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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 5
230 SOUTH DEARBORN ST.
CHICAGO, ILLINOIS 60604

REPLY TO THE ATTENTION OF:

22 JUN 1989

5HR-JCK-13

Captain C.E. Johnson
Commanding Officer
Department of the Navy
Naval Weapons Support Center
Crane, Indiana 47522-5000

RE: Technical Review
Geologic Reports and Activities
Naval Weapons Support Center
Crane, Indiana
IN5 170 023 498

Dear Captain Johnson:

The United States Environmental Protection Agency (U.S. EPA) has completed a technical review of the following documents submitted by the above referenced facility:

1. Geology and Hydrogeology of the Ammunition Burning Grounds, Crane Naval Weapons Support Center, Final Technical Report (October 1988),

2. Ground Water Assessment Plan for the Ammunition Burning Grounds (January 24, 1989); and

3. Proposed Dye Tracer Tests in the Beech Creek Aquifer at the Ammunition Burning Grounds (April 3, 1989).

Enclosed is a copy of our review comments, requirements, and support information. The additional requirements or changes in workplans must be incorporated into the corrective action work being done at the Ammunition Burning Grounds (ABG). The monitoring program that will be developed shall incorporate the individual monitoring requirements of closure, permitting, and corrective action into one main program for the entire ABG area. We feel that the programs can not and should not be broken into repetitive requirements, but should be comprehensive for this area.

Please submit a revised tracer test proposal as soon as possible, so that the approved plan can be incorporated into the corrective action portion of the draft container storage permit for the facility. Soil characterization for the ABG will also be incorporated into the draft permit. The Navy may want to consider doing some public affairs activities, notifying the people living near the area of the ABG that the tracer test will be taking place, to assure no future problems with the testing activities on-site.

If you have any questions regarding this matter, please contact Carol Witt of my staff, at (312) 886-6146, for assistance.

Sincerely,

Karl E. Bremer

Karl E. Bremer, Chief
RCRA Permitting Branch

cc: J. Hunsicker, USNC
T. Linson, IDEM
T. Miller, IDEM
B. Muno, REB

ATTACHMENT I
Technical Review of NWSC-CAAA's Geologic Reports and Activities
Crane, Indiana
IN5 170 023 498

DOCUMENT: Geology and Hydrogeology of the Ammunition Burning Grounds, Crane Naval Weapons Support Center, Final Technical Report GL-88-27 (October 1988)

1. Regional Geology

In order to distinguish soil types that may be present at the Ammunition Burning Grounds (ABG) and their distribution throughout the facility, the following factors, not included in the general description of the geologic report, should be kept in consideration:

Although the Wisconsinan and Illinoian Glaciations of the Pleistocene Epoch never produced glaciers that reached or surpassed the area now occupied by NWSC; they did significantly influence the overall drainage and landscape form. The very weight of the ice mass depressed the earths crust and probably crushed many of the limestone caves in the area, or glacial drift may have filled some caves or sinkholes (north of the NWSC). As the glacial ice moved forward, it produced end moraines as well as transporting large amounts of till.

As the ice began to ablate, tremendous meltwater streams flowed out to cut deep valleys as the streams flowed towards the Ohio River. These meltwaters transported large quantities of sediment downstream, sorting and depositing the material along the way. Periglacial winds would have deposited loess over the area as well. During the Wisconsinan Glaciation, many preglacial and glacial stream segments became integrated along their lengths. Several of these streams in the Crawford Upland (where the NWSC is located) became entrenched. These entrenched streams are a definite controlling factor on the local ground water flow conditions.

* 2. Site Soils

Additional work

NOTE

The soils in the area of the ABG should be classified using the Unified Soil Classification System (USCS). Also, the constituents released must be identified in order to determine the leachability and pathways of constituents within the soil horizon.

3. Regional Ground Water Trends

Although the geologic report stresses on the ABG, the overall Corrective Action program for the facility should carefully look at regional trends throughout the facility. This is especially true when you have situations like the Dye Burial Grounds investigation going on next to the ABG. This is brought out a little in the report, but the "big picture" must be kept in mind.

a. Aquicludes

Although the shales at the site are effective barriers, especially with the artesian conditions evident at the site, the investigation should be cautious in the fact that some areas may be more highly fractured and constituents may not follow the ground water flow, therefore there is a potential of migration through the shales. The shales are aquicludes not aquitards.

b. Flow Patterns

The fact that regional ground water flows to the southwest is purely coincidental with the stratigraphic dip. The ground water is flowing from areas of high hydrostatic head to areas of low hydrostatic head. Stratigraphic dip probably locally controls various aspects of the ground water flow (as reported on page 15 of the report), but not regional flow trends. **Contaminants that are dense will flow down the stratigraphic dip regardless of the hydraulic gradient.** These comments must be kept in mind during the investigation.

4. Solution Cavern Passages

An understanding of the subsurface conduits is esstential if the extent to which the subsurface has been contaminated is to be established and a corrective measure formulated. Nearly all drainage, subsidence, and collapse are triggered by the development of underlying caves. Thus an understanding of caves is essential to the hydrologic and geomorphic interpretation of such a region, as well as assessing aquifer yield, constituent migration, and soil and bedrock conditions. **The geologic report stresses on the karst conditions and identifies a major solution zone at the site, but more details must be developed.** The following information researched by Malcolm Field, U.S. EPA Headquarters, should be used in developing the investigation of karst flow conditions.

Type of Cave Likely to Occur at the NWSC

Typical caves formed in this area may be classed as network caves which consist of angular grids on intersecting fissure-like passages formed by the solutional widening of nearly all major fractures within given areas of soluable rock. Closed loops are common, and the straight, relatively narrow passages for a pattern like that of city streets. This type of cave is restricted to rocks containing prominent, nearly vertical fractures. Some rudimentary network caves do not contain closed loops but consist of an angular array of dead-end fissures.

Several caves have been mapped at the NWSC. These include Granny's Cave, Aunt Liz Cave, Fisher's Folly, Pleasant Cave, Sargent's Cave, Blume Cave, and Goldsberry Pit Cave. Others likely exist at the facility. A copy of the map of Tow Cave (Figure 1) is enclosed. Although not within the NWSC property boundary, it is nearby. The good quality of this map and its relation to the regional jointing pattern (see rose diagram on the map) make it useful by depicting how jointing controls cave formation in the Crawford Upland.

General Aspects of Cave Development in the Area

Cave formation requires the flow of underground water that is of sufficiently aggressive nature to solutionally remove the bedrock and to keep the solutionally aggressive water in contact with the cave walls. This requires that the initial water movement follow a system of joints and/or bedding plane partings prior to cave development. Solutionally enlarged joints tend to produce fissure-like passages which can determine the pattern of nearly every passage in a cave. Intergranular pores are relatively unimportant in regard to cave development, but are significant in regard to permeability.

Tow Cave, Martin County, Indiana.

