need for Them

A major consideration in protecting natural water supplies is the protection of contributing sources, that is the "upstream" areas of the flow system. For surficial streams such protection entails environmental maintenance of all tributaries within the catchment area (drainiage basin). In groundwater-protection strategies, attention is focused on zones of recharge.

Recharge zones in karst vary considerably within a continuum. On one end of the spectrum is diffuse recharge, whereby water infiltrates through the soil zone or other overburden to the interface with the bedrock. Under these conditions, recharge occurs over a wide geographic area, but the infiltration rate at any one place may be low. At the other end of the spectrum is discrete discharge, a situation whereby water enters the bedrock in distinct places. Sinkholes are excellent examples of discrete recharge. Some sinkholes take the full discharge of one or more surface streams.

The discrete character of drainage through sinkholes is illustrated in the example of Figures 1 and 2. The first figure shows a typical cluster of sinkholes in the Valley and Ridge Province of Scott County in southwesternmost Virginia. The sinkhole contours are taken directly from the Gate City 7.5-minute USGS quadrangle. Note that the dashed contours within the sinkholes are of a 20-foot contour interval. For clarity, only the 100-foot contours are reproduced for the area outside the sinkholes. No sinkholes shown on the original map have been omitted. Some of the sinkholes shown in Figures 1 and 2 swallow entire surficial streams. By noting crenulations in contours of land adjacent to the sinkholes, it is easy to see that many intermittent streams enter the ground in this area as well.

Water coming downslope from non-carbonate rock may also enter carbonate rocks. This usually occurs in close proximity to the contact between the carbonate and non-carbonate rocks. Such allogenic recharge is often derived from large, contributing basins on the upper slopes wherein infiltration rates may be quite low owing to the perching of runoff on crystalline or argillaceous beds of low permeability (Kastning and Watts 1997). If slopes are steep in the uplands, contributing surficial discharge to swallet-type sinkholes may be very high. Oversteepening of slopes (*e.g.,* excavating) or denudation of vegetation (*e.g,.* by logging) may exacerbate erosion, sedimentation, and flooding of the sinkhole, or introduce surface-water contaminants to the subsurface. If any of these conditions are threatening, the effective buffer zone, in terms of watershed management, must include the upland areas.

Methods for Establishing Buffer Zones

It is evident from the foregoing discussion that buffer zones may have to be one or more orders of magnitude larger than the size of sinkholes indicated on a map or by other means. The determination of the size of a buffer zone is based on any of several criteria: (1) the boundary of the drainage basin that contributes recharge to a sinkhole or a clustered sinkhole infiltration system, (2) the area within the contributing basin that is under potential development, (3) the natural settings, including topography, geologic parameters such as bedrock and structure, and vegetative cover, (4) inherent storm-water hydrological responses, and (5) proximity of

Figure 1. Sinkholes near Alley Valley, Scott County, Virginia. Contours within sinkholes have a contour interval of 20 feet. Other contours are at a 100-foot interval.

Figure 2. The same area as in Figure 1. Internally drained areas are indicated. Drainage-basin

land-use activities within the basin that may impact discharge and recharge at the sinkholes.

Consider again the example in the figures. Sinkholes indicated in Figure 1 represent very little of the surface area of the karst plain that surrounds them. Note that considerable allogenic recharge enters some of the larger sinkholes. In fact, these sinkholes may be large because of the amount of recharge that enters them from steep slopes, particularly on the south side of the valley. A typical environmental study, designed to ascertain where sinkhole effects should be avoided, may very well simply delineate the sinkholes as shown in Figure 1, or at best, add a hundred feet or so as a buffer around each outermost closed contour.

Figure 2, on the other hand, shows the effective drainage configuration. The boundaries added to Figure 1 to produce Figure 2 are in essence drainage divides around land that is internally drained. The boundaries were drawn using all of the twenty-foot contours on the original map and by noting ridge lines and high knobs as natural drainage divides.

If it were necessary to avoid virtually all negative influences to the recharge into the sinkholes by activities within the contributing basin, the effective buffer zones would be outlined by the drainage boundaries as shown on Figure 2. Of course that would be impractical in most cases, as it infringes on land under current use. However, some activities may be disallowed, curtailed, or voluntarily eliminated within these zones. If nothing else, constructing the ultimate buffer zones on a map will heighten awareness about potential threats, and these boundaries would then serve as an effective management tool for that area of karst. Because there is often a tendency to ignore allogenic recharge to karst during investigations of sites for development, a rethinking based on buffer-zone delimitation can raise consciousness and prevent adverse environmental impacts.

Conclusions and Recommendations for Managing Karst Recharge Zones

Karst terranes require special consideration for environmental protection. It is imperative to protect zones of recharge in order to maintain high groundwater quality in karst. This requires "best management practices" on the surface overlying the karst and within basins contributing allogenic recharge to the karstic aquifer. Buffer zones may serve as a management tool whereby selected land-use practices may be monitored or controlled as needed. In some cases, often in close proximity to sinkholes, buffer zones are necessary to preserve sinkholes in a natural state with minimal changes to natural levels of erosion, siltation, and flooding and minimal disturbances to ecosystems in sinkholes and in the subsurface (*i.e.* in caves). Hence, in some cases buffer zones may represent zones of exclusion of damaging activity; in other cases, they may represent zones of various levels of management and mitigation. In any event, sinkholes and their buffers should not simply be relegated to small plots of land without regard for the actual size of the sinkholes.

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GROUNDWATER HAZARD MAP OF THE TURNHOLE SPRING KARST GROUNDWATER BASIN, MAMMOTH CAVE NATIONAL PARK

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Abstract

A groundwater hazard map, depicting features of groundwater recharge, landmarks, and road-way drainage elements has been detailed on one-half mile sections of the major transportation corridors that traverse Mammoth Cave's drainage basin. This set of maps is carried by all area environmental emergency responders and allows rapid assessment and mitigation of a hazardous spill before it enters the karst aquifer.

Introduction

Most water flowing through subterranean rivers of Mammoth Cave originate from private lands beyond park boundaries. These rivers, classified by the Commonwealth of Kentucky as Outstanding Resource Waters, support the most biologically diverse cave aquatic ecosystems in the world, including federally endangered Kentucky Cave Shrimp. Groundwater flow properties of karst contributes to the creation of a hydrologic system in which the surface properties and all surface activities are highly integrated with the subsurface and all aquatic ecosystems of the karst aquifer.

Thousands of trucks and several trains each day travel across the recharge area, where surface water is immediately transferred to the cave below. It is typical to have as many as five spills of toxic material per year along these routes. If such a spill occurs at the wrong hydrologic location (e.g., a sinkhole or sinking creek) and/or during a rainfall event, the aquatic communities of the cave could be severely impacted.

Once a spill enters the karst aquifer there is little, if any, chance for mitigation. As the spill must be contained at the surface, both response time and prior knowledge of surface hydrology are critical. Before this project was completed, when a spill occurred, emergency responders arrived with little knowledge of the labyrinth of drainage ditches, culverts, and sinkholes unique to the site, and precious little time for reconnaissance. The time saved by arriving on-site with the knowledge of where the spill is located with respect to a storm drain, sinkhole, or sinking creek might prevent an ecological disaster.

Under the Mammoth Cave Area International Biosphere Reserve, Mammoth Cave National Park, in cooperation with the Kentucky Division of Water (KYDOW), and the Barren River Area Development District, created a set of groundwater hazard maps along the major transportation corridors (Interstate 65, 12 miles; the CSX Railroad, 14 miles; and the Cumberland Parkway, 5 miles) traversing the park's recharge basin (the Turnhole Spring Karst Groundwater Basin). These maps, which detail a one-half mile section of roadway (or 1 mile of railroad), display a host of landmarks (signs, mile-markers, guardrails, outcrops, and bridges), hydrologic features (paved ditches, streams, inlet boxes, pipe headwalls, and sinkholes), and potential hazards that may greatly alter the designed flow of surface waters (cracks, undercuttings, and collapses). Equipped with this map set, the emergency responder knows immediately where, hydrologically speaking, the spill occurred and exactly where to deploy lines of defense for mitigation of the spill.

The map sets were completed and printed in the summer of 1996. Currently, training sessions and map distribution are being held for all area emergency responders. As long as hazardous materials are transported over karst lands there will be a need for rapid assessment and mitigation of spills. It is expected that, through this joint effort of the Mammoth Cave Area International Biosphere cooperators, spills will be dealt with quickly and effectively.

Procedure for Using Maps

The responder to an emergency can locate the detailed map from the index map that is based on highway mile markers (Figure 1). For example, if a spill occurs near mile marker 49 on I-65, the index will direct the responder to look at map sheet I65-13 (Figure 2). The map sheet shows detailed landmarks, such as guardrails, signs, bridges, and outcrops, that will help determine the exact location of the spill. Once the location is determined, information on detailed surface hydrology, drainage basins, paved ditches, drop boxes, culverts, and sinkholes can be obtained from maps. The responder will know exactly in which direction the spill is headed and thus make a decision where to position materials and personnel.

Potential Hazards

It is common that over the years, many of the drainage features of an area such as paved ditches, drop boxes, and culverts experience a structural failure. These failures have been noted on the maps as potential hazards that will greatly affect the movement of water. For example, a crack in a paved ditch will cause surficial water to enter the ground at that point, rather than along its intended route. All potential hazards must be evaluated when a spill-containment plan is developed. It will be of little use to position a sorbent boom at the foot of a paved ditch if the spill has been diverted into a potential hazard upstream. It must be noted that additional potential hazards may develop after these maps were created. The responder must always be alert to these new hazards.

Figure 1. Index of map of Interstate 65, typical of other indexes, which allows responders to find the detailed map sheet based upon mile markers.

Figure 2. Detailed landmarks, roadway drainage, and surface hydrology which allows responders to quickly locate the spill relative to groundwater recharge points and potential groundwater hazards.

Table 1. Description of Mapped Features.

HYDROGEOLOGIC DATABASE FOR SCOTT COUNTY, VIRGINIA — A PROGRESS REPORT

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Abstract

Geologists at the Division of Mineral Resources (DMR) are developing a digital hydrogeologic database of water-well, spring, and geologic information. The author is conducting a water-well and spring inventory of Scott County, Virginia in conjunction with geologic mapping of the county. This will incorporate information extracted from water-well completion reports, chemical and bacteriological analyses, pump tests, and location maps, with spring locations and geologic maps.

As of June 1, 1997, data for 311 water wells and springs have been collected from local, state, and federal agencies, and water-well drillers. Water wells and springs are currently being located using Global Positioning System (GPS) technology to provide accurate locations. Geologic maps are created in a digital format. The water-well, spring, and geologic information are combined into a digital hydrogeologic database management system to provide a platform for cataloguing and analysis of the data. Geologists at the DMR will continue to update and expand the database as additional information becomes available.

Introduction

Groundwater from wells and springs is the main source of water for many residents, businesses, and municipalities of Scott County (Figure 1). The geology of the county has a significant impact on the availability of groundwater, especially in the carbonate rocks. The county is a geologically complex area in which folds and faults have deformed the rocks.

Hundreds, and perhaps thousands, of water wells have been drilled in Scott County to provide water for residences, municipalities, and businesses. Many wells were drilled before accurate records were kept. Data such as depth of well and depth of water-bearing zones was never recorded or was lost. There are only sparse records from wells drilled before the middle

1980s. Data have been kept on most wells drilled since about 1985; however, they have not been gathered into one database. The various records are housed with the local, state, or federal agency responsible for regulating each well.

Geologists at the Division of Mineral Resources are developing a digital hydrogeologic database of water-well, spring, and geologic information. The groundwater and geologic information are combined into a database management system to provide a platform for cataloguing and analysis of the data. The data will be analyzed in an attempt to determine geologic factors, such as lithologic changes and structural features, that impact the occurrence and movement of groundwater in this area.

Methods

Database Management System

The Division uses the Windows-based MapInfo Professional © GIS software package as the platform to digitally display the groundwater and geologic data in a spatial (map) view. MapInfo has Open Database Connectivity (ODBC) capabilities to link the spatial data with groundwater data stored in a relational database in Microsoft Access © [1]. The groundwater data in Microsoft Access is connected to spatial data in MapInfo by executing point or global queries.

Water-well locations and geologic maps are stored in MapInfo as individual "layers". Each layer is independent and so only the layers needed to analyze a particular problem are viewed. MapInfo uses the coordinates of the data, such as latitude and longitude, to display the data as points, lines, or regions on digital topographic or geologic maps.

Development of the Hydrogeologic Database

Water-Well Information

The author, working with Clinch Valley College students, has obtained data for 311 water wells and springs. The data was collected from one or more of the following forms: Water Well Completion Reports (GW-2), Uniform Water Well Completion Reports, Bacteriological Analyses, Water Quality Reports, Pump Tests (up to 48 hours), and maps. This data was provided by the Scott County Health Department, Department of Environmental Health; Department of Environmental Quality, Southwest Regional Office; Department of Health, Office of Water Programs; Division of Mineral Resources; U.S.D.A. Natural Resource Conservation Service; and water-well drillers.

The original paper forms were scanned into a laptop computer using a Visioneer PaperPort Vx ™ scanner and converted to a digital format. Scanning the forms allows the database user to store and organize the mass of information and search for an electronic version of individual files.

The scanned images of the forms were reviewed and selected information was extracted. The following information is stored in a database in Microsoft Access:

- VMDR #
- Depth to Bedrock
- County
- Length of Casing
- Quadrangle
- Completion Date

[1] MapInfo Professional © and Microsoft Access © were selected because each is a commercially available software package. Mention of trade names or commercial products does not constitute endorsement.

Latitude
Well Use
Longitude
Availability of:
Location Accuracy
Drill Cuttings
Source Agency
Geologic Log
Source Agency ID #
Driller's Log
Water-Well Owner
Geophysical Log
Water-Well Driller
Chemical Analyses
Yield (gpm)
Bacteriological Analyses
Static Water Level
Pump Test
Total Depth

Location Accuracy

Water-well locations on the original forms range from sketches or written descriptions to points on a 7.5-minute topographic map that have been located in the field. Many of these locations are imprecise for use at 1:24,000 scale. All water wells and springs are assigned a location accuracy code in the database. Location accuracy ranges from 1 to 4 based on the following:

1-Global Positioning System (GPS) site

2-Located on a 7.5-minute topographic map in the field

3-Located on a 7.5-minute topographic map from verbal description

4-Points on previous maps that cannot be found in the field

The accuracy of water-well locations is upgraded using GPS technology. The DMR uses a six-channel hand-held Trimble GeoExplorer II ™ receiver. Information collected with the GPS receiver is combined with GPS base station data. The raw receiver data is differentially corrected using Trimble Pathfinder Office ™ software to obtain latitude and longitude coordinates.

The original location descriptions are used to locate the wells in the field, followed by using the GeoExplorer II receiver to collect GPS satellite readings. Typically the antenna is placed directly over the well. At least 300 satellite positions are taken in about a 10-minute period.

The information is stored in the receiver and later downloaded to a computer. GPS base station data is collected from the Department of Mines, Minerals and Energy (DMME) base station located in Big Stone Gap, Virginia. The horizontal accuracy of the water-well and spring locations are typically within 5 meters after differential correction is completed.

As of June 1, 1997, 52 wells and springs have been located using GPS. While in the field, undocumented springs are being located using the GPS unit to enhance the information in the groundwater database. The database is updated regularly as additional information on springs such as water flow and chemistry is obtained.

