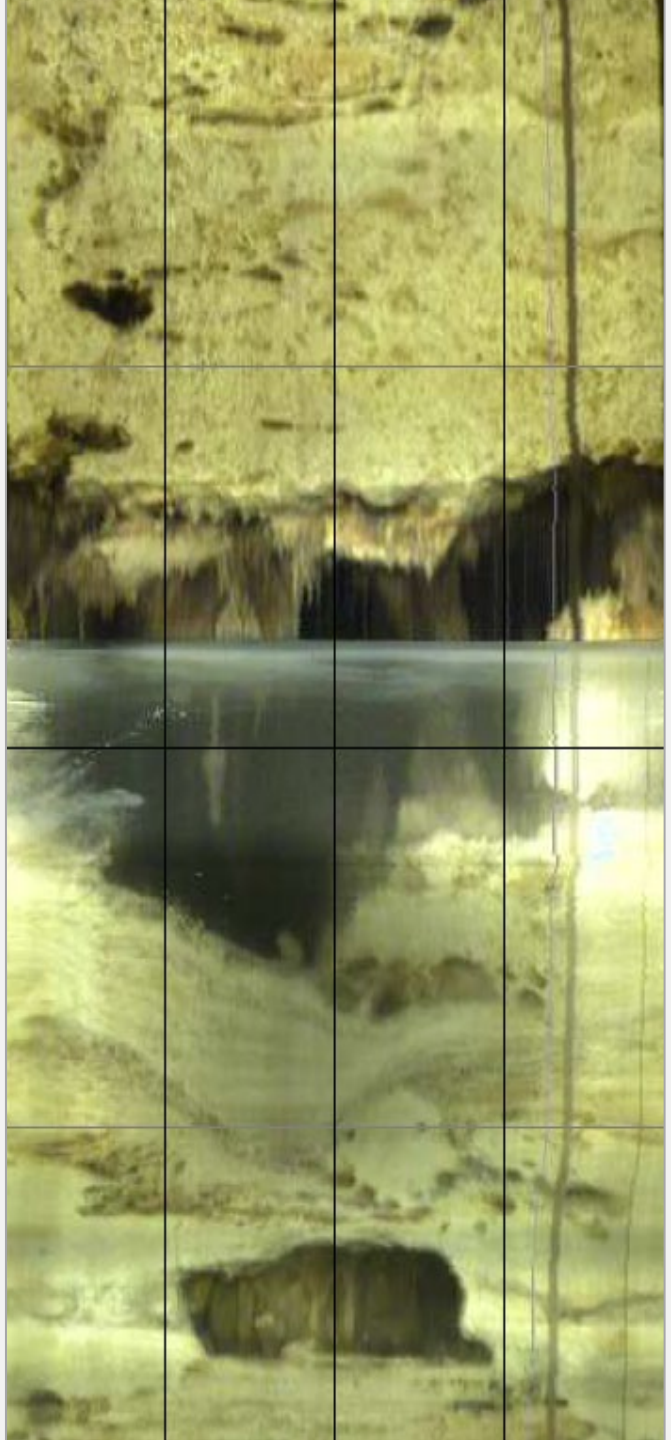
Battelle 2024 Chlorinated Conference

Putting Conduits to Work

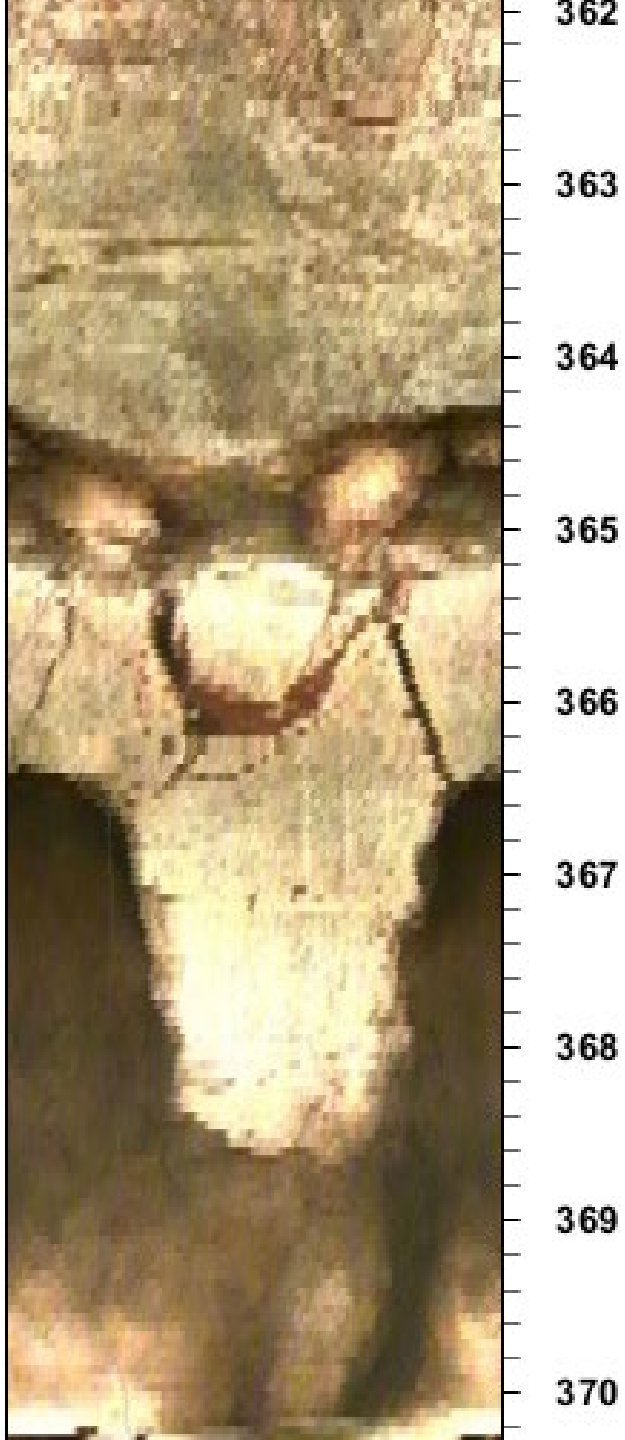
Evidence of Efficient Vapor Extraction in Karst Aquifers

June 3, 2024

Michael Cobb
Keith White



ARCADIS



Remediation in Karst