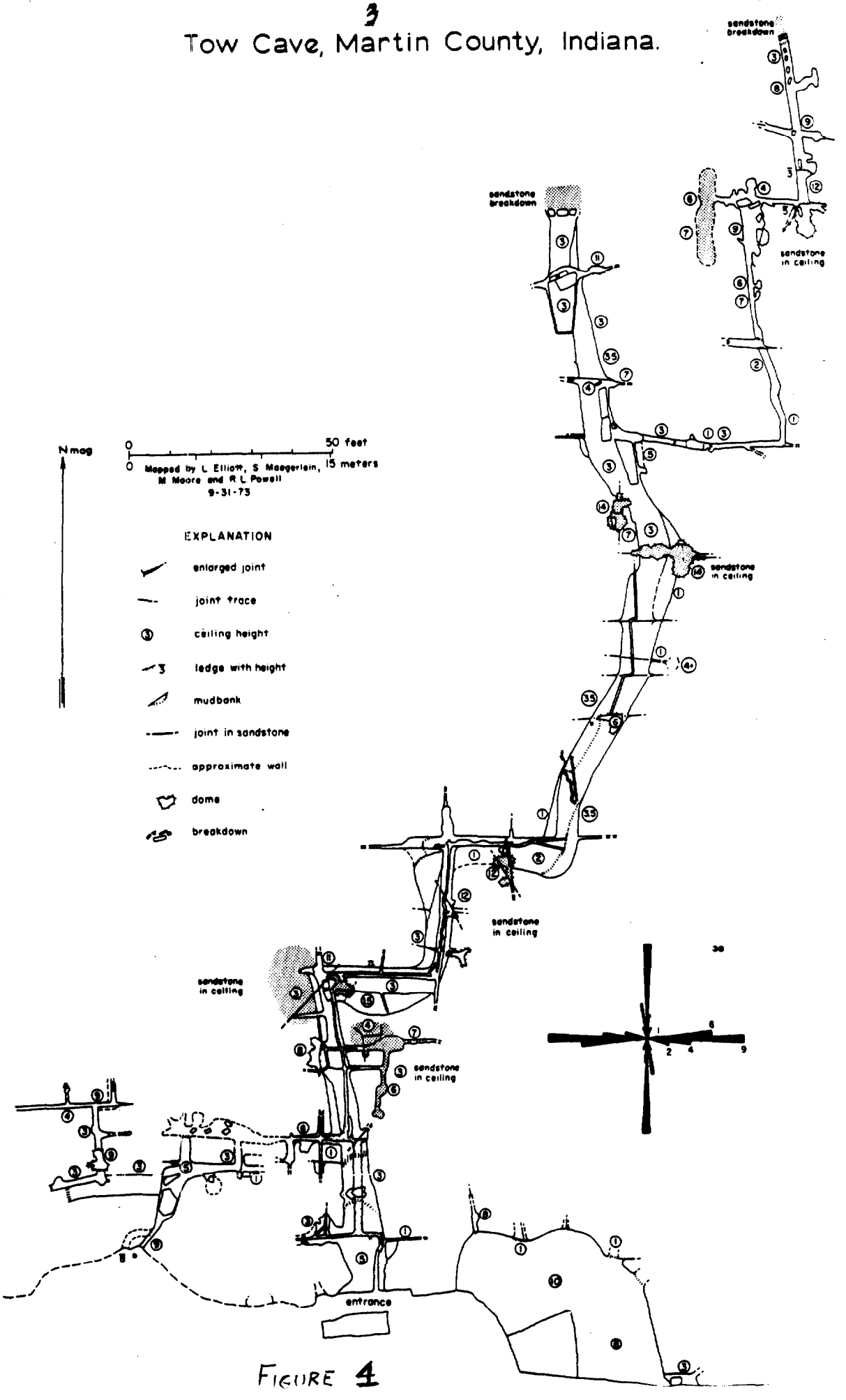

FIGURE 4

Caves are well adjusted to the present pattern of recharge from the land surface indicating that the upper part of the caves is formed in the vadose zone at the same time that the underlying parts are formed in the phreatic zone. The water table in a karst region is highly irregular and discontinuous because of the great variations in the size and distribution of subsurface openings and in the amount of water they transmit. It is crucial to note that water level records are only measures of the hydrostatic head in the diffuse-flow portion of the aquifer (see Attachment II), because it is highly unlikely that any wells actually intercept a cave. Infiltrating water concentrates along narrow paths within a given fracture, thus creating discrete conduits no more than a few feet or tens of feet in diameter rather than a myriad of amorphous interconnected openings. Flow through caves is therefore best described in terms of pipe hyraulics instead of by a continuous potential field.

Water movement in the vadose zone is governed mainly by gravity and capillarity with gravity being the most important in regard to those openings wide enough to enlarge caves. Therefore, vadose passages trend downward in the direction of flow, having been formed by water descending vertically along the steepest available openings. Vadose water descending vertically along a fracture or a cluster of intersecting fractures may eventually form a shaft which may range in size from a few inches in diameter and depth to tens of feet in diameter and hundreds of feet deep. Recharge occurs through surface pits, through an inclined vadose passage, or less commonly, through fractures in overlying insoluable rock. Passages at the bottom of a shaft (or shaft complex) drain the water.

Water in the phreatic zone forms a continuous medium, and its tendency to be drawn downward by gravity is offset to varying degrees by the downward increase in hydrostatic pressure. Phreatic water flow is greatest along the routes affording the greatest efficiency (least expenditure of hyraulic head per unit discharge). Caves form along these preferred routes, extending from where the incoming vadose water reaches the water table to where it emerges at a surface outlet at a lower elevation. A phreatic passage enlarges solutionally over its entire perimeter thus acquiring a smooth rounded cross section with an arched ceiling. Tubular passages and fissures with lenticular cross sections are most common. Only a small amount of solutional enlargement is needed for phreatic passages to become so efficient in transmitting water that the hydraulic gradients within them become very low (almost flat). Those that form entirely along the water table have barely measurable gradients.

Recharge Through Permeable Insoluable Rock

In upland areas where the limestone is capped by thin permeable sandstone, aggressive diffuse recharge is readily transmitted to the underlying limestone. Every major fracture in the limestone, regardless of width, receives comparable amounts of recharge of the same chemical character, allowing all fractures to grow at comparable rates in the initial stages. Fracture enlargement probably begins while the sandstone-limestone contact is still below the fluvial base level. At first, the sandstone has the higher permeability of the two rock types and most of the ground water flows through it. However, the small amount of water entering the limestone gradually widens the fractures until the limestone has the higher permeability. Much or most of the water then flows through the limestone, as the overall resistance to flow is less than through the sandstone alone. Uniform recharge continues to take place after the water table drops below the level of the cave.

A permeable caprock is not enough to ensure an equal distribution of recharge to all major fractures in the underlying limestone. Solutionally widened fractures must extend upward to the sandstone contact, and aggressive water must continue to enter through the caprock after the cave has become exposed above the water table.

In many sandstone-capped network caves, the water is channeled through joints in the caprock that are co-planar with those in the limestone. In this case the soil governs the flow to each joint. If diffuse flow encounters poorly jointed limestone, interstratal solution and complex systems of shafts and narrow canyons are formed. Small caves of this type typically occur in the predominantly bedded Girkin Formation (which contains the Beech Creek Limestone) where a sandstone cap of the Big Clifty Formation is particularly thin along plateau margins (such as the Crawford Upland).

Cave Formation in the Crawford Uplands

The Beech Creek Limestone being overlain by the jointed, permeable sandstone of the Big Clifty Formation and underlain by the relatively impermeable shale of the Elwren Formation has resulted in significant joint dissolution in the Beech Creek Limestone. Initially, ground water flow was induced by infiltration of surface water into the overlying sandstone. This infiltrating water was perched within the sandstone except where underlain by permeable joints in the underlying limestone unit, which accepts water from the sandstone. The release of ground water from the sandstone is regulated by transmissivity, amount of hydrostatic head within the sandstone, and the location and size of the open joints in the limestone.

Water infiltrating into the limestone through joints descends to unite with a perched ground water body within open joints in the limestone. This perched water body generally does not flow through the underlying shale; rather, the ground water will tend to flow on top of the shale layer. Discharge is via outcrop springs or seeps that are perched above the Elwren Formation which is dependent upon the amount of available ground water and joint solution development. It is important to note here that the United States is in the midst of a three (3) year drought, the worst of which occurred last year. Many of the springs and seeps identified at the ABG are probably flowing well below their potential or may not be flowing at all.