Digital Geologic Maps

The DMR uses ABICAS™ GIS software to create digital geologic maps for publication. Previously published geologic maps are prepared in a digital format, as time allows. As new areas are mapped the maps will be created in a digital format. This provides information that can be used in a computer database.

The digital geologic maps created in ABICAS are converted to a MapInfo format through several steps. The linework, such as formation contacts and fault traces, is converted into MapInfo format. The following information about map units is attached to the formation areas in MapInfo:

Unit designation
Formation name
Lithology
Source map and scale
Rock family.

The vectorized geologic data can be analyzed as easily as the water-well and spring data. The digital geologic map of the recently completed Gate City 1:24,000 scale, 7 ½-minute quadrangle, produced in ABICAS, was converted to MapInfo format. As additional Scott County geologic quadrangle maps are digitized they will be added to the database.

Database Use and Application

Development of the hydrogeologic database provides automated capabilities for storage, management, and analysis of the data in a spatial view and in a relational form. In contrast to previous databases displayed on maps and in tables on paper, this computer database will allow for continued input of water-well and spring data and digital geologic maps as they become available. It also provides for connectivity between the spatial data of a map and the relational database.

The power of the database is the ability to view the water-well and spring locations in relation to the geology and then use point or global data queries that will select all wells or springs that meet specific criteria. The database provides the ability to:

- Accurately overlay well and spring locations on digital topographic maps and/or geologic maps (Figure 2).
- View the tabular data on individual wells and springs in Microsoft Access by selecting a point on the maps (Figure 3).
- Use search criteria to globally search the database for specific criteria.
Examples include:
    - Wells with a specific yield (example: yield greater than 100 gpm. Figure 3).
    - Formations with a specific lithology (example: formations composed of limestone).
    - Wells drilled in certain years.
    - Wells drilled by specific companies.

The database provides layers that can be used by local, state, and federal agencies as well as consultants and drillers, to analyze various hydrogeologic components in Scott County, Virginia.

The hydrogeologic database continues to be updated as water-well and spring information is collected, water-well and spring locations are upgraded to GPS accuracy, and additional geologic maps are digitized. In the next phase of the project, the water-well and spring information and the associated geology will be analyzed to gain a better understanding of the groundwater systems of the area. It is anticipated that this will result in identification of areas with potential to provide an adequate groundwater supply for users. The study may also identify areas susceptible to groundwater contamination.

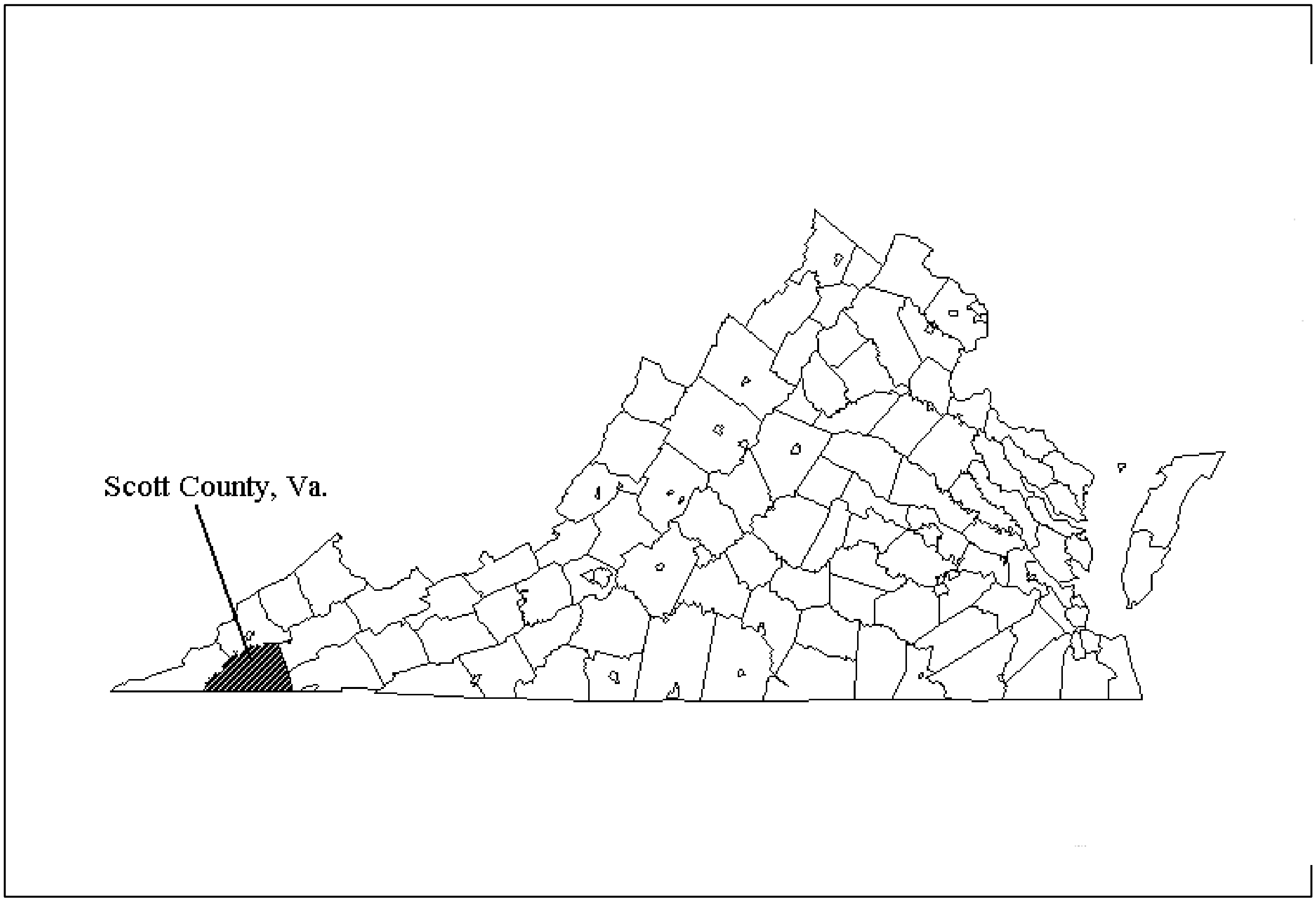

Figure 1. Index Map Showing locating of Scott County, Virginia.

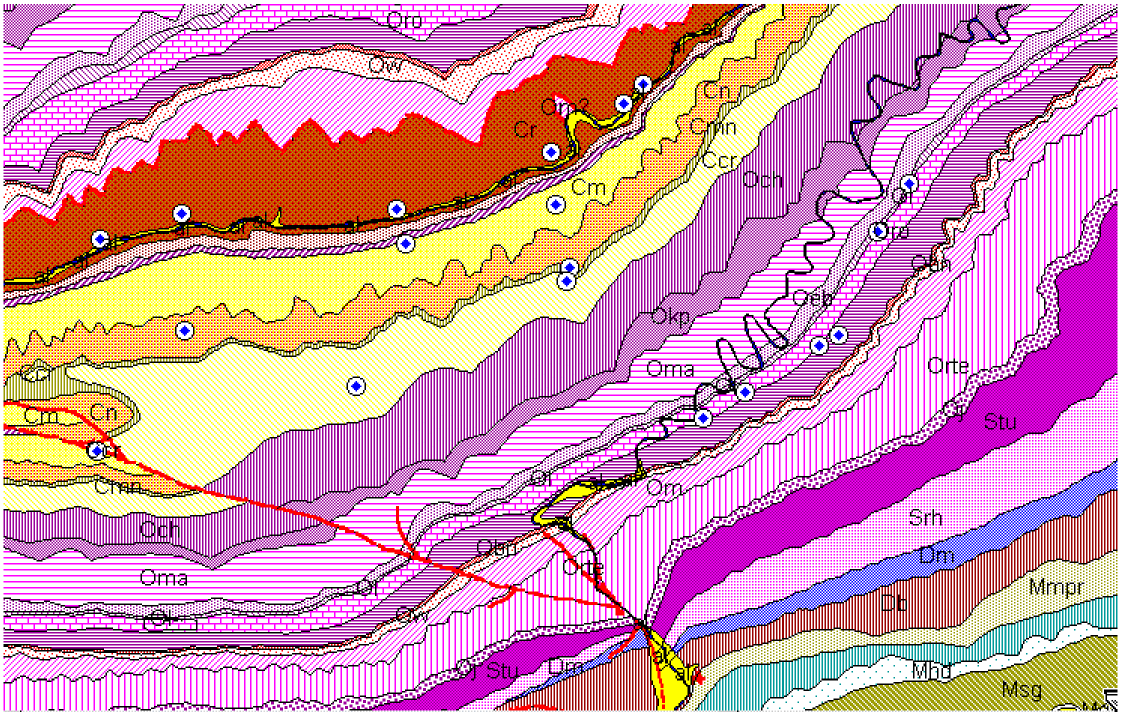

Figure 2. Geologic map of a portion of the Gate City 7.5 minute quadrangle, Scott County, with water-well and spring locations (circles).

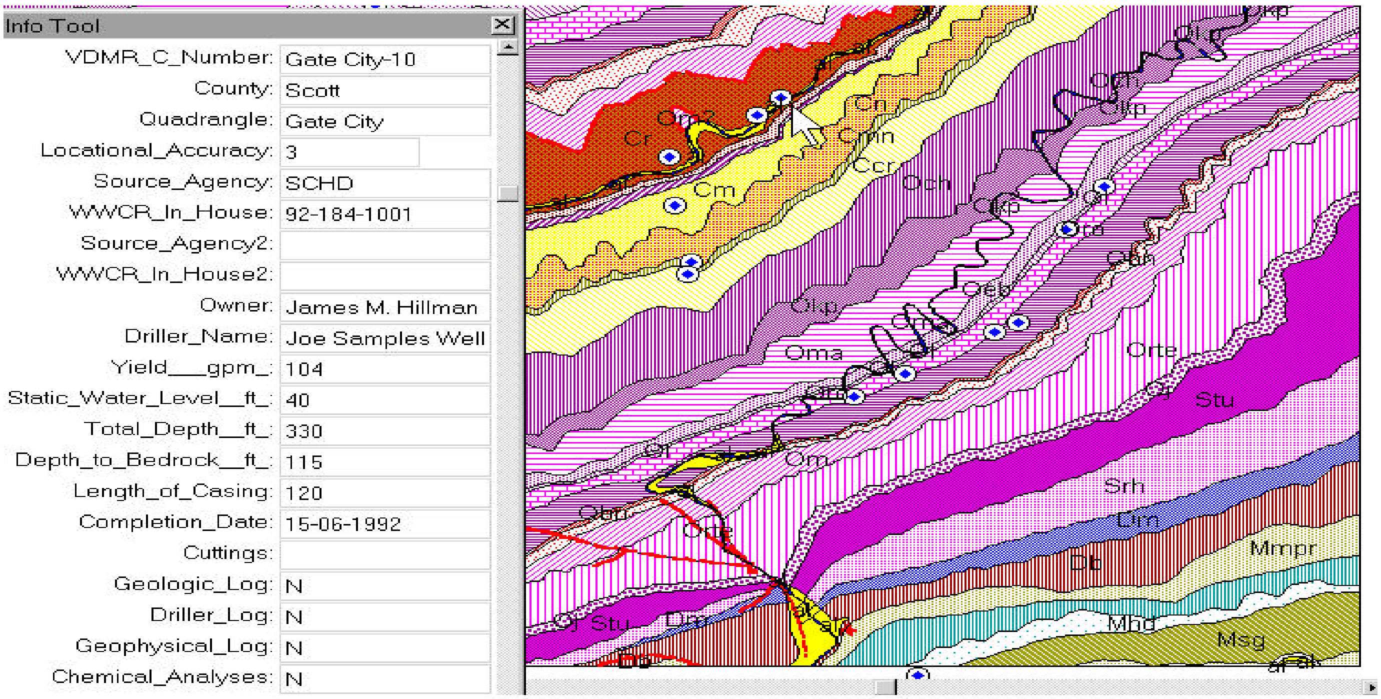

Figure 3. Geologic map of a portion of the Gate City 7.5-minute quadrangle, Scott County, with water-well and spring locations (circles). Info Tool displays data for selected well (see arrow in northwest part of map.

LAND USE IMPACTS ON WATER QUALITY IN SMALL KARST AGRICULTURAL WATERSHEDS

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Abstract

Identification of the impacts of agriculturally related activities on surface and groundwater quality in limestone and karst terranes is important for the management of this natural resource. Kentucky has highly vulnerable water resources in aquifers located in limestone that underlie approximately 50 percent of the state. Karst conditions occur in about 25 percent of the state, and much of the state's most productive agricultural soils are found in these same regions.

Eight years ago, there was very little information about agricultural effects on water resources in Kentucky. The extent and level of contamination of water resources by pesticides and nitrate-N had not been documented in areas of important agricultural production. The Kentucky Agricultural Chemical Use Impacts Assessment Program (SB-271 Project) studied the water quality in several representative and agriculturally significant areas. This program was conducted from October 1990 to September 1993. An analysis of the types of agricultural land uses (row crop and hay/pasture) and their areal percentages was conducted to determine the correlation to the quality of water discharging from eight small agricultural watersheds using the data base developed during the study (1). These eight watersheds were located in limestone geological settings. This report presents a comparison of these eight Kentucky watersheds to other water quality studies of karst/limestone watersheds that were found in the literature.

Introduction

Following the passage of the Federal Water Pollution Control Act Amendments of 1972, several studies were published that began to identify the significance of different land use impact on the watershed water quality. Several of these studies (2,3,4,5) found significant positive correlations between nitrogen concentrations in the discharge water and the area of a watershed in agriculture or row crop. Several papers established the influence of the dominant geology (sedimentary, igneous, metamorphic) on the nitrogen concentration in the water exported from basins (4,5,6). Limestone geology was identified as a significant sedimentary geology (5,6). Of all the geologies identified in the 1976 US National Eutrophication Survey of 930 watersheds, limestone hydrogeologic settings were found to have the highest inorganic nitrogen concentrations for agriculturally dominated basins (5). A 1974 reconnaissance study of seven Kentucky agricultural watersheds also supported the latter determination (6). Soil texture was also a significant influencing factor on the nitrogen concentration (4). These early studies did not present data concerning agricultural pesticides.

Since the mid-80s, studies have extended the understanding of the influence of land use on the inorganic nitrogen and pesticide concentrations in limestone hydrogeologic settings. Positive correlations between the percentage of agricultural land and nitrate-N concentrations in springs, draining basins in karst limestone terranes, were found in Pennsylvania (7), West Virginia (8), and Kentucky (9). In addition, concentrations of the triazine herbicide group have been reported in the literature. A positive association of the triazine concentration of basin drainage water with the intensity of agricultural land-use have been presented in the National Water Quality Assessment Program which started in 1991 (10) and in limestone hydrogeologic settings in Kentucky (9).

The literature was searched for additional water quality data sets in karst/limestone hydrogeologic settings to be included with the nitrate-N and triazines concentration data sets of eight Kentucky watersheds. The objective was to determine whether agricultural practices for crop production in these Kentucky watersheds impacted water quality in a different manner when compared to other watersheds in a karst/limestone setting.

