TECHNICAL GUIDANCE DOCUMENT

INDIANA DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

Proper Investigative Techniques in Karst

Office of Land Quality

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Notice

The Technology Evaluation Group (TEG) completed this evaluation to address the issue of proper investigative techniques in karst. This evaluation offers suggestions of what may be effective strategies for dealing with this issue. It does not approve any technology nor does it verify any technology's effectiveness in conditions not identified here. Mention of trade names or commercial products does not constitute endorsement or recommendation by the IDEM for use.

Introduction

Karst is defined by the United States Geological Survey (USGS) as:

> "A terrain generally underlain by limestone or dolomite in which the topography is chiefly formed by the dissolving of rock, and which may be characterized by sinkholes, sinking streams, closed depressions, subterranean drainage, and caves. [1] The term karst unites specific morphological and hydrological features in soluble (mostly carbonate) rocks. Morphological features (see the karst term glossary for definitions) include; sinkholes, caves, caverns, etc. Hydrological features include; basins of closed drainage, lost rivers, springs, submarine springs, more or less individualized underground streams, and incongruity of surface and underground divides. Karst is understood to be the result of natural processes in and on the earth's crust caused by the solution and leaching of limestones, dolomites, gypsum, halite, and other soluble rocks"[2]

Environmental investigations in karst areas present unique problems. Conventional site investigation methods and installation of monitoring wells may not provide an accurate picture of how contaminants behave in a karst aquifer. Because of the very different morphological and hydrological features, investigations in karst do not typically employ the same techniques used in site characterizations conducted in non-karst environments. This guidance can assist in the development of CSMs for sites located in a karst areas.

KARST OVERVIEW

In Indiana, areas with limestone and dolomite bedrock are susceptible to karst formation. Karst terrains are found throughout Indiana. Karst is present at or near the surface in at least 30 Indiana cFigure 1 is a map with the shaded counties affected by karst.

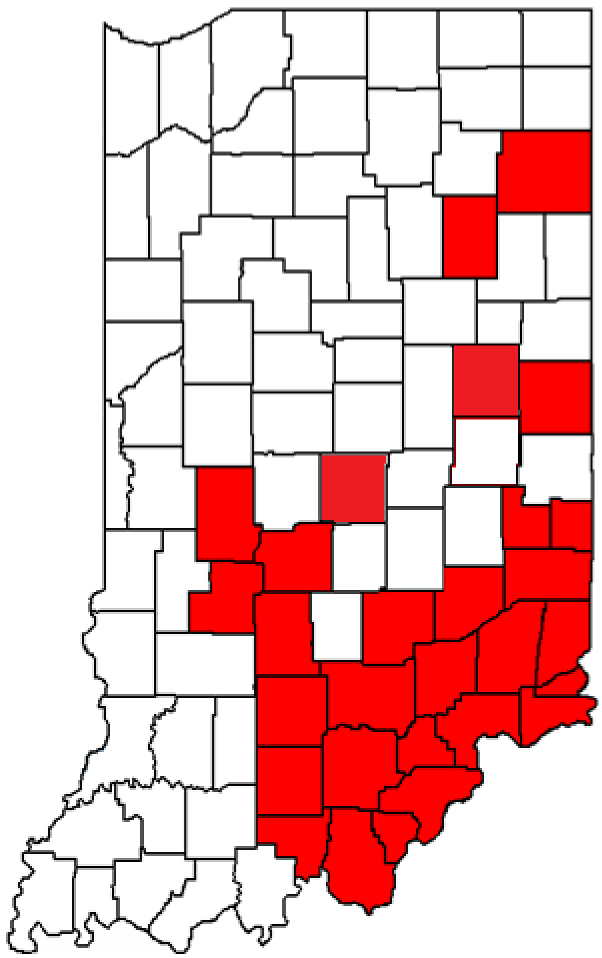

Figure 1

The 30 Indiana Counties are:

1) Allen
2) Huntington
3) Randolph
4) Delaware
5) Fayette
6) Union
7) Franklin
8) Dearborn
9) Ohio
10) Switzerland
11) Jefferson
12) Ripley
13) Decatur
14) Bartholomew
15) Jennings
16) Jefferson
17) Scott
18) Clark
19) Floyd
20) Harrison
21) Washington
22) Jackson
23) Putnam
24) Owen
25) Marion
26) Morgan
27) Monroe
28) Lawrence
29) Orange
30) Crawford

A karst study should begin with a review of the basic concepts of karst formation:

1) **If the bedrock material is made of limestone or other types of carbonate rock; there is the possibility that a karst aquifer could be present.**

   Even if a significant thickness of unconsolidated material exists above the carbonate rock, a karst conduit aquifer could still exist. For example Marion County bedrock includes buried karst that is often 70 to 90 feet below the surface (Fleming, Brown, and Ferguson, 2000)...

2) **The openings (i.e. sinkholes) and conduits are not formed from the disintegration of rocks, but as a result of the dissolution of carbonate bedrock.**

   This process occurs when slightly acidic ground water flows through fractures or along bedding planes in the bedrock and dissolves it.

3) **The dissolution of carbonate rocks is an ongoing process and needs to be factored into long term risk evaluations.**

   Karst by nature is unstable, because the carbonate rock is in a constant state of dissolution. Risk calculations cannot assume that karst will remain stable. This is one of the main reasons why new landfills and treatment storage and disposal facilities should not be located in karst areas.

4) **Ground water in a karst terrain does not behave in the same manner as ground water in a porous medium.**

   Flow in karst aquifers is based on conduit or fracture flow, therefore Darcy's Law does not apply. Darcy's Law is an equation used to predict flow velocity through a porous material, given a hydraulic conductivity for that material. Since water in karst flows through fractures and/or conduits in the bedrock, the use of the hydraulic conductivity of the rock will not accurately predict the flow velocity for the karst aquifer. The fractures may plug with clay and close, or suddenly open; the drainage system is constantly changing. There are also possibilities that fractures and sinkholes from the surface could create a direct conduit to the aquifer. If this is the case, contaminants could enter the aquifer at full strength and not leach through soils and unsaturated materials. However, when fractures and sinkholes are filled with soil and a release occurs that drains into them, the soils will adsorb most of the contamination and then act as a continuing source. Over time the soils erode away and enter the karst system along with the contamination.

The most common way to measure ground water movement in a porous aquifer is with a slug test. Comparisons between slug tests and dye tracer tests in karst aquifers have shown that slug tests are not a valid way to calculate ground water velocity in karst. Results show that ground water flow is as much as five orders of magnitude greater than slug tests results predicted.

5) **Vapors, in addition to free phase liquids (product) and dissolved phase contamination, behave differently in karst aquifers. The potential for vapor migration needs consideration when evaluating the risk.**

If contamination (i.e. free product, vapors, or contamination adhered to colloids) enters the karst system, it is possible that a vapor or gas phase of contamination could develop (much in the same way a release to a sewer system behaves). This is possible because most conduits in karst systems are not completely filled with water. As the water cuts deeper into the bedrock it will leave behind stranded channels that will be dry and may only be wet during storm events. Vapors and gases from contamination can migrate to these areas. If there is an outlet to the surface these vapors or gases may migrate to a receptor.

6) **Low contaminant levels in soils do not necessarily mean that low levels are in the ground water.**

Since it is possible that soil macropores (fractures in soils) exist, and that soil sampling may miss these features; assume (until proven otherwise) that the ground water is contaminated.

7) **Lack of surface expression does not mean the area in question is not in karst.**

There are areas in Indiana where, at the surface karst development is not apparent. This is usually due to a thick soil cover or the area was filled for redevelopment. Over time, sinkholes can become filled in with soils and sediments. Even when a sinkhole is apparently filled in, water can still flow through and leach out or directly carry surface or sub-surface soil contamination into the karst aquifer. Even worse, a sinkhole could suddenly open, swallowing all above.