As ground water slowly seeps from the overlying sandstone into the limestone, a steeply sloping water table may develop in the limestone. Ground water flowing in open master joints tends to develop lower solution channels within the limestone more readily than do cross joints that do not extend through more than one bed without offsets from joints in lower beds. Although some solution channels will develop in the upper beds, ultimate control is by the position of the outlet.

Reports indicate that most cave streams in the Beech Creek Limestone have not dissolved or eroded through the lowermost beds of limestone which are commonly a very fine grained sparitic to micritic limestone, or rarely a calcareous sandstone. The stream progressively grades higher stratigraphically upstream from the spring outlet. It is also apparent that the caves developed in the Beech Creek Limestone appear to have initially developed a large solution conduit or cave passage above the basal unit.

Discharge of ground water from the sandstone is apparently most rapid and greatest into those joints in the limestone which are widest and provide the easiest release of water to the outlet. Most caves in the Beech Creek Limestone fed by ground water perched in the overlying Big Clifty Formation appear to closely parallel the outcrop of the limestone unit.

Cave entrances and solution-subsidence features in the area are associated with the top of the Beech Creek Limestone and the base of the overlying sandstone of the Big Clifty Formation, which illustrates the effectiveness of solution removal of the limestone where the water first contacts the carbonate rock. Several caves in the Beech Creek Limestone contain domes or shafts where continued seepage of water from the overlying sandstone has dissolved a vertical passage along a joint through the limestone. Collapse of the overlying sandstone into a pinnacled and channeled Beech Creek Limestone is thus a common occurrence (as indicated in the ABG geologic report).

Hydrogeology of the ABG Study Area

Overall, this section, especially the Middle Ground-Water Zone description, was exceptionally detailed and representative of actual site conditions at the ABG. Although the geologic report makes a strong case against possible interconnections in this section, the investigation should confirm the possiblity of, or lack of, interconnections.

The section on the Beech Creek Aquifer is consistent with literature on the aquifer and typical karst hydrological principles, but certain facts should be emphasized. All the available literature (published and unpublished), as well as the site geologic conditions would indicate that the Beech Creek Aquifer is in fact the one most likely to be transporting constituents away from the ABG site. The section on the local hydrological situation closely parallels the literature and includes a very good description regarding the recharge mechanisms operating at the site. In addition, several points are brought out. Page 38 of the geologic report explains that flow is primarily down the Little Sulfur Creek drainage way and secondarily down through the Johnson Hollow drainage way with a low ground-water divide separating the two discharge areas. This is probably accurate unless the three (3) year long drought has created an abnormal condition which is probably unlikely.

The next important fact is that surface water infiltrates the sandstone of the Big Clifty Formation which the geologic report claims is "...highly permeable and is capable of taking most of the water that comes in contact with its surface." Clayey alluvium in the area is said to retard the infiltrating water, but not too significantly. Therefore, rapid infiltration is to be expected.

A third important point is that surface runoff occurs from seepage out of the Gloconda/Haney Aquifer into the ABG valley and continues to flow over the Indian Springs Shale until reaching the sandstone of the Big Clifty Formation. This flow of water is to the east of the ground water divide and is therefore likely to flow towards Little Sulfur Creek.

The fourth and most important point is that surface runoff and two creek branches flow into the ABG site from the west and northwest to form the headwaters of Little Sulfur Creek. These branches join at the ABG, but sink into the ground a short distance from the ABG.

Fifth, Little Sulfur Creek remains dry (except under certain rainfall conditions) until Springs A, B, and C produce moderate amounts of water by discharge from the Beech Creek Limestone. The geologic report claims that these springs are outlets for solution conduits within the Beech Creek Limestone. Evidence for this statement occurs in paragraph 68 of the report, where observations of two of the springs after rainfall events showed greatly increased discharge and high turbidity. This is absolutely correct. The only thing this does not tell us is that no evidence yet proves that any connection exists between these springs and the ABG site. It is very possible that flow from the ABG discharges into Johnson Hollow although little evidence exists for this scenario (at least at present).

The final point made in the hydrogeology section of the report occurs in paragraph 66, which states that several springs "...issue from the Beech Creek along the Little Sulfur Creek Valley flanks south of the NWSC boundary." NWSC must identify potential outlets for contaminated ground water off-site, and assure appropriate corrective measures for any "plume" migrating off-site. This must be done through the tracer test proposed.

A generalized model for the area is shown in Figure 2. Condition A in the figure could be representative of the Golconda/Haney Limestone while B and C are indicative of probable conditions in the Beech Creek Limestone. Condition C is very common and is depicted on several of the cross sections contained in the ABG geologic report. Condition B, however has not been shown to exist in any of the cross sections. Although less common than condition C, condition B does occur with some frequency and should be assumed to exist beneath the ABG site. This would mean that it is quite possible that not all of the karst hydrological problems have been established yet.

5. Recommendations and Additional Work

Most of the work conducted to date was of a general geological and hydrological nature, but is still considered essential to the design of more focused studies. The exceptional quality of work conducted and the report describing such has provided the appropriate level of information necessary for designing studies leading to the definintion of the true ground water flow paths underneath the ABG site. The following items of additional work must be incorporated into the overall corrective action program.

a. Additional Borings and Wells

Additional cored borings and wells should be installed, as described in Recommendation C of the ABG geologic report, for the same reasons described in the report. These wells will also provide additional water quality monitoring data prior to any ground water exiting the NWSC facility. The addition of three wells, as discussed in the meeting betweeen USNC and U.S. EPA in May 1989, will determine the potential for any off-site migration towards the eastern boundary.

b. Soil Characterization

Both surface and subsurface soil must be characterized using the USCS and evaluated for hazardous constituent content. The extent of soil contamination must be defined, and will be used to determine fate and transport of any surface water and ground water contamination. This investigation shall be incorporated into the Corrective Action Plan (CAP).

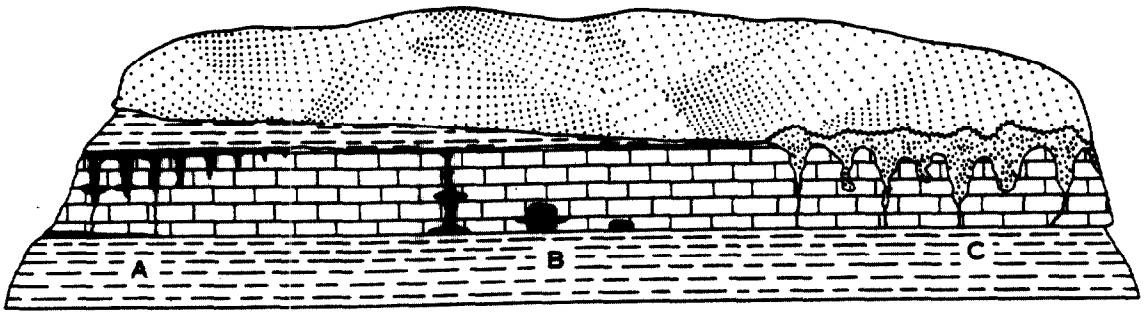

Figure --Three types of solution in limestone. A, limited solution near outcrop; B, deep-seated individual joint enlargement; C, general solution beneath sandstone collecting bed.

FIGURE 2

DOCUMENT: Ground Water Assessment Plan for the Ammunition Burning Grounds (January 24, 1989)

1. Overall Review

A typical assessment plan for the ABG virtually can not be completed. At this stage in the study, USNC began with a simple monitoring well system and has expanded the amount of wells to define the extent of contamination at the site. Due to the karst conditions in the downgradient directions, a tracer test to determine the flow paths was proposed (see review of the tracer test below). A staged approach of investigation is necessary, as discussed in the assessment plan. Once the flow is defined, wells may be selected for continued monitoring. After the plume is characterized, USNC will be required to do a Corrective Measures Study to determine what to do with the plume. Further studies at this point will be incorporated into the Corrective Action work being done under permitting.