Methodology

Kentucky Agricultural Chemical Use Impacts Assessment Program

The details of this study can be found in a series of reports published by the departments of Agronomy and Biosystems and Agricultural Engineering in the College of Agriculture (1,11), and the Kentucky Geological Survey (12, 13, 14). Eleven areas were selected for the assessment. Eight of these sites were located in limestone hydrogeologic settings and these data are being used for this report. The limestone watersheds are referred to by the county in which they are located: Bourbon, Fleming, Jessamine, Logan, Russell, Shelby, Todd, and Woodford. These eight sites represent the five out of the seven agriculturally important physiographic regions of Kentucky: Inner Bluegrass, Outer Bluegrass, Eastern Pennyroyal, Western Pennyroyal, and Western Coalfields. The study watersheds were selected to reflect major agricultural production systems in important soil and hydrogeologic settings of Kentucky. These sites are predominantly agriculture with some residential areas in the large watersheds. One or two individuals owned land at six of eight assessment watersheds, which allowed for ease in determining agricultural production and chemical use. Land use information for the other two watersheds was determined through aerial photography with confirmation by ground truthing and/or from the USDA Farm Services Administration. The sites can also be characterized as being large watershed studies or farm-sized watershed studies. The Logan and Jessamine county sites are large watershed studies (approximately 4,082 and 1,903 ha, respectively) that have many land owners. The other six are smaller farm-sized watersheds (32 to 972 ha). All the watersheds are dominated by well to moderately well drained silt loam soils. Watershed sampling points included springs and streams (Table 1) and were sampled at least monthly, if water flow was present. Additional water testing during the planting season was performed, but these were not included in the analyzed data sets.

On an annual basis, the predominant source of water that discharges from the assessment watersheds is groundwater. Stream discharge points represent an accumulation of water from groundwater sources (springs and seeps) throughout a watershed. Water quality at these watershed discharges is an integration of all the land-use impacts in the watershed. Tables 2 and 3 summarize the average annual land-use and water quality parameters over a three-year period for the Kentucky assessment sites. Row crops would include tobacco, corn, soybeans, and double cropped wheat. The predominant row crop production system in these watersheds was a two-year rotation of corn-wheat-soybeans with some wheat-soybeans double cropped. This rotation is nearly continuous in high row crop percentage watersheds. In low row crop percentage watersheds, forages and tobacco are introduced into a crop rotation. At least one pasture or confinement animal production system for beef, dairy, or swine is found in each watershed with manure nutrients applied to the land.

Published Water Quality Studies of Watersheds in Carbonate Terranes

A search of the literature found 14 water quality study areas which reported nitrate-N and/or triazine concentrations of water discharging from agricultural watersheds in carbonate terrains. These studies were in Arkansas (2 studies), Illinois, Indiana, Iowa, Kentucky, Pennsylvania (3 studies), Tennessee, Virginia, and West Virginia (2 studies). Not all these sites were included in this report. Some reports covered a few synoptic water quality samplings or quarterly water quality samplings and were not used to compare to the

Table 1. Area and water source of Kentucky karst watersheds and other karst studies.

Table 2. Nitrate-N in water from karst watersheds in Kentucky and other karst studies.

Table 3. Triazines in water from karst watersheds in Kentucky and other karst studies.

Kentucky assessment watersheds. Studies included in the comparison are those with monthly data that spanned at least one year with reported data in 10 or more months each year. Further, the reports needed to include the percentages of the watershed in row crop, pasture/hay, and/or agriculture. The dominant soils of these watersheds were silt loam. The chosen studies were Big Spring in Iowa (15), three springs at Mammoth Cave in Kentucky (16,17), two springs in Cumberland Valley (18), and four springs in Nittany Valley (19) in Pennsylvania, and four springs in the Greenbrier Hydrologic Unit in West Virginia (20,21). Two investigations did not include the land use: Monroe County Illinois (2 springs) (22) and Lost River in Indiana (23,24). For these basins, sampling points were able to be identified on soil and topographic maps. USGS Topographic quadrangles (7.5 minute) were used to estimate the areas of the watersheds, assuming the surface watershed matches the groundwater basin, and aerial photography from soil surveys were used to estimate land uses.

Results

Tables 2 and 3 present the available information for medians, arithmetic means for nitrate-N, and triazine concentrations, and also the geometric means for triazine concentration, sample size, and average percent of the watershed in row crop and pasture/hay for the Kentucky watersheds and the other watersheds noted above. In addition, the information available for the frequency distribution of the concentrations is presented. Standard deviations were not found or able to be calculated for all the published watersheds. The distribution of concentration of nitrate-N and triazines from the eight Kentucky SB-271 limestone geology watersheds were statistically assessed for departures from a normal distribution using the Moment Ratio Analysis (25). Nitrate-N observations were normally distributed. Triazine concentration distribution was found to be a log-normal distribution.

Nitrate-N. Figures 1 and 2 present the mean nitrate-N concentrations of the water from 21 watersheds in limestone geologies versus the percent of the watershed in row crop agriculture and percent agriculture (row crop + pasture/hay), respectively. The nitrate-N concentration of Big Spring in Iowa stands well above the rest of the watersheds and was not used in the following statistical analysis. A significant linear regression for nitrate-N versus row crop was found for the watersheds (α = .001). There was no significant difference (α = .025) between Kentucky 271 watersheds and the published watersheds when watersheds, with more than 80 percent of the land in forest, were removed from the analysis. The linear regression line (r^2 = 0.66) for these watersheds, as well as the lines representing +/- one standard error of the regression, are shown in Figure 1. The four forested watersheds lie below the lower standard error line as indicated in Figure 1. When the land use is designated as percent in agriculture, the 24 watersheds (excluding Big Spring IA) yield a significant linear trend (α = .001) with the nitrate-N concentration. Significant linear relationships between watersheds mean nitrate-N and percent of the watershed in agriculture were also found in West Virginia (8) and Pennsylvania (7). The eight Kentucky watersheds are clustered above 80 percent agriculture. A t-test was ran on the nitrate-N means of published watersheds above 79 percent in agriculture and the Kentucky SB-271 watersheds. The nitrate-N mean of the Kentucky 271 watersheds was significantly lower (α = .05).

Triazines. Figures 3 and 4 present the geometric mean triazine concentrations of the water from 13 watersheds in limestone geologies versus the percent of the watershed in row crop agriculture and percent agriculture, respectively. A significant linear regression for triazine geometric mean versus row crop percentage was found for these watersheds (α = .001). The intercept was zero since triazines would not be used on non-agricultural land. There was no significant difference (α = .05) between Kentucky 271 watersheds and the published watersheds. The linear regression line (r^2 = 0.61) for these watersheds, as well as the lines representing +/- one standard error of the regression, are shown in Figure 3. When the land use is designated as percent in agriculture, the 13 watersheds do not yield a significant linear trend (α = .05) with the triazine concentration. A t-test was ran on the triazine geometric means of published watersheds and the Kentucky 271 watersheds and no significant difference was found (α = .05).

Discussion

The mean nitrate-N and geometric mean triazine concentrations in water discharging from watersheds in limestone geologies in the Kentucky 271 Assessment Program are not significantly

Figure 1. Percent of watershed in row crop production versus mean nitrate-N concentration in discharge water.

Figure 2. Percent of watershed in agricultural production (row crop + hay/pasture) versus mean nitrate-N concentration in discharge water.

Figure 3. Percent of watershed in row crop production versus geometric mean triazine concentration in discharge water.

Figure 4. Percent of watershed in agricultural production (row crop + hay/pasture) versus geometric mean triazine concentration in discharge water.

different than other agricultural limestone watersheds when land use is identified as a percent of the watershed in row crop agriculture. This positive relationship occurred even when water quality data was taken in different years, different geographic locations, and possibly different weather conditions; primarily intensity, yearly total and timing of precipitation relative to crop production. The one difference was Big Spring IA where the nitrate-N concentration is 4 ppm higher than the regression line. This watershed was identified as not crediting legume and organic N fertilizers when determining the recommended commercial N fertilizer level (26). Nitrogen fertilizer usage in the Kentucky 271 Assessment watersheds were at recommended levels, e.g., ~170-200 kg/ha. for corn (11). When the watershed land use is identified as percent agriculture, the relationship does not exist and, for similar agriculture land percentages, Kentucky 271 Assessment watersheds were significantly lower. It is apparent that studies of agricultural chemical concentrations in water discharging from watersheds should identify row crop land uses within the study area. A stronger relationship between triazine concentrations and the percent of a watershed in corn production would also lead to a stronger relationship than was found with row crop percent. Triazines are used predominantly on corn production fields for weed control.

Variability of the nitrate-N concentration can be attributed to denitrification as a result of perched water, saturated soils at seeps and riparian zones, and within the stream. These factors are not easily determined or documented for watersheds. The appearance of iron-manganese concretions in the predominant silt loam soils of the Woodford County Kentucky watershed was found during an intensive soil survey (27) and in a reconnaissance of the Bourbon County Kentucky site at some of the monitored springs (28). Iron-manganese concretions form in perched water zones where there is alternating reducing and oxidizing environments. Perched water zones are found at both sites occurring above restrictive clayey soil horizons or above argillacious layers in the limestone bedrock or at the soil-rock interface (13). Seeps and low flowing springs are potential sites of denitrification in Bourbon County Kentucky(28). Denitrification in in-stream water (29) and the riparian zone (30) are significant factors that affect the mean nitrate-N concentrations of water discharging from a watershed and are not identified in the studies cited in this paper.

The variability of the concentration of triazines in the water discharging from a watershed is strongly affected by the timing of rainfall events after the herbicide application to corn fields, the soil moisture content and soil temperature after the time of herbicide application, and the amount active ingredient applied per hectare (31). These factors are also difficult to identify and were not identified in studies cited in this paper.

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THE CHARACTERISTICS OF OIL CONTAMINANT MIGRATION IN A FRACTURED-KARST AQUIFER AND REMEDIATION BY CAPTURE-ZONE TESTING IN DAWU WELL FIELD, CHINA

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Abstract

Dawu Well Field is one of the largest well fields in China, yielding 540 to 560 $\times 10^3$ m^3/day. The aquifer is comprised of Ordovician limestone and dolomite, and the fractured-karst water in those aquifers serves as the sole urban and industrial water supply in Zibo City. A petrochemical company was built on the recharge area of the aquifer in the middle 1980s. Leakage from pipe lines and oil tanks have resulted in serious petroleum contamination of the fractured-karst aquifer. Currently the plume is approaching the pumping wells in the Dawu Well Field. Hence, it is an important task to control and remedy the contamination. In this paper, the characteristics of oil contaminant migration and the distribution of the contaminant in the fractured-karst aquifer are discussed. Because the contaminant transport is predominantly an advection-dominated problem, some underground techniques are too expensive to be used as an engineering application. The hydraulic capture-zone is the most efficient method for mitigation and remediation. The results of the capture-zone test indicated that this technique represents an efficient methodology for controlling contamination in fractured-karst aquifers.

Introduction

Dawu Well Field is located east of Zibo City in the center of Shandong Province, China (Figure 1). Zibo is an industrial and mining city. Due to the lack of surface water, groundwater has become the sole source of urban and industrial water supplies. The major well field in this city is Dawu Well Field — one of the largest well fields in China — which pumps at an average rate of 540 to 560 $\times 10^3$ m^3/day. Recently, the western part of the aquifer has been threatened with contamination. Therefore, it is important to control and clean up the groundwater contamination.

Figure 1. The location of Zibo City.

Hydrogeologic Setting

Geologically, Dawa Well Field is located along the east limb of Zibo Syncline. The strata are comprised of limestone and dolomite of Middle Ordovician age, with thicknesses of about 670m . The strata can be divided into six members (i.e., O^{21}, O_2^2, O_2^3, O_2^4, O_2^5, and O_2^6, see Figure 2). In this area only O_2^4, O_2^5, and O_2^6 are exposed along hilly areas. O_2^4 and O_2^6 are thick-bedded limestone layers and O_2^5 is a dolomite and dolomitic limestone. These Ordivician carbonates represent a fractured-karst aquifer system. The recharge area in the south receives infiltration of rainfall and polluted water. Beneath the well field in the north, the aquifer is covered by Quaternary sandy clay and loam which act to confine the underlying carbonate aquifer (1). The strike of the strata is the ENE and the dip is gently to the north (Figures 2 and 3). Two faults band the region in the east and west. The eastern one is Zihe Fault Zone consisting of two parallel faults that form a graben. The graben represents a highly productive aquifer. The western fault is the NS trending Jinling Fault (Figure 2).

A Carboniferous and Permian shale, sandstone, and mudstone unit lies north of the well field and is relatively impermeable, acting as a groundwater barrier. Groundwater flows from south to north and is obstructed by the northern low-permeable barrier so that a large underground reservoir is formed in Dawu area. Data from pumping tests and mathematical model calibration indicate that transmissivities of the aquifer are several thousand square meters per day and the storativities are 10^{-4}-10^{-5}. The yield of a single well is between 3000 and 6000 m^3/day.

Petroleum Contamination of the Fractured-karst Aquifer System

The western part of the Dawu Well Field is being continuously contaminated with petroleum by-products each year. A petrochemical factory was built in 1984 on the recharge area which supplies the well field. The foundations of oil tanks and waste water pipes were placed directly on the aquifer. Because some waste waters are acid and high in temperature, the pipes are easily corroded. Leakage from pipe lines and oil tanks have resulted in petroleum contamination of the fractured-karst aquifer system. The contamination source areas are shown in Figure 4. The center of the contaminated area is Hougao village. The concentration of total petroleum and benzene as a function of time measured in wells W1 and H1 in Hougao Village is shown in Figure 5.

The maximum concentration of the total oil in well W1 was found to be 78.232 mg/l (July 1994) which exceeds the national standard by 1563.64 times. The maximum concentration measured in well H1 was 39.10 mg/l (February 1995) which exceeds the national standard by 781 times. Local groundwater in Hougao Village can no longer be used for domestic purposes. Consequently, the village was moved away several years ago. The distribution of petroleum contaminants in the groundwater is shown in Figures 6 and 7. Comparing Figure 6 with Figure 7, it is clear that the plume is approaching the pumping wells in the Dawu Well Field. Because of the importance of the Dawu Well Field, it is critical that the petroleum contamination and migration be stopped and the karst aquifer restored.

The Distribution of Oil Contaminants in the Fractured-karst Aquifer

Petroleum is a light nonaqueous phase liquid (LNAPL). A hydrocarbon spill migrating in the subsurface can be divided into three parts (2). In the vadose zone there exists residual LNAPL above the water table. Floating on the groundwater is a LNAPL pool which can migrate along the water table under its own hydraulic head, but its velocity is very slow. In addition, some of the LNAPL components can be dissolved in groundwater and transported by dispersion and advection with groundwater away from the main LNAPL pool. Gasoline will release significant amounts of benzene, toluene, ethylbenzene, and xylene as soluble fractions. All these products are responsible for the groundwater contamination in the well field. This conceptual migration model is typical for a porous aquifer system. The migration is similar in fractured-karst aquifer systems.