8) **Karst systems can carry suspended solids with attached contamination.**

Most investigations do not consider the suspended solids in water exiting springs. When springs are tested, this major contaminant transport mechanism is usually overlooked. This can be a major problem when analyzing for contaminants that prefer to stay attached to suspended solids. Metals and PCBs are two examples of contaminants that will stay attached to the particles in the suspended load. Field filtering water removes suspended soils, and with them a major portion of the contaminant. Since suspended load can be a significant exposure pathway, field filtering is not recommended in karst areas.

9) **Contaminant concentrations can vary greatly depending on flow rates and rainfall amounts.**

Unlike granular aquifers, there is an almost immediate response to rainfall in karst aquifers. Most karst aquifers do not have a defined plume at a consistent concentration level. For example a spring may have a normal discharge rate of 20 gallons per minute (gpm) and a contaminant concentration of 2 parts per billion (ppb). However, after a rain fall event the discharge rate may increase to 200 gpm and the contaminant concentration to 400 ppb. To determine the total risk, sampling is needed at both base and storm flow.

10) **Ground water flow directions may not be apparent and can change direction during storm conditions.**

C conduits fill with water which flows to areas that are normally dry during precipitation events. These dry conduits may connect to springs and seeps that do not flow during low flow conditions (these types of springs are called over-flow springs). Water can also fill up a conduit system enough to cross drainage basin boundaries. Therefore when evaluating karst, both base and storm flow conditions need to be studied.

11) **Monitoring wells are of limited use in karst areas.**

Contamination may not be detected unless the right conduit is intersected at the right location by a monitoring well. For this reason, sites in karst areas are investigated in a different way (i.e. by sampling the outflows). If precautions are taken, it is possible to install useful monitoring wells in karst areas. An understanding of local karst ground water flow is needed for placement of wells.
When monitoring wells are proposed, follow the listed procedures below:

A. Placement of Monitoring Wells

Monitoring wells installed in karst need to measure the wide range in water level fluctuations that occur. The fluctuations are the result of water entering the system through discrete high-permeable zones. Monitoring wells in karst need to monitor all of these zones. Since most of the high-permeable zones occur along bedding planes, knowledge of the local stratigraphy is helpful. In addition to knowledge of the area stratigraphy, video logging of borings (done prior to installation of the well) can be useful. These logs can identify the high –permeable zones that need monitoring.

B. Accurate Well Logs

An accurate log is key to identifying the high-permeable zones. Logs should include at a minimum:

1. The location of zones where circulation (if drilling fluids were used) or air pressure (if air was used) was lost;
2. Where enhanced volumes were obtained during well development; and
3. Where open or mud-filled cavities were encountered.

C. Soil Bedrock Interface

The area at the soil/bedrock interface (epikarst) is important in the transport of contaminants. The investigation should include wells which straddle this zone. The epikarst may be dry during base flow conditions. Wells should be gauged and sampled after rain events (storm conditions). Monitoring this zone is important. Place the epikarst wells in the source area of contamination.

D. Additional Tests

Once the monitoring wells are installed, the hydraulic connection between the wells, source area, and the identified springs is determined. This can be done in two ways:

1. Hydraulic tests; or
2. Dye traces.

ELEMENTS OF A KARST INVESTIGATION

A karst investigation is usually conducted in phases (listed below). The sections provide the iterative steps in the process. It may be possible to collect the data needed without completing all of the steps:

1) Identification of karst in the study area

A. Direct observations may be used to determine if a karst system exists beneath the site.

B. Conduct a literature search to determine if any information exists about the subsurface conditions. Information commonly available includes:

1. Stratigraphic cross sections from previous studies (site specific or regional);
2. Geologic Maps (USGS or State Geologic Surveys);
3. Topographic maps; Consult USGS topographic maps for the area to determine if any surface expressions of karst are located at or near the site. Karst will not form in all limestones and dolomites. Field investigations are usually necessary to verify the presence of karst;
4. Potentiometric surface maps;
5. Geophysical logs/maps/or local studies;
6. Cave maps (USGS, State Survey, or privately produced); and
7. IDNR Water Well Records.