DOCUMENT: Proposed Dye Tracer Tests in the Beech Creek Aquifer at the Ammunition Burning Grounds (April 3, 1989)

1. Other Permits Required

NWSC must submit a written request to the U.S. EPA Water Division to seek permission to conduct the dye tracer test, which involves injection of materials into the ground. The request must include the following:

a. The purpose of the survey;
b. A description of the type of facility, and ABG operations;
c. The general geology of the area; and
d. A detailed description of the procedures of the tracer test, including which wells will be used, construction oe the wells, springs monitored, emplacement areas identified, tracers to be used, and the schedule of the project.

As long as the dye tracer test is a short term event required by RCRA in order to define the ground water flow in the karst conditions at the site, and will not harm human health or the environment, the Water Division may be able to authorize the event under their injection rules for Class V wells. The request must be submitted to:

Mr. Edward P. Watters, Section Chief
UIC Section, Water Division
U.S. EPA Region V 5-WQS-TUB-8
111 West Jackson
Chicago, IL 60604

If you have any questions regarding the information to be submitted, contact Jessie Chiu, at (312) 886-1499, for assistance.

3. Method of Dye Injection

The proposed method of dye injection is satisfactory. USNC must make sure that sufficient quantities of water are used to flush the dye into the aquifer, and they must record the quality of water injected to assure that other hazardous constituents are not being added to the system.

4. Location of Dye Detectors

The proposed dye detector locations are adequate, but NWSC must place more detectors, if possible, in the Johnson Hollow well locations in order to assure that all possible discharge points are monitored.

5. Dye Detector Material

Dye detectors must consist of surgical cotton (tampons are a possible substitute) and activated charcoal. Most cotton is already treated with optical brighteners, but surgical cotton generally is not. All cotton detectors must be examined under a fluorescent light prior to use to ensure that treatment with optical brighteners has not occurred. Activated charcoal is necessary for the proper adsorption of fluorescent dyes. Any other charcoal will be incapable of adsorbing the dyes.

6. Detail of the Report

NWSC must expand on the details concerning the length of time necessary for a proper analysis of background fluorescence; and how the water withdrawn from downgradient wells for dye analysis will be managed and disposed of. Any water withdrawn from wells must be contained and disposed of properly if the ground water was previously found to contain hazardous constituents at that well.

ATTACHMENT II

THE VULNERABILITY OF KARST AQUIFERS TO CHEMICAL CONTAMINATION

Malcolm S. Field
U.S. Environmental Protection Agency
Office of Health and Environmental Assessment
Office of Research and Development (RD-689)
401 M Street, Southwest
Washington, DC 20460

Disclaimer: The views of this paper are those of the author and do not necessarily reflect the views of the U.S. Environmental Protection Agency.

ABSTRACT

Ground-water flow in karst aquifers is very different from flow in granular or fractured aquifers. Karst ground-water flow is often turbulent within discrete conduits that are convergent in the upper reaches and divergent in the lower, simulating the flow pattern of surface water streams that are dendritic or trellised but with discharge to one or more springs. Significant precipitation events tend to flood karst aquifers quickly, causing a rapid rise in the water table that may flood older, higher levels with discharge to a different set of springs. The epikarstic zone in karst terranes stores and directs infiltrating water down discrete percolation points. The vulnerability of karst aquifers to chemical contamination is a result of these unique characteristics.

Chemical contamination may be fed directly to a karst aquifer via overland flow to a sinkhole with little or no attenuation that may contaminate downgradient wells, springs, and sinkholes within a few hours to a few days. Contaminants may also become temporarily stored in the epikarstic zone for eventual release to the aquifer. Flood pulses may flush the contaminants to cause transiently higher levels of contamination in the aquifer and discharge points.

The convergent nature of flow in karst aquifers may result in contamination becoming concentrated in conduits. These contaminants can affect delicate plant and animal life that exists in caves as well as contaminate drinking water supplies too rapidly for adequate warning.

Key Words: Karst Hydrology, Chemical Contamination, Vulnerability

INTRODUCTION

Currently, there is a strong emphasis within the U.S. Environmental Protection Agency (EPA) to classify aquifers that are highly vulnerable to chemical contamination. Karst aquifers were identified as being highly

contamination than are the more common diffuse flow aquifers associated with granular or highly fractured terranes. This is true because of the unusual hydrological characteristics that develop in carbonate rocks that have been subjected to extensive karstification.

Four distinct features of karst terranes are responsible for the vulnerability of karst aquifers to chemical contamination. These are (1) scarcity and poor predictability of ground-water flow, (2) scarcity of surface streams, (3) instability of the ground surface, and (4) an unreliable waste-disposal environment (LeGrand, 1973). Each of these features has long been known to present significant problems to industrial site development in karst terranes, yet many chemical manufacturing companies routinely locate industrial plants in karst terranes. These chemical manufacturing plants usually have on-site underground storage tanks, incinerators, surface impoundments, container storage areas, or landfills. Chemical releases from these hazardous materials management areas are common.

Whereas chemical releases from chemical manufacturing operations and from highway accidents involving tanker trucks are relatively common, their effects on the environment are very poorly understood. Failure to note the specific attributes of the particular geological terrane in relation to a chemical release can result in very serious threats to human health and the environment. Chemical releases to karst terranes are not likely to behave in a manner similar to spills in granular or highly fractured terranes because of the unique features associated with karst terranes.

KARST HYDROLOGY

Ground-water flow in karst terranes is very different from that of granular or highly fractured terranes. In general, the slow, dispersive, laminar flow characteristics defined by Darcy's law are seldom in evidence in karst terranes. Most ground-water flow in most karst terranes is likely to be very rapid, convergent, and turbulent within discrete conduits (Quinlan and Ewers, 1985; Smart and Hobbs, 1986). To understand why a karst aquifer is vulnerable to chemical contamination, a basic recognition of the recharge, storage, and flow properties typical of most karst terranes must be established. The complexity of these three hydrological components is discussed in detail and are shown schematically in Figure 1.

Recharge

Recharge to a karst aquifer can take the form of concentrated input such as flow down a sinkhole (doline) or as diffuse recharge from seepage inflows over the entire extent of the ground-water basin. Flow down a sinkhole may feed directly to a significant conduit or, more commonly, feed small, inaccessible conduits that are tributaries to the main conduit drain (Gunn, 1986).