Because limestone in itself can be nearly impermeable (1), the transport of contaminants pass through solution fissures, cracks, fractures, bedding planes, and solution (karst) openings. Fractured-karst aquifers have much greater heterogeneity and anisotropy than typical porous-media aquifers. In terms of the results of tracer tests conducted in June, 1997, the advective transport rate in the ENE direction (from C6 to T54) was 5455 m/day, and the velocity to the north (from C6 to W1) was 108.5 m/day, and to the NW (from C6 to C7) was 99.8 m/day. The tracer test indicates that contaminant migration occurs more rapidly in the major direction of fractured-karst flow than in the other directions. This migration pattern can be readily observed in Figures 6 and 7. Because the groundwater velocity is very large, the transport in the fractured-karst aquifer is predominantly an advective problem. The observed transverse dispersion of the plume is small. The velocity of transport in the karst openings is much more rapid than in the pores of sand and gravel. This karstic feature is the main reason why the aquifer

Figure 2. The geological map of Dawu Well Field
1. Quaternary; 2. The fourth member of Middle Ordovician; 3. The fifth member of Middle Ordovician; 4. The occurrence of strata; 5. Fault; 6. Factory; 7. Middle Carboniferous

Figure 3. The hydrogeological cross section of Dawu Well Field
1. limestone; 2. dolomite and dolomitic limestone; 3. sandy clay and loam; 4. water table; 5.

Figure 4. Groundwater contamination and the capture-zone in the vicinity of the petrochemical company
1. Double wells for injecting tracer; 2. Pumping well; 3. Well in the capture-zone; 4. Village; 5. Village which has been removed; 6. Major direction for contaminants transport; 7. secondary direction for contaminant transport; 8. Pollution source area.

Figure 5. Concentrations of total petroleum and benzene as a function of time in wells W1 and H1.

Figure 6. The isoconcentration map of petroleum concentration in the fractured-karst aquifer in October, 1994.

Figure 7. The isoconcentration map of petroleum concentrations in the fractured-karst aquifer in October, 1995.

is quickly becoming contaminated. The storage capacity of this type of aquifer is small; therefore, it is easier to be cleaned up by pumping.

Because fractured-karst aquifers are highly heterogeneous and have larger flow velocities through solution openings, the largest concentration of oil in wells or boreholes usually does not appear at the water table, but in the solution fracture or karst opening which is connected with the contamination source. Figure 8 shows the relationship between the vertical distribution of total oil concentration and the depth of solution openings and fractures. High concentrations of oil were found where the wells intersected solution openings (Figure 8). In accordance with the characteristics of dis-ribution and migration of oil contaminant in fractured-karst aquifers, the hydraulic capture method has become the most efficient method for mitigation and remediation.

The Test of Operating Capture-zone for the Remediation

The capture-zone was comprised of six pumping wells: W2, H2, W3, W4, W5, and W6 (Figure 4). The distance between pumping wells varied from 300-400 m and their depth was 200 m. The location of the pumping wells was not predetermined according to optimal geologic or hydrologic conditions. Therefore, the effect of pumping on measured drawdowns and the effectiveness in controlling contamination varied from well to well.

The duration of the capture-zone pump test was from November 4-30, 1995, with a total discharge of 26,452 m^3/day. The total discharge and resulting water levels for each well are listed in Table 1.

Table 1. The situation of running capture-zone

Well	H2	W2	W3	W4	W5	W6
discharge (m^3/day)	4800	4680	0	6912	4320	5740
Water level before pumping (m)	36.90	40.56	39.16	41.44	42.68	42.37

water level after pumping 25 days (m)	36.89	38.50	24.16	20.22	30.88	39.54

The contour map of water level by the end of the 26-day test is shown in Figure 9. The effect of performing a capture-zone test for the remediation is shown in Table 2. The capture-zone test proved to be an efficient method for remediation of the contaminated fractured-karst aquifer, particularly for those wells that initially had the highest levels of contamination.

Conclusions

Contaminants migrate more rapidly in fractured-karst aquifers than in typical porous-media aquifers. The typical groundwater flow velocities in fractured-karst formations are more than 100 meters per day. However, the longitudinal and transverse dispersivities are much smaller than those of porous-media aquifers, suggesting that transport is an advection-dominated process.

The vertical distribution of oil concentrations in wells and boreholes in the fractured-karst aquifer is different from those expected in porous-media aquifers. The highest concentration does not appear at the water surface, but in the solution openings which are connected with the major sources of pollution.

The capture-zone test is an efficient method for controlling loose concentrations of contamination in fractured-karst aquifers. The geologic conditions of the aquifer should be taken into consideration for proper placement of the capture-zone wells in fractured-karst aquifers.

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Table 2. Comparison between total oil concentrations at the start and end of the capture-zone test.

Number of observation well	Content of total oil before the capture-zone test (mg/l)	Content of total oil after the capture-zone test (mg/l)	Percent decrease in contamination
Hu1	0.26	0.17	34
Hu3	0.66	0.39	41
Hu15	0.29	0.14	52
J18	0.24	0.00	100
J17	0.22	0.13	41
H1	22.6	2.55	89
W1u	18.0	0.83	95
W1d	5.90	0.76	87
Wu18	0.19	0.15	21
Wu14	0.13	0.12	8
J10	0.76	0.26	66
J34	0.23	0.13	43
S14	0.19	0.28	-47
J31	0.18	0.06	67

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Figure 8. The depths of karst development and the vertical distribution of total oil concentrations in wells W1 and W3 (September,1996).
1. The depth of karst opening; 2. The curve of oil concentration versus depth.

Figure 9. Contour map of water levels at the end of the capture-zone test (November 30,

ENVIRONMENTAL MANAGEMENT OF A KARST RESOURCE AREA IN THE GEORGE WASHINGTON AND JEFFERSON NATIONAL FORESTS

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Introduction

In 1996, an exceptional collection of karst land forms were found in the foot hills of the Blue Ridge Mountains in Wythe County, Virginia. The karst features include sinkholes, caves, sinking streams, a blind canyon, springs, and a karst window to a subterranean stream. This karst land occupies approximately one-half square mile of land on the Mt. Rogers National Recreation Area (MRNRA) which is part of the George Washington and Jefferson National Forests (Forest).

The subject karst terrain was identified duringan environmental analysis conducted for a proposed timber sale on the forest. The U.S. Forest Service (USFS) worked with the Virginia Department of Conservation and Recreation (VDCR), and the National Speleological Society (NSS) to conduct a variety of inventories and investigations of the karst land. This paper discusses the results of some field studies, and recommendations to incorporate karst resources into the management of the George Washington and Jefferson National Forests.

Background

Stretching northeastward throughout approximately 300 miles of western Virginia and portions of West Virginia, the George Washington and Jefferson National Forests spans three geomorphic provinces: the Blue Ridge, the Ridge and Valley, and the Appalachian Plateau. The forests are divided into 11 ranger districts which form discontinuous land management units across the region. Because the forest is located primarily in the mountains, rather than the valleys, forest lands are commonly underlain by more resistant rocks, such as sandstone, granite, quartzite, gneiss, and rhyolite. In contrast, the private lands bordering the forest are located in valleys and foot hills, where the bedrock is limestone, dolomite, or shale.

Carbonate rock (limestone and dolomite) is not common on the forest, but does occur generally as linear bands along the lower slopes of the mountains. The carbonate bedrock is poorly exposed in most areas, and exhibits few karst features on the USGS 7.5 minute topographic quadrangles. As the USFS has inventoried these areas more closely in recent years, the importance of carbonate terrains to the habitat requirements of rare, threatened, and endangered species has become recognized. The USFS is now conducting a geologic inventory to determine the acreage and distribution of carbonate bedrock on the forest. These maps will facilitate the assessment and management of karst resources in the future.

About 1.5 million acres, or about 10 percent of the timberland in Virginia, is managed by the National Forests. In contrast with the National Parks, which specialize in providing public recreation facilities, the National Forests are managed to provide not only recreation, but also a wide range of society's needs, including raw materials such as wood for home construction. Timber harvests may require road construction, log skidding, yarding, and other ground disturbing activities. Prior to deciding whether to offer timber for sale in a particular part of the forest, the USFS conducts an environmental analysis to assess potential environmental effects of the timber sale, as well as alternatives to, or modifications of, the proposed project. Based on the results of the environmental analysis for each proposed timber sale, the USFS may decide to 1) offer the timber sale, as originally proposed, 2) offer a modified timber sale, or 3) not offer any timber sale in this area.

The karst land forms on the MRNRA came to the attention of USFS staff during the environmental analysis for a proposed timber sale. The staff asked the forest geologist to investigate whether the unusual land forms were old mine workings or natural features. The forest geologist, Tom Collins, and Emily Smith, a geologist working for the forest during the summer of 1996, found the area contained an unusual collection of karst features: sinkholes, caves, sinking streams, a blind valley in the form of a vertical-walled canyon (Sinking Spring canyon), springs (Resurgent Spring, and others), and a karst window (Deep Spring window). Gary Kappesser, the forest hydrologist, and Terri Brown, of the VDCR Virginia Karst Project, were contacted and joined the core group in a special investigation of the site.

Emily Smith initiated a study which extended beyond the initial field investigation. This study had financial and staff support from the Forest Service, VDCR, and the NSS. Division of Natural Heritage staff and local members of the Virginia Tech Cave Club (a student grotto of the NSS) assisted in the inventory of karst resources.

Site Geology

The subject site is located near the eastern boundary of the Valley and Ridge Physiographic Province and the western toe of the Blue Ridge Mountains. In this region, the rocks have been tightly folded and broken by thrust faulting during the Paleozoic deformation and orogeny (Butts 1933; Stose and Stose 1957). The development of caves, karst, and internal drainage patterns in the carbonate valleys and foothills is strongly influenced by the tortuous geologic structure of the Appalachian region (Jennings 1985). Elevations in the study area range from greater than 3300 feet above mean sea level (MSL) on Ewing Mountain to approximately 2100 ft MSL on the flood plain of Cripple Creek (Figure 1). Cripple Creek receives drainage and base flow from the study site and is a major tributary to the New River.

Geologically, this site lies along the northern edge of the Gossan Lead district, where fractured belts of the Shady formation (three to six miles wide) are exposed in Wythe and Pulaski Counties for a length of approximately 27 miles (Stose and Stose, 1957; Currier, 1935). According to local history, the area became a major lead mining center soon after 1756, when Colonel John Chiswell discovered lead and zinc ore in the walls of a cave (SCS 1992). In Geology and Mineral Resources of the Gossan Lead District, Virginia (VDMR 1957), authors Anna J. and George W. Stose describe the Gossan Lead district as a historically important producer of "...copper from 1850 to 1858, of iron ore after 1880, and of sulphides from about 1850 to the present time." The mineral wealth of this district has been attributed both to the residual accumulation of manganese and iron-rich sediments at the base of the Shady formation (via deposition by circulating groundwater), and to the tectonic injection of ore-bearing solutions into Precambrian and Early Cambrian rocks. The geology, mineral resources, and mining history of the area were described in detail by Boyd in 1881, and others, including Watson (1905, 1907), Holden (1907), Currier (1935), and Stose and Stose, (1957).

The Early Cambrian Chilhowie Group rocks consist of the Unicoi conglomerates and arkoses, the Hampton shale, and the Erwin quartzites. Although the Shady dolomite originally rested conformably on top of the Erwin quartzite, it now underlies resistant Chilhowie Group rocks that were thrust northwestward along faults. In the study area, the Patterson member of the Shady dolomite is over-ridden by the Gleaves Knob overthrust fault, and is exposed in a window in Collins Cove. The carbonate rocks of the Gleaves Knob fault block are believed to have been deposited much further to the southeast as a shaley limestone facies of the Shady dolomite, perhaps on the outer slopes of the early continental margin (Stose and Stose 1957). The current position of these strata is illustrated in Figure 2.

The distinctive carbonate rocks exposed in the Gleaves Knob fault block include the Vintage dolomite at the bottom, the Kinzers formation in the middle, and the Ledger dolomite at the top. The Stoses correlated the Vintage and Ledger dolomites to similar units in southeastern Pennsylvania. Only the Vintage dolomite member is exposed at the study site, and is estimated to be approximately 700 feet thick. The strata chiefly consists of dark, blue-grey, dense, nodular limestone and dolomite with siliceous bands and thin, wavy, argillaceous partings (Stose and Stose

Figure 1. Study Area Cripple Creek, VA Quadrangle.

Figure 2. Schematic cross sections along traverses indicated on geologic map modified from Stose's *Geologic Map and Structure. Sections of the Gossan Lead District and Adjacent Areas in Virginia*, 1957.

Figure 2. (continued).

1957). Bedrock at the site also displays very massive structure in places, such as in the Sinking Spring canyon, where enormous dolomite pinnacles form sheer cliffs at the end of a blind valley.

At the eastern edge of Sinking Spring canyon a small surface stream, recharged by springs, flows from the Erwin quartzite and forms a waterfall as it drops over a shale ledge onto the Shady dolomite. Small pockets of water are visible along the stream bed for approximately 100 feet, before the stream completely disappears underground. The remaining dry stream bed consists of cobble and gravel sized bed material, and runs through the heart of the canyon. Following the stream bed past the towering pinnacles in this blind valley reveals two adjacent, separate caves. The stream bed leads down into a large impressive cave entrance, but the actual cave opening is only 3 ft by 2 1/2 ft and contains no more than 20 feet of passage. Sinking Spring cave, with 200 feet of passage, lies west of the smaller cave and stream bed. The sloughing and cutting along the banks of this stream bed and the large woody debris shoved into the cave opening are evidence that this stream bed has carried extremely heavy storm flows and\or snow melt.

In addition to the Sinking Spring canyon, the site contains other significant karst features. Fourteen sinkholes, ranging up to 100 feet in depth, have been mapped in the area. The entrance to a third cave (Deep Spring cave) is located in a sinkhole, with a perimeter of approximately 300 feet, that is also a karst window. A stream flows out of the cave, is exposed on the surface for a distance of approximately 60 feet, and disappears into a cavernous swallet. The Resurgent Spring discharges into Cove Branch from cavernous dolostone, approximately northwest of the Deep Spring window. Within the Resurgent Spring cave, stalactites and stalagmites white in purity are seen throughout the stream passage as well as helictites, soda straws, flowstone, draperies with serrated edges, and scallops in the cave walls. Scallops were observed in the cave walls of the entrance to Sinking Spring cave as well. The presence of these solution pockets on the walls is evidence that high velocity streams once gouged their way through these caves (Moore 1978).

Rock outcrops in the study area display large, widely-spaced joints oriented generally N 50 to 60 E. Joints are observed in the bedrock along streams, cave entrances, as well as inside the caves. The joints run perpendicular to cave passage in two of the caves containing streams. Intersecting joint sets are evident along the trunk channels which bear these streams. Due to the highly weathered and deformed nature of the outcrops, strike and bedding plane dips are difficult to discern. The general strike of the rock in this area is approximately N 45 W, although significant variations have been observed along the fault traces. In the Deep Spring window bedrock dips from 43 to 49 NE, along the southern limb of the shallow Eagle Syncline (Stose and Stose 1957). Bedrock lineaments and fracture traces detected from aerial photographs are shown in Figure 3. Soil depths in the area range from nonexistent (where bedrock is exposed), to more than 5 feet deep in sinkholes, fissures, and drainways (SCS 1992). In most locations, the Shady dolomite is covered by a thick clay mantle, alluvium, and/or colluvial apron from nearby quartzite slopes. The soil and weathering products of both the Erwin quartzite and basal Shady dolomite are strongly colored by iron oxides.

Methods and Procedures

Karst features in the study area were mapped using a hand-held Global Position System (GPS) unit and standard orienteering compass. Sinkhole perimeters and depths were measured through use of a hip chain. Fourteen sinkholes have been mapped, with perimeter sizes ranging from 20 ft to 600+ ft. Most of the sinkholes have steep slopes, with conical depressions. The deepest sinkholes are approximately 100 ft deep. Springs, cave streams, and sinking streams were also mapped. The slopes of accessible stream segments, measured with a hand-held clinometer, ranged from 11 percent to 24 percent.

