



INDIANA DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

Proper Investigative Techniques in Karst

Eric J. Holcomb
Governor

Bruno L. Pigott
Commissioner

(317) 232-8603 • (800) 451-6027

www.idem.IN.gov

100 N. Senate Ave., Indianapolis, IN 46204

Guidance Created: December 30, 2011

Updated: April 16, 2015, Reformatted September 15, 2019

Notice

IDEM Technology Evaluation Group (TEG) completed this evaluation of Proper Investigative Techniques in Karst based on review of items listed in the “References” section of this document. The IDEM OLQ technical memorandum *Submittal Guidance for Evaluation of Remediation Technologies* describes criteria for performing these evaluations.

This evaluation does not approve this technology nor does it verify its effectiveness in conditions not identified here. Mention of trade names or commercial products does not constitute endorsement or recommendation by IDEM for use.

Background

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. The guidance in this document will assist in the proper characterization of a site located in a karst area and provide information on the IDEM preferred method to conduct the 2 different types of dye tracing. See Addendum A.

KARST OVERVIEW

In Indiana, areas with limestone and dolomite bedrock are susceptible to karst formation. Karst terrains are not confined to one area of Indiana. Karst can be found at or near the surface in at least 28 Indiana counties. Figure 1 is a map with the shaded counties affected by karst.

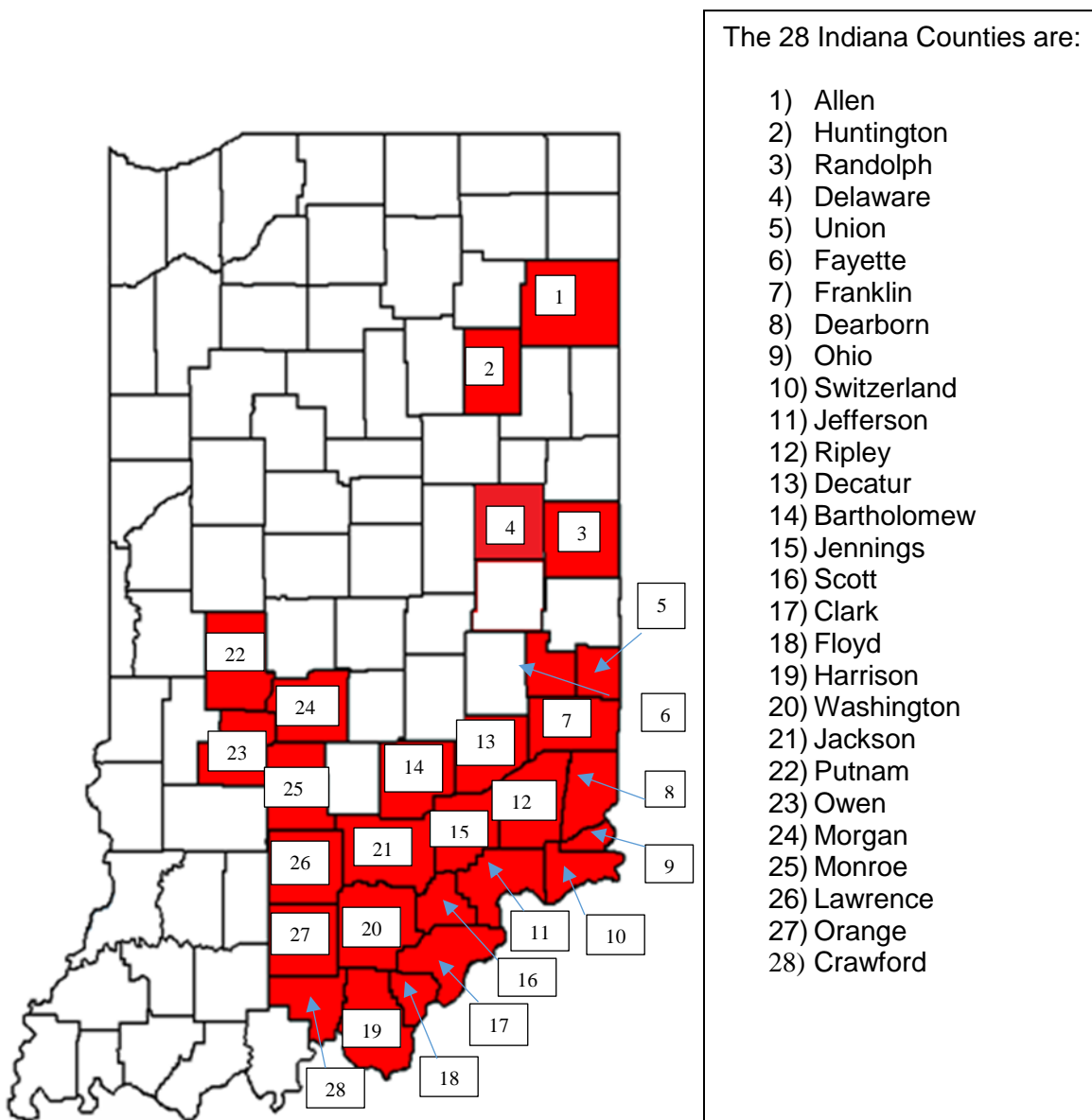


Figure 1

Prior to implementing a karst investigation, there are several key concepts that should be considered:

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.