Both diffuse and concentrated recharge generally enter the epikarstic zone prior to recharging the aquifer. The epikarstic zone is a highly fractured and weathered portion of the bedrock immediately underlying the soil zone and separated from the phreatic zone by a dry, inactive, relatively waterless interval of bedrock that is locally breached by vadose percolation (Quinlan, 1986). Fissures in the epikarstic zone are widened by solution at shallow depths but close rapidly with increasing depth because of overburden pressure and reduced dissolution except for a few remote preferential vertical flow paths termed subcutaneous drains by Smart and Hobbs (1986). The epikarstic hydrology is related directly to these subcutaneous drains. According to Williams (1985), the subcutaneous drains developed more extensively than surrounding fissures because they were able to discharge larger quantities of water early in the process of karstification. The more freshwater discharged by the subcutaneous drains, the greater the extent of dissolution. Significant storm events tend to provide excess amounts of recharge to the epikarst, resulting in a temporary perched water table within the highly porous epikarstic zone. Owing to build up

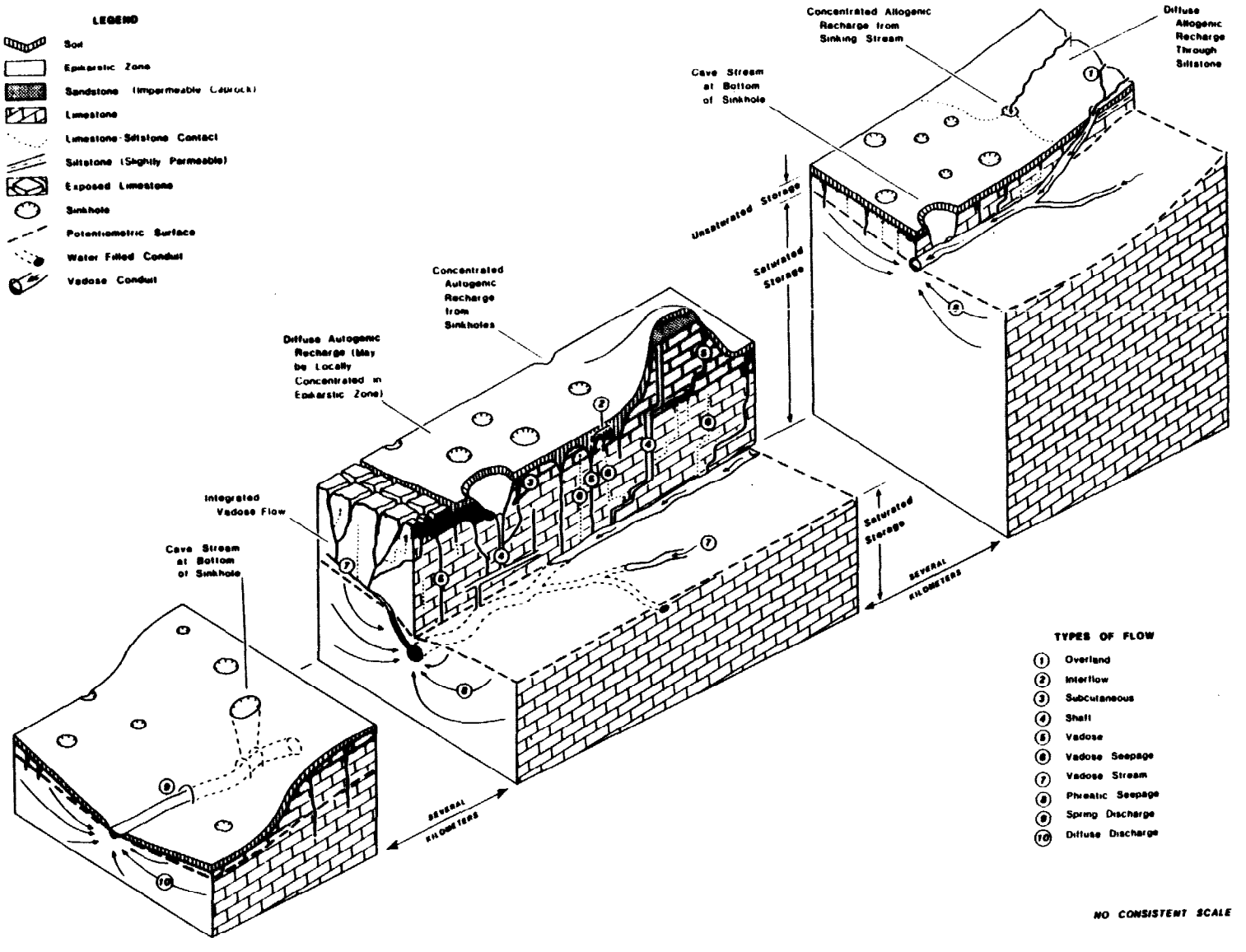

Figure 1. Block diagram depicting the hydrological relationships that exist in a maturely karsted terrane in gently dipping rocks of a low relief landscape. The cave stream is fed by: 1) sinking streams, 2) vertically percolating water infiltrating through soils and dolines (sinkholes), 3) tributary cave streams, and 4) seepage through conduit walls (after Quinlan, 1989).

in hydraulic head, the perched water flows laterally, according to Darcy's law, toward the subcutaneous drains. A depression develops in the epikarstic water table over these subcutaneous drains as the epikarstic water flows down these subcutaneous drains in a turbulent manner. This cone of depression is similar to the cone of depression that develops around a pumped well, except that the cone is extremely elongated. Friederich and Smart (1981) reported lateral flow rates on the order of 100 m/h, which would indicate that Darcy's law is not always applicable to flow in the epikarstic zone. Vertical flow down subcutaneous drains was shown to be in excess of 100 m/h, (at times, flow was as high as 600 m/h), whereas vertical flow down the smaller, less developed fissures was less than 50 m/d. Friederich and Smart (1981) concluded that the subcutaneous drains are responsible for the majority of aquifer recharge.

The lateral flow occurring in the epikarstic zone causes more corrosion at the subcutaneous drains because of the turbulent flow and because of the ability of the subcutaneous drains to take on more water than the surrounding fractures. The more corrosion that occurs, the more the vertical permeability becomes enhanced. This greater corrosion and enhanced vertical permeability also lead to the redirecting of soil water to the subcutaneous drains, eventually causing a catastrophic collapse of the overlying overburden (Williams, 1985).

Once a collapse sinkhole has developed, point-source recharge from above will produce a recharge cone (mound) rather than a cone of depression. This further results in directing recharge down discrete percolation zones such as vadose shafts, which are not part of the epikarstic zone. Vadose shafts are large cylindrical openings ranging in diameter from a few millimeters to many meters and are produced by vertically descending water. This vertically descending water spreads out in a thin film or spray which is responsible for enlarging the shaft. It is because vadose shafts usually appear in complexes that large quantities of water may be recharged to the main conduit system through vadose shaft flow.

Beyond the epikarstic zone, preferential flow paths develop along major vertical joints, faults, and bedding plane partings. Under the influence of gravity, subsurface water moves progressively downward to lower flow routes where the water may feed many different conduits over large distances. For this to happen, a vadose cave stream must leak through underlying fractures or bedding plane partings, some of which will become solutionally enlarged and thus take on all the flow. The important fact to recognize here is that as recharge reaches the phreatic zone it has generally done so in a concentrated form, but to several different conduits that may or may not become integrated along their length, thus causing some dispersion.

Flow

Ground-water flow in karst aquifers ranges between conduit and diffuse flow end members (Smart and Hobbs, 1986; White, 1977), the majority of which are characterized by intermediate members of mixed flow with one of the flow types predominating over the other (Quinlan and Ewers, 1985). Conduit flow occurs in large passages with relatively high flow velocities that result in turbulent flow conditions and an almost insignificant hydraulic gradient, all of which depend almost entirely on the local stratigraphy and structure. The highest flow velocities occur in open-channel vadose passages and less so in phreatic passages (Palmer, 1986).

As conduit flow becomes more dominant, a true water table ceases to be obvious as evidenced by the perching of some springs and the frequent overflow flooding that occurs in conduit flow dominated karst aquifers. This is not to say, however, that a water table does not exist in a karst aquifer. Karst aquifers dominated by conduit flow include diffuse-flow in-feeders which, when tapped by observation wells, allow the construction of a well-defined water table map (White, 1988, pp. 181-183). Diffuse flow occurs within tight fractures and small pores with relatively low flow velocities that are laminar and behave according to Darcy's Law. A much more significant hydraulic gradient occurs in diffuse-flow-dominated karst aquifers and can be accurately mapped if the

importance of conduit flow is recognized. White (1988, p. 182) points out that combining dye-tracing experiments with detailed cave mapping provides important information on the conduit flow portion of a karst aquifer, while water table mapping relates to the diffuse flow portion of the karst aquifer. If conduit flow analysis is combined with a water table map of the area, anisotropic flow (the flow lines will not be orthogonal to the equipotential lines) will become evident. In fact, it is very possible that some flow lines may even run parallel to the equipotential lines (Quinlan and Ray, 1981). This concept is so foreign to conventional wisdom as to be completely ignored in many ground-water investigations in karst terranes, which can lead to devastating effects from chemical contaminant releases because the flow route is incorrectly predicted.