A cave survey team lead by a team of volunteer cavers mapped the length, width, and vertical dimensions of two of the caves in this area. Maps such as this are helpful for understanding the density and orientation of subsurface passages and features, and how surface activities may create an impact to underground resources. The authors consider karst and cave mapping an essential tool for land use and resource management.

Water quality field parameters were measured on August 9, 1996 and July 10, 1997. Dissolved

Figure 3. Fracture trace analysis of study area.

oxygen content, pH, temperature, conductivity, and salinity were recorded at an upstream location in Cove Branch, in the Resurgent Spring, and in the Deep Spring window (Table 1). Relative acidity was measured with a hand-held pH meter. Salinity, electrical conductivity, and temperature were measured with a YSI S-C-T meter. Dissolved oxygen content was measured during the first sampling event, but was not available for the second event due to an equipment malfunction.

Table 1. Water Quality Parameters

The average chemistry of water in the Deep Spring window and the Resurgent Spring was similar, with temperatures ranging from 11.3 to 12C, specific conductivities ranging from 150 to 160 mS/cm, and pH of 8.1. Dissolved oxygen concentrations in the groundwater ranged from 9.6 to 11.5 ppm. The surface water in Cove Branch generally exhibited higher temperatures, lower conductivity, and higher pH than the nearby groundwater sources.

The approximate rates of discharge from the Sinking Spring's losing stream (less than 20 GPM), the Deep Spring window (approximately 40 GPM), and the Resurgent Spring (approximately 50 GPM) are estimated. The flow rates in Cove Branch were calculated based on estimated average velocity readings, taken along cross-sections of the stream, with an in-stream flowmeter (USGS 1967). Upstream from the confluence with the Resurgent Spring, Cove Branch flowed at approximately 0.5 CFS (224 GPM). The Resurgent Spring, plus other diffuse seeps and springs visible along the east bank of the stream, added approximately 0.45 CFS (202 GPM) to the volume of water in Cove Branch. Cove Branch then lost flow to the subsurface prior to its confluence with Cripple Creek. Stream flow measurements taken approximately 3 feet downstream from the Resurgent Spring, and 630 feet upstream from Cripple Creek indicated an estimated flow of 0.3 CFS (135 GPM) in Cove Branch.

Dye Tracer Tests

Qualitative dye tracer tests were conducted in order to determine the presence of groundwater connections between the sinking stream in Sinking Spring canyon, the discharging stream at Deep Spring window, the Resurgent Spring, and Cove Branch. Absorbent activated charcoal packets were strategically placed in these water sources to detect background levels of natural or artificial fluorescence. Based on the lack of background concentrations for rhodamine WT, fluorescein, and similar substances, these two dyes were selected for the tracer test. The packets were secured to rocks with wire and placed in the following locations: Sinking Spring canyon (above fluorescein injection point), downstream Cove Branch, in the Resurgent

Spring discharge, upstream in Cove Branch, in the Deep Spring window, and inside Deep Spring cave (above rhodamine WT dye injection point) (see Figure 4). Approximately 1/4 lb of liquid rhodamine WT dye was injected in the stream discharging from Deep Spring cave. Rhodamine B tablets were previously used, but due to inadequate dissolution of the dye tablets it could not be detected visually. The trickling stream which slowly infiltrates into the dry stream bed of Sinking Spring canyon was chosen as the second dye injection site. Because of its successful underground travel, fluorescein was chosen for this location. About 1/8 lb of powdered fluorescein dye was injected, making sure all powder dissolved completely into the slow moving stream. After six hours each charcoal packet was collected and placed in its own labeled freezer bag, chilled, and replaced with a new packet. Each packet was handled only with the use of dedicated, sterile disposable latex gloves. The same procedure was repeated after 24

Figure 4. Schematic site map (not to scale).

hours. After six hours vividly red water was visible in the Resurgent Spring and downstream Cove Branch towards its confluence with Cripple Creek. The rhodamine dye had traveled through the cave system, and discharged into Cove Branch within 6 hours after dye injection. However, the fluorescein was not visible in Cove Branch, the Resurgent Spring, or the Deep Spring window. The fluorescein had much farther to travel and much more soil and rock media to travel through; therefore, usual detection of the green dye was not anticipated. Packets from the locations of the Resurgent Spring, Downstream Cove Branch, and inside Deep Spring cave (above Rhodamine injection point), were sent to a laboratory for analysis of fluorescein. Fluorescein dye was not detected at any of the locations.

Biological Inventory

Several cave explorations were conducted in order to site any animal species, significant cave features, and make observations of cave lengths and the general trend of cave passages. Cave crickets, salamanders, crayfish, isopods, bats, silk worms and red-headed cave flies were observed throughout these explorations. During an April 1997 trip into Deep Spring cave, over 15 bats were sited within only 50 feet of cave passage. Three of the caves in this study area have at least 200 feet of passage, and bats have been sited in all of them. In August, 1996, a blind white millipede was found in the two cave entrances in Sinking Spring canyon. With a Department of Game and Inland Fisheries collection permit, specimens were obtained and sent to the Virginia Museum of Natural History in Martinsville, Virginia for identification. The specimens found were at the immature stage of growth, the adults which were found a month later were characterized as having an olive-grey appearance and pink spots on the dorsal side (personal communication with Dr. Richard Hoffman). The isopod was confirmed to be a nondescribed species, for which taxonomic analysis is pending.

The soil in this area is very rich in dolomite and limestone, and certain plant species thrive on this type of substrate. Phytobiological investigations of any rare or endangered plant species before land use management is necessary in order to ensure there survival. In their ongoing efforts to inventory plant species in the Valley and Ridge Province, botanists from VDCR Division of Natural Heritage surveyed the area. Several plant species vigorously growing due to the fertility of the limestone/dolomite rich soil were identified, including one plant species of concern according to the Federal Endangered Species Act, Carolina saxifrage (L. *saxifraga caroliniana).*

Management Considerations and Recommendations

According to the Federal Cave Resources Protection Act of 1988, the definition of a cave resource "...includes any material or substance occurring naturally in caves on federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems." Cave formations such as stalactites, stalagmites, helictites, flowstone, and draperies observed in the study area caves are classified as speleothems, and dissolutional/ erosional features such as scallops are classified as speleogens under Section 3 Definitions of the Act. From these observations alone, it is apparent that these caves are candidates for the significant cave list and deserve federal and state statutory protection.

Karst terrains exhibit unique natural resource values associated with significant hydrological, biological, archaeological, paleontological, and geological characteristics of a given area. As a public resource, caves and karst lands represent an important link to the local economy in terms of drinking water supplies, ecological diversity, cultural history, recreational opportunities, tourism, and aesthetics. Balancing these various demands on the karst resource with the concept of ecosystem protection is a fundamental goal within the George Washington-Jefferson National Forests.

A focus of the planned revisions to the GW-JNF Land and Resource Management Plan is to improve biodiversity and productivity through an ecological approach to forest management. For the first time in this plan, karst terrains will be included as ecological units, for which special management provisions will be developed. Guidelines and policies are being developed for land use activities that generate erosion and sedimentation, water quality impacts, and habitat changes in the karst lands scattered throughout the forest.

Because of their location, geology, climate, and protected status, National Forest lands serve as the primary catchment zone, or Source Water Areas (U.S. EPA 1997) for major aquifers and rivers along the fringe of the forest. It is estimated that at least 75 percent of the residents in rural karst areas along the forest boundary depend on wells, springs, or streams recharged by karst groundwater. Some municipal water supplies also have Source Water Areas within the forest. Noncarbonate areas that are directly connected to adjacent or underlying karst formations require special management solutions to prevent adverse impacts to water quality and rare habitats. In such cases, it will become necessary to delineate the groundwater basins and establish protection zones around sensitive karst areas that are directly connected to groundwater and surface streams.

Timber harvests are the most obvious land use activity within the forest that could impact karst drainage systems. If road-building, skidding, and logging are conducted without consideration of the receiving karst aquifer, cave entrances, sinking streams, and open-bottomed sinkholes can become clogged with sediment, silts, slash, and debris. The result could be the contamination of down gradient water supplies, off-site flooding caused by plugged sinkholes and re-routed drainage, and subsidence and instability problems. The application of herbicides and pesticides, petroleum leaks from heavy equipment, and improper waste disposal associated with forestry or construction activities in the forest could also contribute excessive sediment and pollutants to off-site karst waters.

Recommendations for future management decisions concerning the site and other karst areas on the forest (Collins 1996) include:

- Consider site designation as a Geologic Special Interest Area (GSIA)
- Delineate the boundary of the GSIA to maximize resource protection
- Consider educational and interpretive opportunities offered by the site
- Develop specific Best Management Practices for silvicultural activities in karst
- Recognize the need to conduct comprehensive, site-specific inventories of karst areas prior to planning timber sales, and other management actions
- Form an interdisciplinary team to design a work plan for inventorying karst areas
- Provide support to other partners in the inventory process

- Delineate the karst drainage basin and modify any management activities planned within influence of the basin, as needed.

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KARST REGULATIONS IN NEW JERSEY

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ABSTRACT

There is a large body of regulations that affect planning, design and construction in the karst areas of New Jersey currently under pressure from development, but few that specifically address the environmental and safety concerns related to solution-prone carbonates. The non-textbook nature of New Jersey karst and the existence of numerous void in the soils above shallow, pinnacled rock make subsurface investigation and remediation difficult, complex, and costly. Municipal karst regulations are often lacking, sometimes confusing, and may be difficult to respond to by the uninitiated. State regulations regarding karst are scattered through a number of programs. Additional state regulations and guidelines are presently being formulated. Although the number of municipal regulations relating to karst are expanding, it appears that many communities will be slow to adopt them as a result of a lack of familiarity with the subject, lack of in-house expertise, and a reluctance to impose any new regulation that is endemic to the current political climate in New Jersey.

INTRODUCTION

There is a fairly large area of northwestern New Jersey underlain by solutionally modified carbonate rocks: Precambrian marbles and Cambrian through Devonian limestones and dolostones. The limestones and dolostones are generally located in the valleys of the Highlands and Valley and Ridge physiographic provinces (Figure 1). Much of these valleys were farm land until relatively recently when increasing pressures of development have resulted in a residential movement westward from the general New York City region. Formerly, the region's karst concerns were recognized primarily by the state and the farmers who had lost tractors, livestock, and tillable land to sinkholes. More recently, federal and municipal agencies have begun to enter the karst-regulation arena.

New Jersey operates in a combination of both a layered and concordant system of rules and regulations. In many instances, state statutes have superceded federal regulations with regard to environmental protection. The New Jersey Department of Transportation (NJDOT) builds state and federal highways. State planning and land-use laws have delegated a great deal of authority to local municipalities. County jurisdiction over development is limited to reviewing the impact of projects on county roads, bridges, some stormwater management facilities, and some regional transportation bond issues. Amazingly, considering this amalgam of jurisdictions and variability of regulations, the process has worked remarkably well for conventional structures and facilities constructed in non-karst areas. A recent attempt to "streamline" some of the engineering-design aspects of statewide residential development did allow for an exemption process for areas underlain by solutionally modified carbonate rocks.

KARST CONCERNS

The problems inherent at any site overlying solutionally modified carbonates include technical

Figure 1. Carbonate rocks of New Jersey.

(environmental and engineering) aspects of appropriate development, as well as the economics of design and construction. In New Jersey, one adds the sociological aspects of attempting to integrate new governmental regulations into an already overcrowded legal battleground. To understand the need for appropriate regulation in relation to karst sites, a brief introduction to the relationship between karst in New Jersey and currently regulated concerns may be useful.

First, New Jersey karst is formed by solution-prone, tilted limestones, marbles, and dolostones. Generally, New Jersey sinkholes are formed by the failure of voids in soil above the solutionally modified rock (Figure 2), not collapse of cave roofs that may be more common in flatter-lying rocks.

With Figure 2 in mind, it is quite easy to understand the potential for problems if a project increases the volume and rate of stormwater flows. New Jersey stormwater regulations require communities to control both the rate and volume of runoff leaving a development site. The typical stormwater management technique involves development of a collection system directing runoff into some type of basin. Basins can retain water, act as a groundwater-recharge system, detain the stormwater for 24 to 36 hours, release it at a controlled rate, and act as a contaminant filter. Obviously, a sinkhole in the bottom of the basin does little to control release of contaminants into the groundwater.

For obvious reasons, the lowest area(s) of a site are selected for impounding water. Often these areas are excavated, and in most cases embankments are constructed. Thus, from a geologic standpoint, the area selected is likely to already be a zone of weakness. Any excavation will decrease (or eliminate) the thickness of the supporting arch over a void in the soil (Figure 2). The construction of berms or the impoundment of water increases the load on the underlying soil arch, hastening collapse. Hence, the conventional treatment of stormwater in New Jersey is a "do-it-yourself sinkhole formation kit." Design and construction of detention basins fall under both state and municipal regulation.

Of no less importance is the need to provide for the safety of constructed facilities including utility lines, structures, bridges, and roadways. There are numerous reports of disappearing stormwater pipes in karst areas. Federal and state highways, as well as local streets, have suffered collapses. A home in the western part of the state tilted into a large sinkhole and reports of utility-line breaks and septic-system collapse are numerous.

Until recently, little attention was paid to the difficulties of safely constructing atop karst. To date, many municipalities, most developers and the state Department of Transportation have not understood the problems that can result from a subsurface that looks like Figure 2, although currently the New Jersey Department of Transportation is becoming more aware of the problem. The first ordinance to regulate construction in carbonate terrane that considered both groundwater protection and structural safety, passed in Clinton Township in 1987 (2). Subsequently, the federal and county government-sponsored Resource Conservation and Development (RC&D) Council created (3) and publicized (5) a model limestone ordinance. Ordinances of this type have been adopted by several New Jersey municipalities. In addition, a number of unrelated ordinances, of varying quality and content that have been developed by attorneys, planners, environmental commissions, and geologic consultants, have been adopted by a number of townships. Hence, a variety of municipal ordinances exist, some of which are quite consistent with each other and others that are not.

From an economic standpoint, there is also a wide variety of attitudes and levels of awareness. Without the experience of working in karst, most individuals do not recognize the extensive costs that can result. For example, one of the authors has worked on a project in which subsurface remediation costs have ranged up to $20,000 per lot for a conventional home, and over $50,000 for a detention basin. Increased costs for unexpected rock blasting for the widening of Route 31 through Clinton, New Jersey, are believed to be greater than a quarter of a million dollars, whereas sinkhole investigation and remediation of a 5-mile stretch of Route 78 near Alpha, New Jersey, is estimated to be in the million-dollar range with work still going on.

The RC&D-type municipal ordinance essentially requires a step-by-step process which allows a rational organization to estimate site costs through the planning, design, and construction

Figure 2. Typical New Jersey karst cross section.

phases. A prudent purchaser can even assess additional site costs against the price of a property prior to final purchase. However, most federal, state, county, and many municipal ordinances function under the *caveat emptor* philosophy.

Thus, in many ways a number of karst concerns are addressed in regulations of some type. These regulatory programs focus on the control and management of stormwater runoff, soil-erosion-control programs on construction projects, state and local land-development regulatory programs, groundwater contamination, and the construction-code-enforcement process. However, to effectively encourage state and local governments to modify existing statutes, codes and regulations, so as to recognize the complexity of karst conditions, is an extremely difficult process at best. Working against this process is the growing national trend to try to reduce the amount of "government" regulation. New Jersey has generally been in the forefront of the deregulation movement.