C. Check the location of the site against the list of counties found earlier in this document (Fig 1).

2) Soil Bedrock Interface Study

Once the site is identified as in an area known to be susceptible to karst development, the interface between the soil and bedrock is tested for contaminated ground water. There are several initial tests:

A. Map the bedrock surface.

Mapping the bedrock surface is a simple way to determine how water drains through the subsurface materials beneath the site. Due to tremendous lateral variations in subsurface conditions, correlating even closely spaced borings is highly speculative. For instance, depth to rock may be five feet in one boring, and 50 feet in a boring only yards away. Geophysics can provide data both to locate potential “problem areas” where sampling programs should be focused, and allow accurate extension of data between borings. Examples of land-based geophysical methods include:

- **Electromagnetics (EM)** and **electric imaging (EI)**: Detects variations in subsurface electrical properties related to anomalously thick or wet soils (will produce an electrical conductivity high response), or voids in the electrically conductive clay soil (will produce an electrical conductivity low response).

- **Spontaneous potential (SP)**: Detects naturally occurring minute electrical currents/potentials commonly associated with concentrated infiltration or subsurface water movement.

- **Microgravity**: Maps minute variations in gravity that, in karst terrains, may be due to soil voids or bedrock solution cavities where "missing" subsurface mass results in measurably lower gravity.

- **Seismic refraction, reflection, and surface wave analysis:** Provides profiles of the top-of-rock which may display conical depressions of the type associated with paleo sinks, or linear deeps which may represent sinkhole-prone faults, fractures, bedding planes, or other lineaments. Seismic rock depths are also used to calibrate microgravity results where no boring data are available. The latter two methods (microgravity and seismic profiling) are also often used to discern the difference between EM or EI conductive anomalies (which could represent either a bedrock deep or wet, saturated soils), or between EM or EI resistive anomalies (which could be caused by either dry, competent rock or air filled voids).

- **Ground Penetrating Radar (GPR):** Uses high frequency electromagnetic energy to acquire subsurface information. Energy is radiated downward into the ground from a transmitter and is reflected back to a receiving antenna. Reflections of the radar wave occur where there is a change in the dielectric constant between two materials. The reflected signals are recorded and produce a continuous cross-sectional image of shallow subsurface conditions.

These techniques work best when there is little near-surface interference (sometimes called cultural interference). Types of near-surface interference can include, but are not limited to:

- Utility corridors
- Fill materials, and
- Reinforced concrete

When there is significant near surface interference, geophysical investigation results can be misleading and soil borings will produce better results.

Once the area of interest is known, a series of probe points are advanced (on a grid pattern) until refusal (collect soil samples in a subset of these “borings”). Map the depths of refusal and contaminant levels, if possible, identify any “low spots” on the bedrock surface. If high levels of soil contamination are identified in the “low spot”, there is a high probability the contamination is entering the karst aquifer.

B. Sample the soil and epikarstic water, to determine if the karst aquifer is contaminated.

1. Soil Sampling:

   Soil sampling in karst settings should be conducted both above and below the water table. Since soils in karst settings can become entrained in water flowing through the karst system, migration of contaminated soil particles is a concern.

2. Epikarstic Ground Water Sampling:

   Once bedrock mapping is complete, and the “low spots” are identified; install several monitoring wells so that the screens intersect the interface between the unconsolidated materials and the bedrock surface. Install at least one monitoring well in each of the “low spots” identified on the bedrock surface map. These wells will monitor water flowing along the bedrock surface.

3. Sampling Schedule

   One of the most difficult aspects of sampling this type of ground water is knowing when to sample.

   Sampling ground water at the soil-bedrock interface is dependent on rainfall. Sampling needs to occur soon (no later than 24 hours) after a storm event (0.75 inch or more of rain is needed to qualify as a storm); otherwise, contamination (or even water) could be missed.

3) Karst Drainage Basin Study

A field investigation of the karst drainage basin is needed to determine possible contaminant migration pathways. The exact boundaries of the basin are unknown until a dye trace is conducted, but this investigation will give the investigator an idea of the size of the karst drainage basin. Prior to any sampling or dye tracing, identify and locate the following karst features:

- Springs
- Blue Holes (springs in streams)
- Karst Windows
- Caves
- Soil Springs (seeps)
- Sinkholes
- Swallets (openings to the conduit system not
- associated with sinkholes)

These features can initially be located by using maps and literature searches, however, all karst features need to be field verified.