In pollution monitoring of granular or highly fractured terranes, the importance of the hydraulic gradient in relation to Darcy's law is critical to identifying the flow rates and direction of the ground water, but Darcy's law is not valid when applied to karst aquifers because turbulent flow within discrete conduits is common in karst aquifers. Therefore, Darcy's law cannot be used to predict flow velocity in a karst aquifer; to do so is to commit a grave error in judgment, yet many ground-water investigations in karst terranes still rely on Darcy's law.

The importance of the hydraulic gradient in a karst aquifer still remains crucial to understanding the migration of chemical contaminants. Water flow through carbonate rock is more dependent upon variations in channel size than upon variations in discharge (Palmer, 1975). Imagine two adjacent flow paths of differing sizes in the phreatic zone that exhibit unequal hydraulic gradients along their lengths. The larger flow path will have a much lower hydraulic gradient while transmitting greater amounts of water. The consequence of this, especially for pollution monitoring, is that the less efficient flow channels will possess a steep gradient that is directed to the more efficient flow channel, but which is unlikely to be recognized from water level measurements alone.

Many investigations fail to accurately define the true flow paths in karst terranes because of an unfailing reliance on measuring the hydraulic gradient in observation wells. Methodology put forth by Quinlan and Ewers (1985) suggests that dye-tracing studies conducted to define the true flow paths will allow accurate monitoring for pollution studies to be conducted at springs rather than wells. Quinlan (1989) has now concluded that if dye-tracing to wells proves positive, then the monitoring of wells coupled with spring monitoring may also be appropriate. The rationale for this is that monitoring wells must intersect the major conduit(s) draining a basin, but the probability of this occurring is highly unlikely.

Recognition of only a single conduit draining a ground-water basin can be as serious as ignoring the existence of conduit flow altogether. Caves develop in stages, that is, through time the uplift of land surface and a lowering of the base level of nearby rivers will cause the ground water to progressively develop lower cave levels in an attempt to establish equilibrium with its surroundings. The result is a series of levels in the vadose zone leading to younger cave levels in the phreatic zone.

Head build-up in phreatic conduits from floodwaters entering the conduits can cause tremendous water level rises in observation wells in a few hours (Quinlan and Ewers, 1985; Milanović, 1981, pp. 128-132) and additional ground-water divergence (Palmer, 1986). Because head build-up in phreatic conduits is much greater than the less efficient flow passages, the hydraulic gradient leading to the phreatic conduit inverts. Now water is forced under very steep gradients back into all available openings in the rock formation and up into older, higher levels in what are usually vadose passages. This water is then discharged from ephemeral perched springs or forms a temporary bank storage within the rock matrix for release to main conduits once the flood pulse begins to subside.

Conduits are excellent traps for many things, the most common being sediment (Palmer, 1984). This clastic sediment may shield the conduit floor from further dissolution. Due to the insoluble nature of the clastic material, chemical contaminants may flow along this bed of quartz sand and clay minerals (White, 1988, p. 400). Adsorption and desorption by the clay particles then become

significant in the rate of contaminant releases.

Discharge of karst water occurs as divergent distributaries which is a result of the periodic fluctuation of the water table. This is evident in the change that occurs from low flow to high flow. Rapid flooding during high flow with a corresponding hydraulic gradient increase causes the water to follow alternate routes in an effort to find the most efficient flow route for eventual discharge (Palmer, 1986). Clusters of springs usually represent multiple levels of overflow routes for water in the same catchment area. Adjacent springs are not necessarily draining the same catchment area, however.

Discharge will be divergent and to distinct springs that may exceed many cubic meters per second each. Milanovic (1981, p. 84) reports that the capacity of springs is dependent mostly upon surface catchment area and the active volume of the aquifer. Recognition of this fact emphasizes the ability of a karst aquifer to concentrate flow and discharge to discrete points. Drainage basin mapping by dye-tracing and water table measurements are essential to accurately define the hydrology of a karst aquifer, which is a necessary requisite to determining the extent of contamination from spills in a karst terrane.

Storage

Although storage in granular or highly fractured terranes is often difficult to accurately assess, storage in karst terranes is far more complex. This difficulty is partially due to the confusion regarding the hydrology of the phreatic zone, but it is also due to the complexity of the hydrology of the vadose zone. Essentially, four zones of storage exist in karst terranes, each with varying degrees of significance that are never the same from one karst terrane to the next. These four storage zones are the overburden, the epikarstic zone, the phreatic conduits, and the saturated rock mass (Gunn, 1986).

Storage, or soil moisture, in the soil zone has long been recognized as an important factor in the hydrology of a particular area, especially in the soil science literature. Soil moisture is the water content of the pores in the soil zone that is retained against the force of gravity. The two most important forces acting against the influence of gravity are adsorption and capillarity, both of which are molecular forces (Kovács, 1981, p. 209; Hillel, 1980, p. 150).

Water in the soil zone is still capable of movement but under a negative pressure gradient. During storm events the soil zone becomes fully saturated and begins releasing water to the underlying water table. As the soil desaturates, some of the pores become air-filled, and the hydraulic conductivity decreases and tortuosity increases (Hillel, 1980, p. 197), thus restricting infiltration.

It is not the intention of this paper to review the extensive literature available on soil water storage. Suffice it to note that large quantities of water will become stored in the soil zone, which controls the infiltration of water to the phreatic zone in most geological terranes. The infiltration of soil water will be through the tortuous pathways of soil pores that are not completely blocked by soil gas and by the occurrence of macropores in the form of root zones or soil fractures. Karst terranes are an exception to the regulating effect of the soil zone on recharge to the phreatic zone.

Recharge to karst aquifers commonly occurs as point sources at sinkholes and other types of drains that tend to diminish the importance of the soil zone on storage. This fact must not be ignored when investigating chemical contamination of karst aquifers. At the same time it must be remembered that the soil zone still regulates enough infiltrating water to have a controlling effect on the saturating of the epikarstic zone.

According to Smart and Friederich (1986), storage in the epikarstic zone initially appears to be very large and can easily be accommodated in a 3-m deep layer of about 0.01 specific yield, while the next 6- to 10-m layer (which in this context is not part of the epikarstic zone and is termed the transmission zone by Smart and Friederich) has a specific yield of only 0.001, which is more than adequate to handle the rest of the unsaturated zone storage. The difference in specific yields is directly attributable to the difference in permeabilities. A relatively high permeability in the epikarstic zone is responsible for rapid

drainage of stored water, which causes high rates of recession and a flashy flow regime. Alternatively, the transmission zone drains much more slowly because storage occurs in fissures and fractures with little solutional development. Water is held in the tighter fractures and fissures by surface tension through Van der Waals forces in the same way that water is retained in the soil zone. Because the epikarstic water flows toward and drains down the subcutaneous drains into the transmission zone where vadose shafts dominate, and because permeability is greatly reduced in this zone, the rate of recession is greatly reduced.

Naturally, storage in the epikarstic and transmission zones is unrelated to water table measurements and aquifer testing in the phreatic zone, yet as explained above these two zones can account for very large amounts of storage in karst terranes. For chemical contamination investigations in karst terranes, this is an essential factor that must be realized. The retention of large quantities of water in the vadose zone very easily translates into storage of large quantities of chemical contaminants when these are released in karst terranes. Some of the storage mechanisms will be the same for chemicals as for water, but many other retention mechanisms unique to the physicochemical parameters of the specific chemicals released will also be responsible for chemical storage in the vadose zone.