RULES AND REGULATIONS

The state has regulations governing the siting of a proposed low-level-waste facility, as well as the generation of low-level waste itself. Federal regulations, as currently written, require states to develop siting criteria, which New Jersey has completed. Karst is an evaluation criterion as follows:

> "The disposal site selection process shall avoid areas where surface and near-surface geologic processes such as erosion, mass wasting/ weathering, slumping, landsliding, or the development of karst occur with such frequency and extent as to significantly affect the ability of the Disposal Site to meet the Performance Objectives ... or preclude the defensible modeling of prediction of long-term impacts." (1).

However, the presence of karst does not automatically exclude a site from construction (Figure 3), but such sites would likely be excluded upon the basis of the inability to perform "defensible" groundwater modeling.

Currently, the siting of landfills above solutionally modified carbonates is prohibited by law. However, there are no regulations that suggest any difference in investigation or treatment of land-fill cleanup programs if the site lies above a karstic subsurface.

There are specific requirements in well-drilling regulations in relation to "limestone or other creviced rock formations." Specifically, the minimum depth of installation of casing into rock is increased from 20 to 50 feet. In addition, the following caveat is added:

> "Channels and crevices in limestone may not hold grout. Packers must frequently be used to seal large water filled channels and crevices so as to hold the grout. Limestone and grouting may not be successful in excluding contamination." (4).

Another item addressed includes the required distances from a well to a "subsurface sewage disposal system" which is ordinarily 100 feet, but "a greater distance ... may be required by the administrative authority" in the case of "limestone, fractured, creviced, or fissured rock formations."

The state also has laws regulating the installation and removal of underground storage tanks that do not identify karst areas as needing increased concern.

There are two other proposed sets of state guidelines that should be officially promulgated in the near-future. The first is a well-head-protection regulation, but there is no specific reference to karst within the current draft. A generic treatment to well-head protection will be proscribed, although aquifer parameters appropriate to carbonate-rock areas in the state will likely be specified in the groundwater modeling process that generates protection areas.

Also in progress is a guidance document regarding sinkhole occurrences on private or public lands. The document will eventually cover the means of contacting responsible government officials in relation to formation of dolines, mine-shaft openings, and subsidence (garbage) pit formation. Identification, state inspection provisos, and remediation will all be addressed in a preliminary manner.

Figure 3. Categories of site selection criteria and factors.

NEW JERSEY RESIDENTIAL-SITE IMPROVEMENT STANDARDS

State-Wide/Semi-Municipal Administration

After four years of development and review, New Jersey's Site Improvement Standards (SIS) became operative on June 3, 1997. The SIS are statewide, uniform, mandatory rules governing the development of residential sites within New Jersey. They apply to any development that requires approval of a major subdivision or a site-plan review pursuant to the New Jersey municipal Land Use Law and any implementing ordinance. These standards are designed to increase the predictability of the physical-improvement requirements without limiting municipal authority in areas of use, design, and layout. The site standards cover the design of streets, water supply, sanitary sewers, and stormwater systems.

The applicability of these standards in defining design and construction materials made it imperative that some recognition of karst issues be addressed. Members of the Site Improvement Advisory Board received information and heard presentations regarding the need to adequately address karst-related issues during the development of these "uniform" design standards. Complicating the process was the desire of the board to receive definitive karst design standards for all development activities concerning roadways, stormwater, sewer, and water-system construction. Given that the best design solution to karst related problems depends upon the actual subsurface conditions below a particular site, the preparation of a one-design-fits-all-conditions was ruled out as costly and unreasonable. The final resolution of the issue came by permitting communities with solution-prone carbonate rocks to modify the state's uniform design and construction standards to deal with these features. It also allowed definitive, municipally enforced ordinances addressing karst concerns to remain in force.

SOIL EROSION AND SEDIMENT CONTROL LAW

Revisions to New Jersey's Soil Erosion and Sediment Control Law have recently been introduced in the state register. This law attempts to regulate the off-site impacts of development activities by controlling on-site soil erosion and overland-water flows. An appendix that specifically addresses karst areas will accompany the revised rules. Many best management practices routinely incorporated into comprehensive soil-erosion and sediment-control plans have a propensity for facilitating the opening of existing solution features. Of major concern is the design of stormwater-management systems. Numerous failures of stormwater-collection systems and sinkhole development within detention basins have made the proper design, construction, and management of these facilities an important priority. The regulatory authority (New Jersey Department of Agriculture, State Soil Conservation Committee) for these design standards was hoping for a quick fix to these problems in the form of a sinkhole-closure design. The focus on fixing sinkholes after they develop misses the important concept of comprehensive planning and design to minimize geoenvironmental risks at a development site. The present goal is to encourage the adoption of a site assessment and design process for karst areas that allows the development community and local regulators to identify any karst concerns at a site and to incorporate the appropriate design features in order to minimize future sinkhole formation and to reduce the potential for groundwater contamination.

MUNICIPAL LAW

As a result of the karst exception to the SIS, the final recourses at most karst sites are municipal laws. In New Jersey, local land-use regulation is quite comprehensive and covers a variety of concerns from safety in construction to stormwater flows. Obviously, much of this local jurisdiction will be superceded by the SIS, except in karst areas.

The variety of municipal limestone regulations is extensive. There are some regulations that have been so badly formulated that they could not be administered if township regulators went by the letter of the law. Others have serious technical errors that would immediately invalidate them if a legal challenge was raised.

The RC&D-model-ordinance variants (and their Clinton township forerunner) seem to work. The required multi-stage investigation allows both the developer and the municipality to predict problems and to estimate the associated costs based upon a growing body of knowledge for the area in question. The initial phase of work is accomplished inexpensively, yet the designer can develop preliminary costs and evaluate the feasibility of the development.

The rationale for passing municipal ordinances has ranged from the environmental concern of groundwater protection to fears of the personal liability of township officials. Both "for" and "against" votes by the governing board have been made on the basis of loss of income by a board member/property owner or realtor because of the effect of increased construction costs reducing the value of their land (no votes), and pro-votes in the hope that the law will scare away newcomers.

SUMMARY AND CONCLUSION

A plethora of regulations governing new construction in karst exist in New Jersey. Taken together, the protection available can be quite good, at least in the municipalities having appropriate land-use law. Unfortunately, the regulations are scattered throughout many federal, state, county, and municipal jurisdictions. Even more unfortunate is that often both the developer and the regulator are unaware of the existence or significance of both the regulations and karst. The authors, when wearing their regulator hats, have often been surprised at the lack of understanding of karst issues when dealing with both regulators and technical professionals. The good news is - progress is being made, albeit slowly.

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PSEUDOKARST OF AZERBAIJAN

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Abstract

This paper presents a short summary of the development of pseudokarst in the geologically recent foothills of the Big Caucasus Mountains in Azerbaijan. A dry climate, low permeability of rocks, and a network of ravines that drain the area have contributed to pseudokarst development. These factors, as well as deeply entrenched valleys and a large number of thrust and other faults, have contributed to the dryness of the region. Nearly all precipitation is absorbed by the dry terrane. Water is stored in the rifts and slopes, particularly at their bottoms which receive a large amount of water, promoting the formation of hollows. Subsequent streamflow continues to enlarge to rifts. Gradually, infiltration forms separate hollows and the rifts and small canals become underground passages contributing to the pseudokarst terrane. There are several geometric forms of pseudokarst The principal process of development of this pseudokarst is mechanical suffusion (also known as piping). This is in contrast to karst where the principal process is dissolution and chemical leaching.

Introduction

Azerbaijan is situated between the large anticlinoria of the Big and Small Caucasus Mountains. The region has a complicated geologic structure and there is a mixed lithology among the rocks. The rocks and sediments range in age from Cambrian to Quaternary. The neogenic foothills of the Big Caucasus occupy the extensive area of the country. The entire complex of deposits in the region lie within long, narrow anticlines consistent with the structural trend of the Caucasus. The folds are compact and commonly overturned to the south and cut by numerous thrust faults; in places the northern flanks of anticlines are thrusted over the southern ones. A wide range of deposits are present in the area. Molasse deposits of Oligocene, Miocene, and upper

Pliocene ages indicate marine facies, shale intercalated with sandstone. Lower to middle Quaternary molasse deposits occur with Pliocene beds that are dense, sandy, and pebbly. Units of the Pliocene-Oligocene-Miocene sequence reach thicknesses of 2000 to 3000 meters. Recent deposits of talus, colluvium, and sandy loams occupy the valleys.

Processes of Pseudokarst Development

The region is characterized by a shortage of both surficial and subsurficial water. This is the result of several factors: (1) a dry climate, (2) low permeability of the bedrock, (3) a network of ravines that drain the area, and (4) deeply entrenched valleys, a large number of thrust and other faults that isolate the landscape into separate blocks. The rocks of the region are nearly completely drained of water.

A result of these conditions is that precipitation running from the slopes and onto the horizontal surfaces is nearly totally absorbed by the dry rocks. Stream water collects in the rifts and in erosional furrows on the slopes and becomes concentrated at the bottom of the slopes. This begins to form small hollows. Circulation within the rifts loosens particles, promoting the erosion and transport of these particles of sediment. The sediments of this region have a low resistance to erosion. This is particularly true of the sandstone deposits wherein water seeps in and erodes at higher rates.

Rifts and underground passages remain quite dry between successive rains and the only outside influence during these periods is a slight dusting by wind. After each rain, water flow once again continues to enlarge the rifts. Gradually, wells are formed from the hollows and the rifts and small conduits merge, forming subsurficial passages, a primary feature of this form of pseudokarst.

Forms of Pseudokarstic Features

Based on form, the pseudokarst feature of this region of Azerbaijan may be grouped into the following general categories:

1. Cones, wells, sinks, and similar features formed directly by absorption of water from the surface.

2. Underground passages or conduits formed by convergence of flowpaths and by transport of particles through the process of horizontal suffusion.

3. Exit forms where underground openings come to the surface.

Cones, wells, sinks, and the like form in linear patterns consisting of chains along the centerlines of ravines. Funnel-like sinks are separated by steep benches. Subsurficial conduits lie parallel to the land surface approximately 5 to 8 m below the ground. The funnel shaped sinks are located at the bottoms of ravines, are elliptical in shape and range from 1 to 30-35 meters in horizontal dimension. In many places, the edges of the ravines are the vertical walls of the sinks. Wells have a round and elongated form. Swallow holes are small in size. On the flanks of ravines, hollows formed by percolation of water are found in the saddles between cones. Underground passages (pipes) passing directly beneath cones consist of narrow pipes, approximately 0. 3 to 0. 7 m in diameter. Underground galleries are less well developed.

Underground passages or conduits consist of holes approximately 20 to 30 cm in diameter. Smaller holes, 2 to 3 cm in diameter are formed in some deposits.

Exit forms often appear as miniature versions of the forms of the first group (cones, wells, and sinks). Ravines with funnel-shaped sinks are characterized by a stepped longitudinal profile. There are no apparent pseudokarst features in ravines with wide and level bottoms. In many places, deposits of talus collect in the bottoms of narrow and deep ravines and partition the latter. Runoff from rain infiltrates the loose debris of the talus and excavates underground galleries resembling the features of the first group above. Pseudokarstic landforms formed where water is absorbed by the ground typically form under benches. These forms correlated well with underlying geological conditions with the exception of where these forms are strongly controlled by local relief. Formation of pseudokarst is most favorable on steep flanks where beds are exposed that exhibit strong jointing, tectonic brecciation, crush zones from landslides, or low resistance to erosion.

In ravines with steep walls and those that have stepped longitudinal profiles, development of pseudokarst is facilitated by considerable ponding of water. Flow velocity is accelerated through narrow segments of channels where the cross-sectional areas are reduced. Higher velocities, in turn, intensify erosion.

Water drained through underground galleries is directed along the steepest hydraulic gradients. This water typically issues at the surface where hydraulic gradients suddenly change. The development of underground passages to resurgences is directed by the hydraulic gradient, especially where steep gradients make a transition to gentle horizontal gradients. Important reasons that openings develop along outcrops is the presence of water-resistant beds (impermeable strata) or thinning of the water-bearing units having conduits where water comes close to the surface.

Development of depressions (cones and wells, for example) in areas where water is absorbed, leads to expansion of underground passages. Seepage water intensifies the excavation of the passages and development of an underground drainage network. These conduits may attain large dimensions and may initiate secondary underground passages.

Peculiarities of Pseudokarst

The principal characteristic of pseudokarst of Azerbaijan is that the mode of origin of the landforms is by mechanical suffusion (piping) rather than by dissolution or chemical leaching as is the case in true karst. The suffusional processes are caused by surface waters infiltrating the ground. Some of the rocks contain salt and are weathered. Water containing salt (less than 1. 5 to 2. 5 percent) may result in dissolution and development of karst through subsurficial chemical excavation. However, suffusional processes dominate in this region.

The rocks underlying the region have a low coefficient of filtration. This impedes the dissolution of salt.

Gypsum fills many of the fractures in this terrane. The role of gypsum fillings is insignificant. However, under conditions where occasional wetting occurs, gypsum reduces the filtration ability of the rocks. Thus dissolving of salt and its removal from the subsurface is of secondary importance in developing pseudokarst.

Pseudokarst can lead to environmental problems. In particular, development of pseudokarst can lead to landslides and collapses.

GEOPHYSICAL AND GEOTECHNICAL EVALUATION IN SUPPORT OF SITING A FEDERAL PRISON FACILITY IN MATURE DEVELOPED KARST - A CASE STUDY

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ABSTRACT

The U.S. Federal Bureau of Prisons plans to construct and operate a Federal Correctional Institution and Federal Prison Camp at a site approximately eight miles south of Pennington Gap, in southwestern Virginia. The study area consists of approximately 288 acres located in an area of mature developed karst. The objective of this study was to obtain site specific information about subsurface conditions to determine the feasibility of constructing the proposed facility.

The highest frequency of differential subsidence features with respect to sinkholes exist in the lower lying eastern half of the site (27 sinkholes per 100 acres). Recent sink activity is evident in this area in the formation of depressions with steep side-walls. Fewer and smaller differential subsidence features were observed at higher elevations in the western half of the site (4 sinkholes per 100 acres). An electromagnetic (EM) geophysical survey revealed circular and linear conductive anomalies (>18 mS/m) in the shallow subsurface indicative of solution features and zones of structural weakness containing disaggregated bedrock. Areas of relatively high EM apparent conductivity values generally correlate to visible subsidence features in the eastern segment. This correlation was not apparent in the western segment.

Soil test borings and test pits revealed a soil profile consisting of very soft to very stiff, high plasticity clay and moderately hard to very hard, massive limestone in areas identified as suspect by the EM survey. Highly variable depths to rock over short distances, indicative of pinnacled weathering were evident, especially in the eastern segment. Ground water was frequently encountered overlying the carbonate bedrock. The results of this preliminary study indicate that the western segment is more favorable for construction of a prison facility, due primarily to the apparent lack of significant solution features. Eliminating the risk of ground subsidence due to sinkhole activation is very difficult for any site. However, methods for reducing risk to the prison facility can be mitigated by optimization of the building location on the site, correction or mitigation of known ground defects, modifying shallow foundations to bridge localized undermining, utilizing deep foundations, and modifying drainage design to reduce potential for future activation of sinkhole activity.