If the drainage basin investigation identifies a limited number of springs, or other features, it may be simpler to evaluate the discharge points first. This will save the expense and time of a dye trace. If contamination is found at any of the karst features, a qualitative dye trace may be needed. In addition to the dye trace, investigation of surface activities between the site and the contaminated feature could identify additional sources that could account for the contamination.

Sampling needs to include both base and storm flow conditions. Base flow conditions are in effect when there has been less than 0.1 inch of rain within 24 hours. Periods of no rainfall are preferred. Periods where 24 hour rainfall exceeds 0.1 inch may be acceptable for base flow conditions on case by case basis. Storm flow events are classified as greater than 0.75 inch of rainfall in 24 hours.

4) Qualitative Dye Trace

If ground water flow pathways are unknown, a qualitative dye trace (basic trace designed to find out where the water flows) is needed. To implement a dye trace study, the karst ground water basin(s) is (are) surveyed to locate springs beyond the facility boundary. All of the features listed in item 3 should be inventoried, described, and placed on a map. The spring survey should include the following:

A. Spring Locations

Locations accurately placed on a topographic map (springs are surveyed for a quantitative dye trace).

B. Spring Descriptions

Collect the following information for each spring:

- A physical description;
- The nature of discharge (i.e. type of spring; bedrock or soil);
- The number of output locations;
- The characteristics of the discharge;
- The conductivity, pH, temperature, total suspended solids, and dissolved oxygen of the waters; and
- Discharge measurements.

This information should be submitted in a report to IDEM prior to conducting the dye trace. The report needs to include a map of the hypothesized ground water basins.

Discharge measurements are needed for each identifiable spring within the karst ground water basin(s) where contamination may exist. Discharge measurements are collected during conditions when all springs are flowing. Provide justification regarding the method selected for spring discharge measurements.

C. Background Sample Collection.

Background sampling is needed to determine if any of the commonly used dyes are already in the area (this test is usually run for four weeks). The following provides steps necessary to collect background information:

1. Assign each spring an inventory number or name and accurately locate on a U.S.G.S topographic map;
2. Construct a set of dye receptors for each spring. Each dye receptor is tagged and assigned an inventory number;
3. Station two sets of background dye receptors, each consisting of different dye sorbents (cotton and charcoal) for multiple dyes, in each spring;
    a. Dye receptors are usually made of coconut grade charcoal and surgical cotton for receiving corresponding types of dyes;

   b. Dye receptor sets are stationed apart from each other and hidden to avoid vandalism or theft;
4. Take a grab sample of the spring water for background determination once a week for four weeks prior to dye injection;
5. Use a black-light and dye elutriants to test dye receptors for background levels of dye or fluorescent chemicals;
6. Test grab-samples on a Model 10 Turner Designs Fluorometer, Spectroflourometer, or similar device;
7. Install new dye receptors at all previous locations and repeat steps 1 through 6 until the four week period is complete;
8. Once the background dye concentrations are known, select the proper dyes for the tracer study.

D. Qualitative Dye Trace.

A qualitative dye trace does not provide travel times or concentrations at the receptor points. It is used to determine which springs are connected or linked to the site in question. The following steps are needed to conduct a qualitative dye trace:

1. Select multiple dye injection locations. Several possible locations may include the soil bedrock interface (will require trenching), sinkholes, swallow holes, or losing streams;
2. Select dye such as water soluble sodium fluorescein or optical brightener. There are other types of dyes but fluorescein and optical brightener are the most common;
   a. Dye receptors made of coconut grade charcoal or surgical cotton capable of receiving the types of dyes used in the test are placed at all springs in the drainage basin;
   b. If monitoring wells have already been installed, dye receptors are also placed in them;
   c. Dye is flushed into the system with a large volume of water, ten parts water to one part dye is a standard ratio;
3. Replace the dye receptors weekly until dye is recovered;
4. Analyze the dye receptors, and;
5. Show the inferred path or route of ground water flow from dye injection point to dye recovery point on a map.