2) 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.

3) Groundwater in a karst terrain does not behave in the same manner as groundwater 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 groundwater velocity 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 groundwater velocity in a karst aquifer. Results show that groundwater flow is as much as five orders of magnitude greater than slug tests results predicted.

4) 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.

5) Groundwater flow directions may not be apparent and can change direction during storm conditions.

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.

ELEMENTS OF A KARST INVESTIGATION

An 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

The process of mapping of the soil bedrock interface the same process used when investigating shallow bedrock (for more information see: Proper Investigative Techniques for Shallow Bedrock Technical Document at:

https://www.in.gov/idem/cleanups/files/remediation_tech_guidance_shallow_bedrock.pdf). Once the soil bedrock interface is mapped, 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. Both soil and epikarstic water should be collected.

A. 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.

B. Epikarstic Groundwater 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.

C. Sampling Schedule

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

Sampling groundwater 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 (see Addendum A) 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. If information is needed regarding peak flow rates of peaks COC concentrations a quantitative dye trace would be needed (see Addendum A).

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.

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) Monitoring Well Installation

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 groundwater 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.

The top of the well screen should be at a minimum six feet bgs to allow for:

- 2 feet of filter pack above the top of the well screen (USEPA 2013),
- 2 feet of bentonite grout (USEPA 2013) , and
- 2 feet of concrete for the surface pad (USEPA 2013).

If a well is installed closer than six feet to the surface, there is a possibility that surface water could enter the well (potential preferential pathway).

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.

5) Vapor Intrusion Study

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.

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 or sewer investigations 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 groundwater 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 groundwater contaminant plume. In karst, vapors can originate from the contaminated groundwater, 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 OLQ technical staff 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).

6) 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.

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

Fleming, A. H., Brown, S. E., and Ferguson, V. R., 2000, Geologic and hydrogeologic framework, in Brown, S. E., and Laudick, A. J., eds., 2003, Hydrogeologic framework of Marion County, Indiana-a digital atlas illustrating hydrogeologic terrain and sequence: Indiana Geological Survey [Open-File Study 00-14](#), CD-ROM.

Monroe, W.H. (Compiler). 1970. A Glossary of Karst Terminology, USGS Water Supply Paper 1899-K. U.S.G.S. U.S. Government Printing Office. Washington, D.C. 26 pp.

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

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

State of Indiana. 2016. Vapor Intrusion Investigation Documentation Guidance Document, State of Indiana, Indianapolis IN.
https://www.in.gov/idem/cleanups/files/remediation_tech_guidance_vi_investigation.pdf

USEPA. 1988. Application of dye-tracing techniques for determining solute-transport characteristics of ground water in karst terranes

USEPA January 29, 2013, https://www.epa.gov/sites/production/files/2016-01/documents/design_and_installation_of_monitoring_wells.pdf

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 that 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>
- USEPA January 29, 2013, https://www.epa.gov/sites/production/files/2016-01/documents/design_and_installation_of_monitoring_wells.pdf

Indiana Case Study

- P.E. LaMoreaux & Associates, Inc. March 18, 1998 Karst Investigation of Planned Cement Kiln Dust Monofill Site at the Lehigh Portland Cement Company in Mitchell, Indiana, (Section VI. Groundwater Tracing). [VFC # 26923966](#)

ADDENDUM A

Dye traces are needed when a clear groundwater flow pathway cannot be identified. A qualitative dye trace is the primary way of identifying groundwater flow pathways from sites to karst springs. A qualitative dye trace cannot provide information regarding concentration trends or flow rates and should not be used to develop a remedial strategy involving treatment of spring water. If information is needed regarding peak flow rates of peaks COC concentrations and data needed to design treatment for the spring water a quantitative dye trace would be needed.

Qualitative Dye Trace

If groundwater 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 groundwater basin(s) is (are) surveyed to locate springs beyond the facility boundary. All of the features listed in item C 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 groundwater basins.

Discharge measurements are needed for each identifiable spring within the karst groundwater 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 USGS 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, Spectrofluorometer, 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 groundwater 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 groundwater 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.

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 groundwater 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 groundwater 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, dye recovery curves from a quantitative dye trace are one way to better understand the time of travel, peak concentration, and flow duration of the dye (USEPA 1988). 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 groundwater discharge, apparent groundwater 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 groundwater. Predicting the contaminant concentration maxima, relative to storm hydrographs, should provide information on optimal conditions for sampling at springs, seeps, cave streams, and relevant groundwater 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, that information is incorporated into a groundwater sampling plan. The plan is designed to sample groundwater 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 groundwater collected before, during and shortly after a heavy rain. Groundwater is collected from monitoring wells at the same time springs are sampled. Automatic water samplers can be used to collect groundwater 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 groundwater treatment system requires an understanding of the contaminant concentrations with respect to characteristics of the storm hydrograph of the springs.