INTRODUCTION

The Federal Bureau of Prisons plans to construct and operate a Federal Correctional Institution (FCI) to house medium-security inmates, a

Federal Prison Camp (FPC) to house minimum-security inmates, staff training facilities, and other related facilities. The proposed site consists of approximately 288 acres located northwest of the intersection of US Route 58 and VA Route 638, in central Lee County, Virginia (Figure 1). The estimated area required for these facilities is approximately 40 to 60 acres. The purpose of this preliminary assessment was to obtain specific information about the site and subsurface conditions to determine the feasibility of constructing the proposed facility in an area of mature developed karst and to identify the most favorable areas of the site for development.

The topography of the site is generally hilly to rolling with elevations ranging from about 1650 feet mean sea level (msl) at the west edge of the site to about 1340 feet msl at the southeast corner of the site. The major consideration from a geotechnical engineering perspective for this site is the unusual weathering patterns of limestone and other carbonate rock. The weathering occurs

Fgure 1. Location of study area.

primarily by solutioning of the rock and some collapse, leaving a highly irregular rock surface (i.e., differential subsidence), with continued potential for development of solution cavities and/or caverns.

All structures of the proposed FCI and FPC will be generally residential in scale, not unlike a college campus. Most buildings will be one- to three-story structures. The general site design of the proposed facility will present an intergrated composition of structures reflecting the differing characteristics of the facility's major components. A buffer zone of undeveloped acreage surrounding the property will provide a visual setback from the property boundaries.

Pursuant to existing regulations for federally funded projects, an Environmental Impact Statement (EIS) for the proposed facility was completed (1). The EIS, the assessment it presents and the procedures by which the environmental investigations are conducted and incorporated in decision making, are parts of a process established under the National Environmental Policy Act (NEPA) of 1969 to ensure that the environmental consequences of federal projects are adequately taken into account. The process is designed to ensure that public officials make decisions based on a full understanding of the environmental impacts of proposed actions and take all appropriate steps to "protect, restore and enhance the environment".

GEOLOGIC SETTING

The project site lies within the Valley and Ridge Physiographic Province of Virginia. The rock formations in the vicinity of the proposed FCI are Middle to Late Ordovician limestones that are principally thick-bedded, light brown to light-gray, and cryptocrystalline to fine-grained. Harris and Miller (2) and Nolde (3) indicate that the site contains up to three distinct carbonate formations, the Poteet Limestone (eastern section), the Dot Formation (central area) and the Mascot Dolomite (western section) (2). The project site lies near the axis of the Sandy Ridge Anticline, a northeast-southwest trending structure (3).

The site showed significant karst development in the southeast corner of the site, including several sinkholes, solution depressions, and a cave that extended under US Route 58. On a per acre basis, the frequency of sinkholes/solution depressions varied across the sight. The area east of a line drawn down the center of the site showed a frequency of about 27 sink holes or solution depressions per 100 acres. The number of observed sinkholes/solution depressions to the west decreased to about 3 or 4 per 100 acres. Rock outcrops were present throughout the site with significant numbers in the southeast corner. Some recent sink activity is also evident in the formation of new depressions with steep scarp walls that are free of vegetation.

In November 1995, Ewers Water Consultants, Inc. (EWC), conducted a hydrogeologic study of the site to identify significant concentrated groundwater discharge points which could be connected with dye injection points on the site (4). EWC confirmed that groundwater flow in the eastern portion of the site is dominated by conduits produced by dissolution of the carbonate bedrock.

EM GEOPHYSICAL SURVEY

An electromagnetic survey (EM) was conducted to identify areas of potential sinkhole development across the site. The EM study area was roughly 6,560 by 8,200 meters in overall dimensions (115 acres) (5). Survey equipment consisted of an EM-31 terrain conductivity instrument, manufactured by Geonics, Ltd. The

EM geophysical method measures the electrical conductivity of the subsurface using the induction of EM fields. For this survey, the vertical dipole mode was used. The vertical dipole mode of the EM-31 is predominantly sensitive to the material at depths ranging from about 0 to 5 meters depending on subsurface conditions. About 81,254 linear meters (50.5 miles) were profiled, with data recorded at about 53,300 stations.

Overall, the apparent conductivities measured by the survey decrease from west to east across the site. The range of apparent conductivities in the western portion of the site typically fell within 16 to 24 mS/m, 10 to 16 mS/m in the central portion of the site, and 4 to 16 mS/m in the eastern portion of the site. Figure 2 depicts several circular, linear to nearly linear, east-west trending features of relatively high conductivity (18-24 mS/m) in the survey area. The conductivity features appear to correlate with closed depressions and surface drainage swales

Figure 2. Proposed FCI Site - EM survey results (Approximate scale, 1cm = 76m)
a)Dark shaded portion represents conductivity anomalies, b) Circular outlines represent visible

observed in the central and eastern sections of the site. The correlation of surface drainage features with areas of relatively high conductivity can be attributed to an increased moisture content. Areas of higher conductivity correlate with areas of observed subsidence and/or solution weathering in the central and eastern portions of the site, but high apparent conductivity values did not always correlate with obvious solution features in the western portion of the site.

SUBSURFACE EXPLORATION

The subsurface conditions were explored with 10 soil test pits and 16 soil test borings in areas identified as suspect by the EM survey (6). The soil test pits were excavated to depths of about 3 meters or refusal. Soil test borings were drilled to depths ranging from 0.5 feet at refusal near the western end of the site to 11 meters near the eastern end of the site. Rock core drilling was performed at six of the soil test boring locations to depths of 3 meters below auger and/or split-spoon refusal. Standard penetration tests (SPTs) were conducted in the borings at regular intervals in general accordance with ASTM D 1586.

Soil Conditions

The test pits and borings encountered two basic strata within their termination depths. Beneath a surface layer of topsoil ranging from 0.1 to 0.5 meters in thickness, the test pits and borings generally encountered strata briefly described in the following paragraphs.

STRATUM I: Very soft to very stiff, red-brown, brown, and tan, high plasticity CLAY (CH). The thickness of the Stratum I clays in the area of the proposed FCI ranges from 0.4 to greater than 9 meters. Standard penetration test (SPT) resistance generally ranged from 1 to 27 blows per foot (bpf) with an average value of about 9 bpf. Classification tests indicated that the soils were high plasticity CLAY (CH) with percent fines ranging from 88 to 99, liquid limits (LL) ranging from 53 to 84, and plasticity indices (PI) ranging from 32 to 47.

STRATUM II: Moderately hard to very hard, gray-white and brown-gray, fine to medium grained, massive LIMESTONE with close to moderately close joints and slight to moderate weathering. Evidence of solution includes the presence of open cavities and complete joint weathering at some rock coring locations. Backhoe refusal on bedrock was encountered at 8 test pit locations at depths ranging from 0.6 to 3.0 meters.

Groundwater was encountered in apparent perched conditions in several test pits and borings, primarily in the eastern portion of the site. Groundwater was found to directly overlie bedrock when present.

Bedrock Surface

Depths to bedrock appear to be generally shallower and more consistent over the western half of the site. Rock outcrops are more deceiving in the eastern and southeastern portions of the site. As an example, the high density of rock outcrops in the southeastern corner of the site appears to indicate shallow rock over a relatively large area. However, when excavating soil test pits and drilling soil test borings in close proximity to the outcrops, depths to rock sometimes exceeded 7.6 meters. This variability in depth to bedrock is indicative of highly solutioned limestone which can present difficulties during construction. Problems associated with constructing fills in this area may also be experienced in terms of possible large differential settlements unless some form of ground improvement is performed.

CORRELATION OF SUBSURFACE EXPLORATION AND EM DATA

The results of the EM surveys and subsurface exploration program suggest that high conductivity is the result of a combination of two criteria, the moisture content of the soil overlying the bedrock, and to a lesser degree, the depth to bedrock. The two criteria are closely related since moisture in the form of groundwater appeared to accumulate in perched conditions immediately over bedrock (i.e., the closer the bedrock is to the ground surface the closer the horizon of high moisture is to the ground surface). Areas mapped as being highly conductive typically contained a high water table and/or high levels of moisture in the soil. In areas of limestone outcrop, where a moist weathered horizon was not present, the apparent conductivity values represented measurements of bedrock only, and were relatively low (5 to 10 mS/m). The karst features on site act as drainage basins, creating conduits, or preferred surface and subsurface drainage routes, thus forming zones of increased moisture. The EM survey results suggest that high apparent conductivity can be used as an indicator of solution (karst) weathering in the subsurface, especially in the eastern portion of the study area.

GEOTECHNICAL CONSIDERATIONS

The site contains many sinkholes and solution depressions and has potential for further sinkhole development. Methods for eliminating the risk of any site due to sinkholes are very difficult, if not impractical. There are however, several methods for reducing the risk by both design and construction measures. The methods include optimization of the building location on the site, correction or mitigation of known defects (e.g., sinkholes), modifying shallow foundations to bridge localized undermining, utilizing deep foundations, and modifying drainage design to reduce potential for future activation of sinkhole activity.

Optimization of Facility Location

Optimization of facility location involves identification of previous sinkhole activity or areas most prone to sinkhole activation and locating structures to avoid these areas. The structures are then repositioned and oriented so the exposure to risk is minimized based on these findings.

Mitigation of Known Defects

Mitigation involves partially correcting known defects by grout injection, filling voids with concrete, dental work in pinnacle limestone areas, and removing and replacing loose material. However, if erosion develops, and grout or concrete loosens, the perceived benefits from the mitigation methods are lost.

Modification of Shallow Foundations

Modification of shallow foundations includes the mitigation procedures described above. Another alternative is to bridge over subsurface openings by utilizing a bridging beam bearing on separate foundations. A third alternative is to use rock anchors, rock bolts, or grouted dowels. With this alternative, detached blocks of rock are tied together to produce a rigid mass. A fourth alternative would be to build structures with sufficient strength and rigidity to resist catastrophic deflection (mat foundation) if a cavity develops beneath an unsupported point. The maximum unsupported width would be selected based on diameters of nearby sinkholes.

Utilization of Deep Foundations

Deep foundations supported directly on competent rock may be used when the risk of sinkhole formation is great or when upper layers of soil or rock cannot support the foundation loading. However, installation of these foundations may introduce other problems due to sloping rock surfaces, pinnacles, and groundwater.

Minimizing Activation

Steps to minimize future activation typically include significant surface-water control. Site grading should be designed to have sufficient slope to discharge surface runoff away from buildings and pavements. Groundwater lowering also should be avoided. In addition, structure elevations should be selected to minimize blasting and disturbance of existing water flows.

CONCLUSIONS

Although some areas of smaller solution depressions were noted, fewer solution features were observed at higher elevations over the western portion of the site. In general, it appears that rock is shallower and that surficial and subsurface drainage are more confined and consistent over the western portion of the site. The higher consistency and lower frequency of solution features makes the western portion of the site more favorable for development with respect to minimizing risk associated with sink activity. Although the shallow rock will increase excavation costs if deep cuts are planned, the consistency in depth will allow more reliable cost estimating.

Methods for eliminating the risk of any site due to sinkholes are very difficult, if not impractical. The several available methods for reducing the risk by both design and construction measures include, optimization of the building location on the site, correction or mitigation of known defects, modifying shallow foundations to bridge localized undermining, utilizing deep foundations, and modifying drainage design to reduce potential for future activation of sinkhole activity. Optimization of the building location, in addition to modifying drainage design appears to be the least intrusive of the design/placement options, if adequate acreage is available for the desired orientation. Further investigation of the bedrock is necessary to determine whether mitigation should be used and the most appropriate methods once a conceptual facility layout has been determined.

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ABSTRACTS

HYDROGEOLOGIC CHARACTERIZATION OF A KARST GROUNDWATER SUPPLY SOURCE TO DETERMINE SURFACE WATER INFLUENCE

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A hydrogeologic investigation to evaluate surface water influence on an 864,000 GPD (1.34 CFS) karst spring was conducted near Taylors Valley in Washington County, Virginia. In response to the U.S. EPA Surface Water Treatment Rule (SWTR), the most recent Virginia Department of Health (VDH) Waterworks Regulations require all groundwater sources (wells and springs) utilized by public waterworks to be evaluated to determine whether they are influenced by surface waters. The objective of the spring evaluations are to identify surface-to-aquifer connections that increase the risk of groundwater contamination and waterborne disease outbreaks due to the presence of pathogenic organisms commonly found in surface waters. If it is determined that a spring or well is under the influence of surface water, the SWTR requires that the source undergo a treatment process that includes both filtration and disinfection. Currently, the majority of public groundwater supplies employ disinfection only.

Reservation Spring resurges from karst bedrock exposed at the northernmost end of the Mountain City window which occurs along the eastern margin of the Valley and Ridge Physiographic Province. The karst bedrock lies subjacent to intersecting overthrust sheets comprised of non-carbonate rock types. The investigation included a spring survey, karst features and geologic mapping, multiyear water quality data trend analyses, and the geochemical characterization of various springs and surface waters in the area. While several potential sources for surface water influence were identified during field reconnaissance activities, the water from Reservation Spring was shown to be geochemically different compared with water from nearby surface streams. No correlations between spring water quality trends and climatic or seismic events were observed. Groundwater tracing to confirm or confute the initial findings was recommended. Tracer testing using fluorescent dyes was approved by VDH and was used to demonstrate there were no subsurface connections between nearby surface streams and Reservation Spring. Based on the investigative findings, it was determined the spring was not influenced by surface water.

To facilitate long-term protection of Reservation Spring as a public water supply resource, a source water protection area (SWPA) was proposed in accordance with the source water assessment and protection initiatives adopted by U.S. EPA in the 1996 amendments to the Safe Drinking Water Act (SDWA).

THE USE OF REGIONAL HYDROLOGICAL MODELS IN HYDROLOGICAL INVESTIGATIONS OF KARST TERRAINS

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The Valjevo karst area extends over 3600 square kilometers in western Serbia. Karstified rocks in the area have a surface coverage of more than 500 square kilometers. A regional hydrological model was developed using all available geological and hydrogeological data and conditions for karst aquifer. Regional model test results were used to locate general key areas for understanding the geological and hydrogeological relationships in the region. Model results confirmed that regional hydrogeological models can be used as an essential method for preliminary investigations.

DESCRIPTION OF ANISOTROPY AND HETEROGENEITY AND THEIR EFFECT ON GROUNDWATER FLOW AND AREAS OF CONTRIBUTION TO PUBLIC SUPPLY WELLS IN A KARST CARBONATE AQUIFER SYSETM

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Delineation of areas of contribution to wells tapping a karst carbonate aquifer system can be extremely difficult using conventional approaches designed for isotropic and homogeneous aquifers because groundwater flow tends to be through solution-enhanced conduits. Non-radial flow along preferential zones can result in inaccurate estimates of flow paths and travel times. Because of the large variability in factors affecting contributing areas and an imperfect understanding of how these factors can vary, the estimation of contributing areas is an approximation at best.

In this study, an exploratory modeling approach was used to better understand the effects of aquifer anisotropy and heterogeneity on areas of contribution. The MODFLOW, numerical flow model, and MODPATH, particle tracking program, were used to generate time-related areas of contribution for six hypothetical carbonate aquifer system types. The six types were conceptualized to approximate different types of aquifer anisotropy and heterogeneity. These include: 1) isotropic and homogeneous single-layer system; 2) anisotropic in a horizontal plane single-layer system; 3) discrete vertically fractured single-layer system; 4) multilayered system; 5) doubly-porous single-layer system; and 6) interconnected vertically and horizontally heterogeneous system.