The qualitative dye trace is used to determine the general path of conduit flow between the points of dye injection and dye recovery. Provide quality control protocol for handling dye and dye receptors to ensure the prevention of dye receptor contamination.

Once the qualitative dye trace is concluded, identify all springs and wells connected to the karst system. Water and sediment from the springs and wells are then analyzed to determine if contamination is present in ground water and sediment discharging from the springs. Sampling needs to include both base and storm flow conditions. Base flow conditions exist during times when the cumulative precipitation amount is less than 0.10 inch in 24 hours. If the cumulative precipitation amount is greater than 0.75 inch in 24 hours, storm flow conditions exist.

5) Quantitative Dye Trace.

Once the investigations show where the water is going, and verify that COCs from the site are discharging from the springs, evaluate whether a quantitative dye trace (used to design remedial measures at the springs) would be appropriate and valuable.

Conduct a quantitative dye trace to determine the ground water flow rates as well as contaminant concentrations over time. In addition to the dye tracer study, conduct a water well survey. Once the survey has identified all domestic, municipal, industry and livestock wells and springs, develop a potentiometric contour map of the karst ground water basin(s). Documentation for the map should include:

- The locations of all active and inactive water wells within three miles of the facility;
- Depth to the water surface in each well;
- Well depth;
- Well activity (i.e., human and or livestock use, and in use or abandoned);
- Any construction details or well logs;
- Surface elevation of the well from a known datum point (National Geodetic Vertical Datum). Use elevation datum from mean sea level for each well;
- Elevation and location of springs and blue holes; and
- Last precipitation event at time wells were measured.

Once hydrologic outputs and flow paths are established, a quantitative dye trace and use the dye recovery curves are used to better understand the time of travel, peak concentration, and flow duration of the dye. Frequent sampling (usually hourly) is needed.

Conducting quantitative dye traces during varying discharge conditions provides an understanding of aquifer response to storm events and is a useful predictive tool to determine ground water discharge, apparent ground water flow velocity, and solute characteristics. Normalized peak-solute concentration, mean travel time, and standard deviation of time of travel are used to simulate solute-transport characteristics for selected discharges. The analysis of recovery curves, in conjunction with discharge measurements is used to estimate arrival time, peak concentration, duration or persistence, and dispersion of a soluble conservative (travels at the same speed as the flow of water) contaminant at a spring.

The time of travel, peak concentration, and flow duration results are used to directly describe general fate and transport characteristics of contaminants in the ground water. Predicting the contaminant concentration maxima, relative to storm hydrographs, should provide information on optimal conditions for sampling at springs, seeps, cave streams, and relevant ground water monitoring wells. Automatic water sampling equipment is used to record this information. The equipment needs to be capable of measuring, temperature, conductivity, pH, and flow rates. Use equipment capable of collecting samples that can be sent to a laboratory for analyses of the contaminants of concern for that site, as well as the tracer dye.

Once a spring and optimal sampling time are identified, incorporate that information into a ground water sampling plan. The plan is designed to sample ground water hourly, before, during and after a significant storm event. A significant storm event is defined as: A storm event that produces 0.75 inch of precipitation in a 24 hour period. While a quantitative dye trace may provide a cost effective fate and transport model, compare the model to actual concentrations in the ground water collected before, during and shortly after a heavy rain. Ground water is collected from monitoring wells at the same time springs are sampled. Automatic water samplers can be used to collect ground water from monitoring wells.

Use a hydrograph to continuously monitor peaks in flow. This may indicate multiple slugs of contaminant are passing through the aquifer. Design of an efficient ground water treatment system requires an understanding of the contaminant concentrations with respect to characteristics of the storm hydrograph of the springs.

6) Vapor Intrusion Study

Karst systems are natural preferential pathways composed of caves and bedrock fractures enlarged by dissolution. The assumptions made to evaluate vapor intrusion for sites in non-karst areas are not the same as those in karst areas.

When human activities intersect karst areas, additional preferential pathways are created. These pathways can be underground utility lines, basements, sump pumps or any subsurface alteration that provides vapors a path of least resistance into a structure.