Storage within phreatic conduits is often considered to be minimal, which may or may not be true. The problem of defining the amount of storage in phreatic conduits relates to the inaccessibility of perennially flooded conduits. If a pumping well were to intercept one of these phreatic conduits, storage would still be difficult to define because of the tiny diameter of the well bore relative to the phreatic conduit. A pumping well installed in a phreatic conduit will result in almost no drawdown, whereas a pumping well installed just a few meters away from a phreatic conduit may yield only minimal amounts of water (White, 1988, pp. 186-189; Milanović, 1981, pp. 235-237). Quite often, blockages or low flow conditions can result in storage in phreatic passages, but in no way does this storage even begin to match that of the vadose zone or rock matrix in the phreatic zone.

CONTAMINATION

Much of the previous discussion dealt with the hydrology of karst terranes because of the need to understand the basics prior to recognizing the reasons underlying the vulnerability of karst aquifers to chemical contamination. Chemical spills in karst terranes will be stored and transported in many ways that are very similar to the storage and flow of water in karst terranes, but it is necessary to relate the hydrology of karst terranes to public health and the environment to establish the extent to which karst aquifers are vulnerable.

A popular misconception suggests that a karst aquifer will rapidly flush chemical contaminants out and thus will have cleansed itself. Admittedly, large chemical spills will be rapidly transported from a zone of recharge to a discharge point (on the order of several meters per day to several meters per hour), but very large quantities of the chemical may be stored throughout the subsurface either through geological means or through some physicochemical means. According to work conducted by Kurtz and Parizek (1986), a disposal site in the Nittany Valley of Pennsylvania has released several contaminants that have become stored and are slowly being released from unsaturated soil and bedrock and are likely to persist for many years.

Initially, chemical releases will either infiltrate the soil zone (if present), flow overland to run down a sinkhole, or enter a nearby stream that sinks to the subsurface somewhere along its route. If released to a soil-covered area, the chemicals will be somewhat retarded in their downward migration depending on their physicochemical parameters, but can still be expected to migrate to an underlying aquifer. Sorption to microparticles will actually do little to prevent downward migration of chemical constituents because transport of the microparticles themselves occurs very readily in all types of terranes, but especially so in karst terranes. Lyman and Loreti (1987) report in what they call "real-world applications" of their work on sorption coefficients that some

highly sorbing chemical constituents may be very mobile because of the natural mobility of soil particles. In karst terranes this effect is magnified many times by the existence of very large vadose and phreatic cave passages and their attendant ability to transport very large materials.

If a soil zone is absent, then contaminants will readily flow down the exposed karren features with essentially no retardation whatsoever. This exposed zone is the epikarstic zone, the surface of which is fully visible to the naked eye. Once in this zone, chemical constituents will become sorbed to the limestone walls and to any soil particles washed down from an overlying soil zone (if one is present). This zone can effectively retain the released chemicals for many years, slowly releasing some during significant recharge events to continue supplying contaminants to the underlying aquifer (Even et al., 1986). The bulk of the released chemicals will probably reach the aquifer through the same recharge mechanisms that affect the flow of water to the aquifer.

Upon reaching the epikarstic zone, chemical contaminants will either flow relatively freely or will be stored until a significant storm event flushes portions of them into the epikarstic water table. Once in the epikarstic water table, these chemicals will flow toward the subcutaneous drains for rapid transport to the underlying aquifer. If these chemical contaminants reach the transmission zone via some mechanism other than by a subcutaneous drain, then long-term storage characterized by the specific partitioning of the released chemical will dominate the rate of release. If, however, the chemical contaminants reach any vadose shafts underlying the epikarstic zone, then transport of the chemicals to the aquifer will be virtually unimpeded.

These same factors can be expected if the released chemicals flow overland to run down a sinkhole. Because most sinkholes are a result of collapse of the soil zone over karren features, little retardation can be expected. Quite often, sinkhole bottoms have large quantities of soil which will help in retarding flow, but more often they are direct feeders to underlying karren features that include subcutaneous drains.

Spills to sinking streams will dilute the chemicals to a certain extent, but these sinking streams are also vadose cave streams that generally flow down the dip as vertically as possible to gain the phreatic zone where hydraulic gradient takes over. Streams transport large amounts of sediment that will sorb some chemical constituents. Because these sediment particles are still being transported, sorption to them does little to retard contaminant transport.

None of the above takes into account the likelihood of immiscible contaminants in the subsurface in that they will probably behave in a manner very different from the subsurface water. Palmer (1986) points out that the density differences of certain chemicals, such as light nonaqueous phase liquids (LNAPLs) will cause chemicals to float on water surfaces, and that dense nonaqueous phase liquids (DNAPLs) will tend to sink to the bottom of the aquifer. In karst terranes, LNAPLs will not be very susceptible to the effects of dispersion caused by the bifurcation of vadose water along various routes, thus allowing contaminants to become concentrated in major active conduits. Because the LNAPLs will float on water surfaces in water-filled passages that become constricted during floods, rises in the water surface will cause a decrease in velocity, drive contaminants into the surrounding rock matrix, and drive the contaminants up into older higher levels. DNAPLs will tend to sink rapidly and to collect as sludges at the bottom of deep pools and to sorb onto microparticles. These contaminants will also be driven into the rock matrix during flooding and will thus be retained for long periods.

Flooding will also drive portions of these contaminants out of the rock matrix and into the main conduit for rapid transport. Sampling experiments conducted by Quinlan and Alexander (1987) showed that storm events flush contaminants out periodically for discharge, so sampling of spring waters should be accelerated during storm events and be continued at a lesser rate during the flood hydrograph recession.

A special emphasis must be placed on the likelihood of sinkhole development underneath an existing disposal unit that is either synthetically lined or unlined. Man-induced sinkhole development, mostly through pressure head changes, is quite common in karst terranes. Excessive ground-water pumpage (Beck and

Sinclair, 1986) or directing storm water runoff down existing sinkholes (Crawford, 1984) has been known to stimulate additional sinkhole development for many years. Loading, such as the construction of retention basins, has also caused substantial sinkhole development.

Owing to the lateral flow of water in both the soil and the epikarstic zones, sinkholes cannot be prevented from developing by attempts to restrict storm water infiltration at sites. Lateral through-flow can allow water to travel distances in excess of hundreds of meters and may even exceed a kilometer or more.

Collapses of surficial materials beneath disposal units usually result in rapid transmittal of potentially toxic wastes to underlying karst aquifers via subcutaneous drains while still leaving substantially large portions of the waste in vadose storage. Leaching tests and other forms of evidence showing that chemicals cannot leach to the subsurface are inapplicable in these circumstances. In fact, leachate collection systems underneath land disposal units may induce sinkhole development beneath the unit if for some reason a leak develops in the system. The resulting discharge of leachate, besides contaminating the subsurface, will slowly transport the clastic supporting material away, thus causing a collapse to occur.

Another form of ground-water contamination associated with sinkholes is their continued use as disposal units. Farmers sometimes conveniently dump empty pesticide containers and the carcasses of livestock into sinkholes. Other places have actually utilized large sinkholes as landfills for municipal and industrial waste disposal. This practice is equivalent to dumping potentially toxic materials into a funnel leading to a water supply pipeline. Owing to the efficiency with which transport may occur in karst terranes, this analogy is not too unrealistic.