The simulated aquifer anisotropy was 5:1 (Kxx/Kyy), determined from TENSOR2D results. The simulated vertical, discrete fracture network represents locations inferred from mapped photolineaments. The simulated enhanced flow zones were determined from borehole video and geophysical logs. Areas of contribution were simulated for two prototype regions. The two prototypes were selected to be representative of the hydrologic diversity within the study area and were designated the Central Swamp and Lake Terrace regions.

This study indicates that the distribution and type of aquifer anistropy and heterogeneity will affect the size, shape, and orientation of areas of contribution in a karst carbonate aquifer system. The size of the 50-year time-related areas of contribution ranged from 8.2 to 39.1 square miles in the Central Swamp region and from 4.0 to 18.3 square miles in the Lake Terrace region. Simulations showed that the size of areas of contribution is affected primarily by simulated withdrawal rates, effective porosity of the carbonate rock, and transmissivity. The shape and orientation of the simulated areas of contribution result primarily from aquifer anisotropy, well distribution, flow along solution-enhanced zones, and short-circuiting of flow through fracture networks.

Comparisons were also made between protection zones delineated by analytical models and areas of contribution delineated by numerical models. The size of the five-year time-related protection zone in the Central Swamp region using an analytical model was almost twice as large as the numerically simulated area of contribution, and more than eight times larger than the numerically simulated area of contribution in the Lake Terrace region. Differences in size are primarily the result of how the flow field is approximated. The analytical method assumes only lateral flow to wells, but numerical methods allow particles to move laterally and vertically. In addition, multiple-well-interference effects resulting from the close proximity of several pumping wells cause individual capture zones to converge or diverge depending on the difference in pumping rates and orientation among the wells.

FACTORS DETERMINING UNDEGROUND WATER REGIME OF KUNGUR CAVE (the URALS)

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Kungur Cave is the only cave in Russia where regime observations on underground water level and composition have been conducted since 1934. The cave is located in the vicinity of Kungur City (Perm region), to the northwest of Ufimskoye plateau. The cave entrance is in the lower part of the northern side of Sylva river valley at the level of aggradation terrace. The terrace width near the cave entrance is 100-150 meter. Downstream, the terrace is pinched out and a valley borders the river. The total length of grottos and passages of the cave is about 5 to 6 kilometers.

The cave is formed in gypsum and anhydrite of Lower Permian Kungur state Iren horizon represented by alternation of gypsum-anhydrite and limestone-dolomite members. In the cave basement there occurs dolomite of Filippovsky horizon. Eluvial loam and detrital-shaly sediments, their thickness exceeding 10 meters, cover Lower Permian rocks. The field over the cave is complicated by the existence of numerous sinks. The largest ones are situated over large grottos.

Near the entrance the southeastern part of the cave is cold. In this location, various ice crystals, stalagmites, stalactites, columns, and overflow ice can be observed. The central and northwestern part of the cave are notable for the existence of more than 60 lakes. The cave is horizontal, grottos and passages are stretched mainly northeast and north-west.

Karst water in the cave occurs on the dolomite. Water containing rocks are cleaved through karstic gypsum, and anhydrite and detrial-shaly products of rock destruction. The aquifer is recharged by atmospheric precipitation which is absorbed by numerous sinks, water in the aeration zone (its thickness equals 70-80 m), and river water during flood periods. Karst water in the cave is exposed through three wells and underground lake basins.

The regime of cave massif karst water is formed under the influence of climatic, hydrologic, and geologic factors. The climate of the region is moderately continental, with average annual precipitation of about 500 mm. Maximum precipitation occurs in the summer time and snow cover lasts up to 180 days a year.

Climatic factors cause seasonal fluctuations of regime data. They influence the flood height and level of the river and karst waters. The influence of hydrological factors is expressed by close connection of cave karst water level with the Sylva River level. During the flood period, river water penetrates in cave massif for a short time by infiltrating through alluvial deposits of the first terrace or by inflow in karst rocks adjacent to the river. Lowest levels of river water (low-flow) are registered in the winter period and before floods.

The following geological factors influence karst water regime: the degree of fissuring and karsting of rocks, and their composition and condition of occurrence. According to G.N. Kamensky's classification, the cave massif is attributed to the near-bank type of regime. In heavily karsted areas the near-bank regime is changed by the absorption regime, and far away from the river it is changed by the divide regime.

Regime hydrochemical observations showed that after a flood period the mineralization of sulfate-calcic karst water decreases. Water becomes aggressive to gypsum and anhydrite. Seasonal fluctuations of rock and water temperature, air humidity, wind regime, level and mineralization of karst water are the factors that activate karst processes causing the evolution of the complex cave system.

KARST-WATER AND SINKHOLES

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Formerly, it was believed that karst develops very slowly. However, today the evidence contradicts this notion. Formation of new sinkholes may begin within a few decades of the beginning of a high rate of development of carbonate aquifers, even in areas where sinkholes were not previously observed. Such a situation may occur where carbonate aquifers overlying unconsolidated deposits are present beneath the contemporary drainage basin, and where in fact karst did not previously exist.

Karst water is closely associated with the environment, and therefore changes in the environment actively and rapidly affect karst-groundwater.

The central Moscow artesian basin is a highly urbanized area. Solution cavities of various volume and length are mainly located in the Upper and Middle carboniferous rocks. The over exploitation of the confined aquifer in the years 1900 to 1996 through the carboniferous aquifers resulted in the formation of three extensive and prolonged recharge areas. More dynamic changes in confined water chemical composition are observed in intensive water withdrawal areas. From a year of observation, it is evident that changes in the chemical composition of the confined aquifer depend on the water withdrawal regime. Thermodynamic modeling makes it possible to determine the indice of calcite and dolomite.

Transformation of the natural hydrogeological conditions led to an increase in the dissolved solids content and concentration of sulfates in the water of karstified aquifers. The inflow of river and shallow groundwater to kartified aquifers intensifies microbiological processes.

STUDY OF KARST GROUNDWATER SYSTEMS IN SHANXI PROVINCE, CHINA

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In this project, the hydrology of karst groundwater has been evaluated by studying the isotope composition of karst groundwater in two distinguished karst water system, i.e., west mountain system and the east-north mountain system. Isotope and chemical data were used to determine the mixing ratios of various groundwater and to trace the movement of karst groundwater.

As a result, a mixing line for the west mountain karst water system and shallow water was determined. The author concluded that in this area about 36 percent of karst water is recharged by the shallow water. Isotope data indicate that there is some water supply from the west mountain karst water system to the Lan spring which is located in the east-north mountain system.

EPA'S GROUNDWATER DISINFECTION RULE : IMPLICATIONS FOR KARST AQUIFER WELLS

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U.S. EPA, in concert with states, tribes, utilities, and other interested parties, is in the process of developing drinking water regulations to provide the public protection from microbial contamination of groundwater systems. The anticipated proposal is expected in late 1998, and promulgation of a final rule is expected in the year 2001. Implications of the rule are discussed in this paper.

This regulation, the Groundwater Disinfection Rule, will focus on providing multiple barriers to contamination reaching the consumer. The rule work group is considering requirements based on best management practices and adequate operations and maintenance, rather than relying solely on disinfection treatment. Regulatory elements will likely include: 1) source water protection and groundwater vulnerability assessments; 2) sanitary surveys to determine system integrity and correction of defects; 3) maintenance of a distribution system residual or equivalent, where appropriate; 4) disinfection where indicated; and 5) microbial monitoring of sources and distribution system. Systems with known fecal contamination and systems identified as vulnerable to such contamination will need to disinfect. Evidence to date indicates that wells in karst and other highly porous aquifers are highly vulnerable.

ANTHROPOGENIC INFLUENCE ON KARST GROUNDWATER QUALITY: A CASE OF NITRATE POLLUTION

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Anthropogenic and techonogenic factors play an important role in the formation of chemical composition of karst groundwater. In this study, the increase of nitrate ion concentrations in karst groundwater was observed as a result of those influences. Nitrate ion has a special place among various pollutants. In this paper, nitrate ion's influence on groundwater quality is presented using examples of hydrochemical regime observations in several karst terrains of Yugoslavia, such as wide surroundings of Belgrade and Valjevo and large industrial centers. Results of this research indicate that non-industrialized and non-populated drainage basins of karst springs do not necessarily provide good quality groundwater.

KARST GROUNDWATER CHEMESTRY IN CARPATHO-BALKANIDES OF SERBIA

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The chemical composition of karst groundwater in the Carpatho-Balkanides of Serbia reflects the condition of their formation. More than 300 chemical analyses of karst springs were conducted in the laboratory. The gravity springs on higher peaks are characterized by rapid infiltration, while the ascending springs have more favorable characteristics and a much lower rate of chemical and biological impurity. The regression and factor analyses were applied for differentiation of many variable influences.

A PILOT WELLHEAD PROTECTION STUDY AND PLAN TO PROTECT PUBLIC WATER SUPPLIES IN KARST TERRAIN

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Communities of the Central Shenandoah Planning District which encompass the counties of Augusta, Bath, Highland, Rockbridge, and Rockingham, and the cities of Buena Vista, Harrisonburg, Lexington, Staunton, and Waynesboro with a total population of 240,000 persons, are extremely dependent upon groundwater for domestic use and other purposes. More than 125 community wells are in use throughout the region. Many localities are entirely dependent on wells and springs as a source of public water supplies and with few exceptions, all localities receive at least half of their drinking water from groundwater sources. At the same time, an extensive karst formation predominates the region and increases the risk of contamination of a valuable water resource because of the rapid intrusion of surface and sub-surface pollutants into groundwater recharge areas. Intensive agriculture, extensive use of septic systems, and burgeoning residential and industrial development heighten the reason for concern. Unfortunately, the jurisdictions of the Central Shenandoah Valley have not developed a comprehensive groundwater or wellhead protection plan to prevent contamination of groundwater supplies.

Using a 1995 U.S. EPA grant, the Central Shenandoah Planning District Commission initiated a wellhead protection program. The program include: 1) maps which show locations of all community wells in the planning district and their proximity to features such as leaking underground storage tanks, surface waters, roads, landfills, toxic release inventory sites, and sinkholes; 2) delineation of a wellhead protection area, for selected public wells, based on detailed analysis of surrounding hydrogeology, survey of land use and possible contamination sources, and detailed resource management plans; 3) a planning document; and 4) a public information brochure. In addition, the program include establishment of an inventory of local well and spring data and hydrological characteristics; a data management system that utilizes the existing Planning District's Geographic Information System; and a demonstration model for future wellhead protection activities.

It is expected that the initiative will instigate further wellhead protection activities, enhance public education regarding the importance of wellhead and groundwater protection, and prompt localities to pursue a variety of groundwater protection measures. Localities can utilize collected data for site planning, sub-division and building permitting, development of zoning, performance standards and other ordinances, comprehensive planning, emergency response planning, and planning for future water needs. Taking appropriate measures to prevent groundwater pollution can reduce threats to public health and save a locality the expense of remedying or replacing a contaminated well or spring.

KARST EDUCATION MATERIALS FOR TARGETED AUDIENCES (Poster Session)

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There is a tremendous need for public education about karst resources for all age groups. The following materials that have been developed for general use in Virginia and other states will be discussed.

1. Living on Karst – A Reference Guide for Virginia Communities

A central focus of the Virginia Karst Protection Project is to enhance the local management and stewardship of karst resources through training and public awareness activities, technical assistance, and karst basin investigation/delineation demonstrations. Demands for readily available protection strategies are increasing as localities react to contamination incidents, condemnation of groundwater resources, uncontrolled growth, and geohazards in population centers. The document "Living on Karst: A Reference Guide for Virginia Communities" was designed and developed to meet this widespread need for information and exchange of ideas at the community level. "Living on Karst" contains lists of contacts and references for karst resource information and assistance, a collection of ordinances, in addition to fact sheets, brochures, and other general educational materials.

2. Landowners Land Use Guide for Karst

Communities in the karst region need to be aware of how day-to-day activities affect the groundwater and fragile ecosystem in the karst region. "Landowners Land Use Guide for Karst" is a user friendly reference guide developed by the Virginia Karst Project in cooperation with the Cave Conservancy of Virginias. The Guide explains the karst environment and how activities on the ground surface may influence the underground ecosystem and groundwater quality. It outlines specific measures a landowner can use to protect this special environment.

3. Project Underground

The Project Underground is an environmental education program designed for use by teachers of kindergarten through high school age students. The project goal is to build awareness of, and foster responsible attitude towards, conserving of karst resources and management needs. The program provides activity guides such as student oriented projects, games, and discussion guidance for classroom use. The program participants will gain an understanding of the underground environment as an integral and important part of the total environment, and how very fragile karst resources be conserved and protected.

LINEAMENTS, FRACTURE-SUPPORTED LINEAMENTS, AND YIELDS OF EXISTING WELLS IN THE VALLEY & RIDGE OF NORTHERN VIRGINIA (Poster Session)

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The yields of existing wells were compared with lineaments mapped in the Valley and Ridge Physiological Province of Virginia to test a long-standing assumption that lineaments and their intersections mark the location of preferentially fractured bedrock capable of yielding significant volumes of groundwater. Bedrock in the area is comprised of limestone, dolomite, and shale, some of which exhibit significant karst development.

Two observational trails on each of three different remote-sensing platforms produced 5271 lineaments in four study areas. These were reduced to 920 coincident lineaments 514 or 56 percent of which are fracture-supported. Detailed fracture characteristics were recorded for 891 fractures at 55 outcrops distributed across the study areas.

Well data were compiled from three sources: EPA-STORET database, county health department records, and local well drillers. Analyses included comparison of yields and depths for 416 wells with rock type and distance to fracture-supported and non-fracture-supported lineaments and lineament intersection in four distance categories: 0-15 m, 16-30 m, 31-100 m, and >100 m.

Well yields within the carbonate rocks ranged from 0 to 2540 gpm. Within the shale, well yields were less than 100 gpm. Well depths in the carbonates and shale had similar ranges: 10 to 325 meters. The average yield was greatest for the 0-15 m category (93.23 gpm) and median yields were greater for the 0-15 m and 16-30 m categories. However, the few wells with yields greater than 500 gpm are located more than 30 meters from lineaments and their intersection. Most of these very high yielding wells are located in regions with significant karst development.

These results suggest that the use of lineaments to map bedrock fractures capable of yielding appreciable amounts of groundwater must be performed in combination with other hydrogeologic data. The findings of a recent hydrogeologic study serve to illustrate the above conclusions. This case study was conducted along a gas pipeline underlain by carbonate rocks of the Shenandoah Valley.

A public water supply well was located approximately 500 feet from the nearest portion of the transmission line. Recently developed sinkholes, up to approximately 25 feet in diameter, exist near the well and the gas transmission line. To assess the potential for future sinkhole development in the area of the gas transmission line, a hydrogeologic study was conducted that included detailed geologic mapping, lineament analysis, fracture fabric analysis, and surface geophysics.

Coincident lineaments intersecting in the area of interest suggest that the area is underlain by preferentially fractured bedrock and, therefore, the potential for karst development is high. The presence of karst features within the bedrock is supported by data derived from resistivity arrays. The arrays clearly show that the area proximal to the gas transmission line, and the lineaments, is underlain by extensive karst development.

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