It is important to investigate both the natural pathways and those created by human activity. Either one, both, or some combination, may be the path of least resistance into a structure. Vapor intrusion in karst areas is not necessarily linear; therefore the processes for investigation are somewhat different than for non-karst situations.

Many of the assumptions from the vapor intrusion guidance cannot be applied in karst settings:

- The default attenuation factors are not applicable because there is often a direct connection between the contaminant source and the receptor.
- The ground water screening values do not consider open conduit flow, therefore they cannot be used.
- Soil gas sampling is not representative, because the soil porosity may not be homogeneous due to open conduits or soil fractures.
- Vapors may not be derived solely from the ground water contaminant plume. In karst, vapors can originate from the contaminated ground water, traveling as a separate phase, or contaminated sediments. The investigation needs to account for all phases of contamination.

A comprehensive vapor investigation will only be successful if the karst drainage basin is identified. Because the open conduits can allow vapors to travel much greater distances without attenuating, default distance assumptions do not apply. Vapor sampling is conducted the same way as investigating in non-karst areas, however; locations are based on the source's relative position in the drainage basin and not linear distances from the source. Each karst vapor investigation is site specific, consult with Geological Services when developing a work plan.

Do not apply attenuation factors developed for non-chlorinated compound exposure concentrations in karst settings. Both chlorinated and non-chlorinated compounds are treated the same way unless the investigation demonstrates that ample oxygen is present to biodegrade the non-chlorinated contaminants. However, it is also possible that non-chlorinated vapors could be displacing oxygen. If this has happened, biodegradation of non-chlorinated contaminants may not occur. Given these factors, the best way to assess risk is to sample at the point of exposure (i.e. collect indoor air samples).

7) Sampling Schedule and Frequency

Water flow in karst aquifers is not the same as in granular aquifers. Therefore a sampling frequency based on pre-specified fixed intervals will not yield representative samples of aquifer conditions. Sampling is based on recharge and discharge rates (determined during the dye trace study) of the springs and wells that are connected to the contaminant source area. Measurements of both high and low rates of discharge are needed. Measure low rates (also known as base flow) of discharge on fixed time intervals.

Vapor sampling follows the same pattern as water sampling. In most cases vapor concentrations will be higher when water levels are low (base flow). However, it is also possible that sudden increases in water levels can force vapors into structures and utilities. Therefore, measurements of both high and low water levels are needed. Low water level vapor samples can be collected on fixed time intervals.

8) Design of Remedial Measures

A. Soils

Soil excavation is the best way to deal with contamination above the soil/bedrock interface. In addition to removing source material, there is also a reduction in the amount of soil present that could become mobile in the karst aquifer.

B. Ground water

It is necessary to treat contaminated water at all of the known discharge points (i.e. springs and seeps) to be successful in remediating ground water at a site containing a karst aquifer. Attempting to treat water up-gradient of the discharge point may mean that some contaminated ground water is not treated and will be discharged to surface water. In addition to treating the discharge from a karst aquifer, it is necessary to control surface water infiltration. This is done in a variety of ways:

1. A surface impoundment, will allow water to slowly infiltrate into the aquifer. If the velocity of the water flowing through the karst conduits is controlled, the erosion of contaminated sediments are minimized. This will also reduce the peak concentrations seen during storm events.
2. A surface water diversion structure will control the amount of surface water entering the karst system. Since the volume is reduced, less water will need treatment. In addition, if the conduits are not allowed to fill, leaching of contaminants in upper portions of the system is minimized.
3. Treatment system(s) modified to operate only during peak flow (storm events) or only run during low flow conditions. Depending on the results of the dye trace and the types of contaminants of concern it is possible to design a remediation system that only runs part of the time.
4. Karst investigations can aid in the design of the remediation system. Systems more often fail as a result of being

undersized and cannot treat the necessary volume of water.

5. Information gathered during the karst investigation help determine the type of equipment needed to properly treat the ground water.