VULNERABILITY

The vulnerability of karst aquifers is a direct result of the above discussion on the hydrological and chemical release aspects of karst terranes and the relation of human health and the environment to karst terranes. Ground water is very often utilized for drinking water supplies because of the scarcity of surface water supplies. Therefore, contamination of the subsurface of a karst terrane and its effect on human health are easily recognizable. Other forms of contamination, such as toxic fumes, have only recently come to light. The threat to the environment is much less recognized, because few people know of the very delicate forms of life that have evolved through eons to exist in cave environments.

Because chemical releases in a karst terrane, in general, are rapidly transported to discharge points, a false belief that the karst aquifer will quickly flush itself is perpetuated. True, in most karst aquifers, most chemical releases are transported rapidly through the system, but storage within the vadose and phreatic zones must not be ignored. It has been established in this paper that the epikarstic zone has the capability to retain large quantities of chemical constituents for very long periods while slowly releasing them to the underlying aquifer. Both the transmission zone and the rock matrix within the phreatic zone contain diffuse feeders to conduits that may also retain large amounts of chemicals. Chemicals with high sorption coefficients will be retained irrespectively of the karst geology.

What needs to be recognized most clearly is that a chemical release may have a serious impact on downgradient drinking water supplies within a few hours and that the drinking water supplies may remain seriously impacted for many years. These drinking water supplies, whether for human beings or for livestock, must be restricted from use immediately following a spill in the respective catchment area. Since a conduit system tends to concentrate flow as opposed to dispersing flow, chemical contaminants will likely become very concentrated in conduits feeding drinking water supplies. Stroud et al. (1986) have reported gasoline fumes from leaking underground storage tanks are so high in the Lost River Cave System under Bowling Green, Kentucky, that even a flame would become snuffed out owing to a lack of oxygen. As ground water transports toxic chemicals into the

cave system, volatiles from the chemicals are released to the cave environment to become very highly concentrated. Stroud et al. rightly point out that if these fumes were ever to ignite, the resulting explosions could travel throughout the cave system, thus destroying overlying homes and other structures. These toxic fumes also rise up to concentrate in basements. The levels of concentration in basements are high enough to require venting (Stroud et at., 1986).

Human Health

To gain insight into the magnitude of the threat posed by chemical facilities located in karst terranes, imagine a large, lined lagoon containing approximately 10,000 liters of a liquid hazardous material. Sinkholes are naturally occurring in the area, but surface loading by the lagoon has increased the potential for sinkhole development. According to federal and state regulations, an approved ground-water monitoring system consisting of ground-water monitoring wells has been installed at the sight; no contamination problems have ever been shown to exist. One day, a sinkhole 2 meters in diameter develops beneath the lagoon. The underlying clay layer has already been removed by lateral through-flow, and the thirty-mil liner cannot support the weight of the liquid. Now imagine a toilet flushing waste to an underground sewer system, and the similarities become evident except that an underlying cave system may be supplying drinking water to a local community. Some of this material may become trapped in the epikarstic and transmission zones, while a very large portion will flow by the quickest route possible to the nearest discharge point. If this discharge point happened to be a very large spring or well field that is used for municipal water supply, a major health crisis could be the result.

Now suppose a large number of underground storage tanks are concentrated in a karst area. Some or all of them may begin leaking, but the leaks will be slow enough as to prevent immediate detection of a developing problem. In the above scenario, the collapse beneath the lagoon by sinkhole development could not go unnoticed. In this scenario, the contamination of the karst area may not be as immediately severe. However, the likelihood that the releases may go unnoticed for many years could result in the local population taking in very concentrated doses of toxic chemicals for very long periods prior to identification of the release.

Environment

Too often the threat of contamination fails to account for the effect on the ecological communities in the affected area. Life forms in and around caves are very diverse and unusual. To ignore the effect of chemical spills on life forms associated with cave passages and their respective points of inflow and resurgences is equivalent to allowing mass destruction of some endangered species.

To understand why cave life is more vulnerable to chemical contamination than are life forms that exist on the earth's surface, it is necessary to recognize the conditions under which cave life exists. Obviously, the most striking characteristic related to cave life is the prevalence of absolute darkness beyond the mouth of the cave. A second characteristic important to cave life is the existence of an almost uniform climate. Except for slight variations in barometric pressure and carbon dioxide partial pressures, the atmosphere in a cave rarely changes (Moore and Sullivan, 1978, p. 87). Temperatures seldom vary more than 5 to 10 degrees throughout the year. Humidity is extremely high in most caves associated with ground-water flow. Water is constantly running down cave walls and dripping from ceilings. Moore and Sullivan (1978, pp. 87-88) show that some aquatic cave organisms are capable of actually crawling up cave walls and surviving on the ceiling of humid caves. Some caves are excessively dry, and no life exists in them during present day conditions.

Because of the very special environmental conditions of natural cave systems, adaptation by various cave organisms is necessary for survival. In certain

instances, regressive evolution (Culver, 1985) is the result of this adaptation. Examples of regressive evolution in a cave environment are the loss of eyesight and pigmentation by cave fish. An example of progressive evolution in a cave environment might be development of improved olfactory organs or extended feelers.

Noting the fact that caves are somewhat limited in distribution and that there is a paucity of life forms capable of survival in this unique environment, it should become apparent that cave environment ecology cannot endure any excessive stresses. A sudden influx of a toxic chemical could have a devastating impact on any of the life forms in the cave. Because chemical spills in karst terranes are likely to become highly concentrated in a phreatic cave, various aquatic cave species will be overwhelmed by the influx of any toxic chemicals. Cave organisms that tend to exist in the older higher vadose cave levels will not be spared from this assault, however. Chemical contaminants can be expected to flow along the vadose passages prior to descending to the lower phreatic levels. Storm events will flood the older higher cave levels, thus carrying these chemicals back up into vadose passages. Crawford (1988) reports that after just such a flooding event in the Lost River Cave System underneath the city of Bowling Green, Kentucky, a film of chemical contamination was left on the walls of the cave (similar in appearance to a bathtub ring) after the flood pulse receded. Toxic chemicals that are also volatile in nature will produce toxic fumes that will rise up into higher cave passages and suffocate the cave life.

Many forms of wildlife, domestic animals, and plants utilize points of inflow and resurgences for drinking water because of the scarcity of surface water bodies. Chemical spills are likely to flow overland or along losing streams to karst inflows. Plant and animal life coming in contact with the spilled chemicals could be seriously affected. Although distributary flow at the terminus of cave streams is common, the convergence of flow in phreatic caves is still sufficient enough to produce highly concentrated discharges of toxic chemicals that could have a devastating effect on the local ecology. Crawford (1988) describes an instance where a naturally occurring cave resurgence was being utilized as a duck pond. One day the ducks walked down to the pond, took a few sips of water, walked a few steps away from the pond, and died. A U.S. EPA official later burned his hand in this duck pond while collecting a water sample for analysis. Dye-tracing subsequently determined the chemical contamination to be emanating from an underground storage tank upgradient several kilometers from the contaminated duck pond. Such and extreme concentration of toxic materials in the duck pond from a single source would indicate that the chemicals were transported by a cave system. Any life forms in the cave system were probably overwhelmed by the intense concentration of the toxic chemicals as well as any surface life forms utilizing the pond for drinking water.

SUMMARY

Karst aquifers are highly vulnerable to the effects of chemical spills because of the unique geologic features associated with karst terranes. Sinkhole development and a lack of recognition of karst hydrological principles by man can allow chemical contaminants to rapidly infiltrate into the subsurface environment. Vadose storage and flow to phreatic conduits tend to concentrate contaminants for discharge at relatively few points. It is this ability to store and transmit large quantities of highly concentrated chemical contaminants to select discharge points that makes karst aquifers so sensitive to the effects of chemical spills. This unusual form of chemical transport and storage readily translates into very serious threats to human health and the environment.

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