(modified from State of Minnesota draft guidelines for investigation of ground water contamination at petroleum release sites in karst areas; Fact Sheet #3.42; April 1996)

C. Vapors

The use of mitigation systems to remove vapors from the subsurface or from the sub-slab of structures is the same regardless if karst is present or not. The most common method to control and remove vapors is to block the migration at the point where vapors enter the building by installing a vapor mitigation system, sometimes called a “Radon System”. The most common type of vapor mitigation system, called a sub-slab depressurization system or a sub-slab ventilation system, has been used for years to prevent radon from infiltrating from soils into buildings, and is also effective for preventing contaminant vapors from entering buildings. The USEPA has a number of publications that describe the proper design, installation, and operation of sub-slab depressurization systems.

Further Information

If you have any additional information regarding investigative techniques in karst or any questions about the evaluation, please contact the Office of Land Quality Science Services Branch at (317) 232-3215. This technical guidance document will be updated periodically or if new information is acquired.

References

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3. UNESCO. 1972. Glossary and Multilingual Equivalents of Karst Terms. United Nations Educational. Scientific. And Cultural Organization. Paris. France. 72 pp.

4. State of Minnesota. 1986. Draft Guidelines for Investigation of Ground Water Contamination at Petroleum Sites in Karst Areas, fact sheet #3.42. State of Minnesota. Minneapolis, MN.

5. State of Indiana. 2006. Draft Vapor Intrusion Pilot Program Guidance Document, State of Indiana, Indianapolis IN.

Information Links

Agencies and organizations

Below is a list of several agencies and organizations that work in karst and that may be helpful when reviewing and designing a karst investigation.

- Speleogenesis. An international website the provides links to the latest papers and publications on karst hydrogeology.
  Web Site: http://speleogenesis.com/

- USGS Karst Website. Provides information on karst in the United States.
  Web Site: http://water.usgs.gov/ogw/karst/

- National Cave and Karst Research Institute A research organization based out of Carlsbad NM and partnered with the national park service conducts research around the US and world
  Web Site: http://www.nature.nps.gov/nckri/

- The Karst Waters Institute: A research organization based out of Baton Rouge, Louisiana and partnered with Louisiana State University conducts research around the US and world.
  Web Site: http://karstwaters.org/index.php

- The Karst Information Portal: A website that provides information not only on karst but also information on the formation of carbonate rocks. This site is run by the University of South Florida.
  Web Site: http://karstportal.org/index.php?P=Home

- International Association of Hydrogeologists: International Group of Hydrogeologists who specialize in karst hydrogeology.
  Web Site http://www.iah.org/karst/default.html

- Western Kentucky University Karst Studies Group: A research organization based out of Bowling Green, Kentucky and partnered with Western Kentucky University conducts research around the US.
  Web Site: http://karst.wku.edu/

Karst Papers, Publications, and Proceedings

Below is a list of several karst publications that may be useful when reviewing and designing a karst investigation.

- Geophysical Choices For Karst and Mine Investigations
  Rick A. Hoover1, P.G., Richard.A.Hoover@saic.com
  1 Senior Geophysicist, Science Applications International Corporation, 6310 Allentown Boulevard, Harrisburg, Pennsylvania 17112
  Web Site:
  http://www.dot.state.fl.us/statematerialsoffice/Geotechnical/conference/materials/hoover.pdf

- Sinkholes in Pennsylvania
  Web Site:
  http://www.dcnr.state.pa.us/cs/groups/public/documents/document/dcnr_014591.pdf

- Karst Characterization Using Geophysics, Part 1:
  "Effective Geophysical Methods for Karst"
  Kochanov, William E., DCNR, Bureau of Topographic and Geologic Survey, 3240 Schoolhouse Road, Middletown, PA 17057-3534.
  Web Site: http://www.midwestgeo.com/webinars/geophysics1-05192011.php

- Geophysical Choices For Karst Investigations
  Rick A. Hoover, P.G.,
  Web Site: http://www.quality-geophysics.net/pdfs/KarstChoices.pdf

- U.S. Geological Survey Karst Interest Group Proceedings, Shepherdstown, West Virginia, August 20-22, 2002

Eve L. Kuniansky, *editor* U.S. Geological Survey Water-Resources Investigations Report 02-4174
Web Site: http://water.usgs.gov/ogw/karst/kig2002/pdffiles/mdk.wrir02-4174.pdf