A Battle Against Conduits

ARCADIS

The challenges:

All the complications of a porous fractured media

+

A self-organized permeability structure

+

Extreme transmissivity range

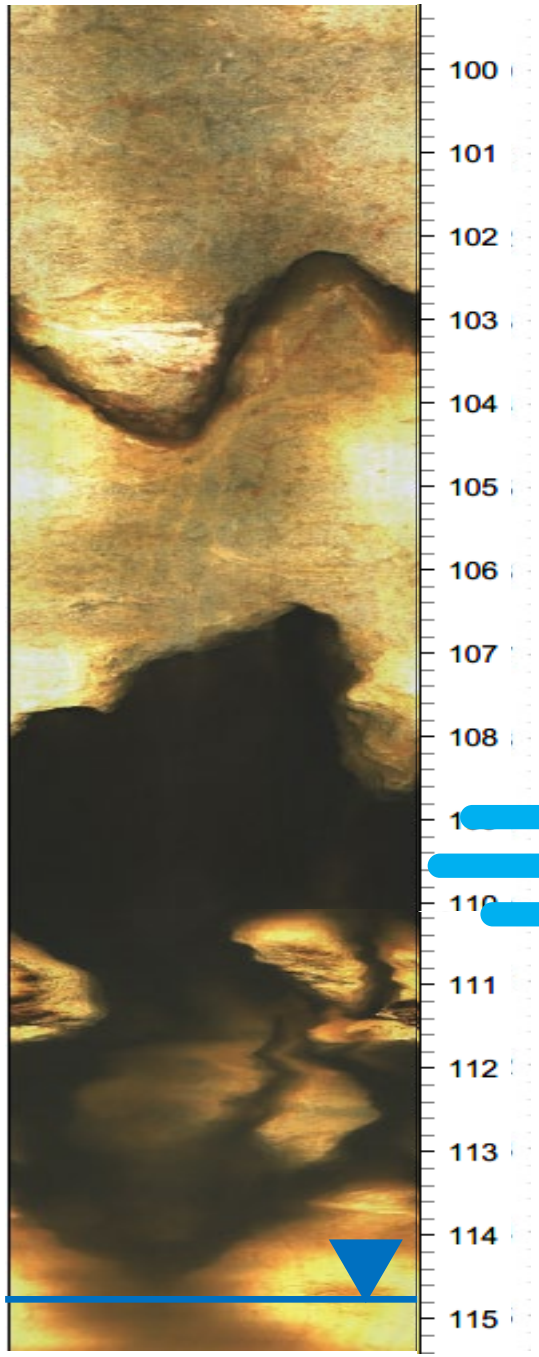
The result:

Unpredictable hydraulic influence or injectate behavior

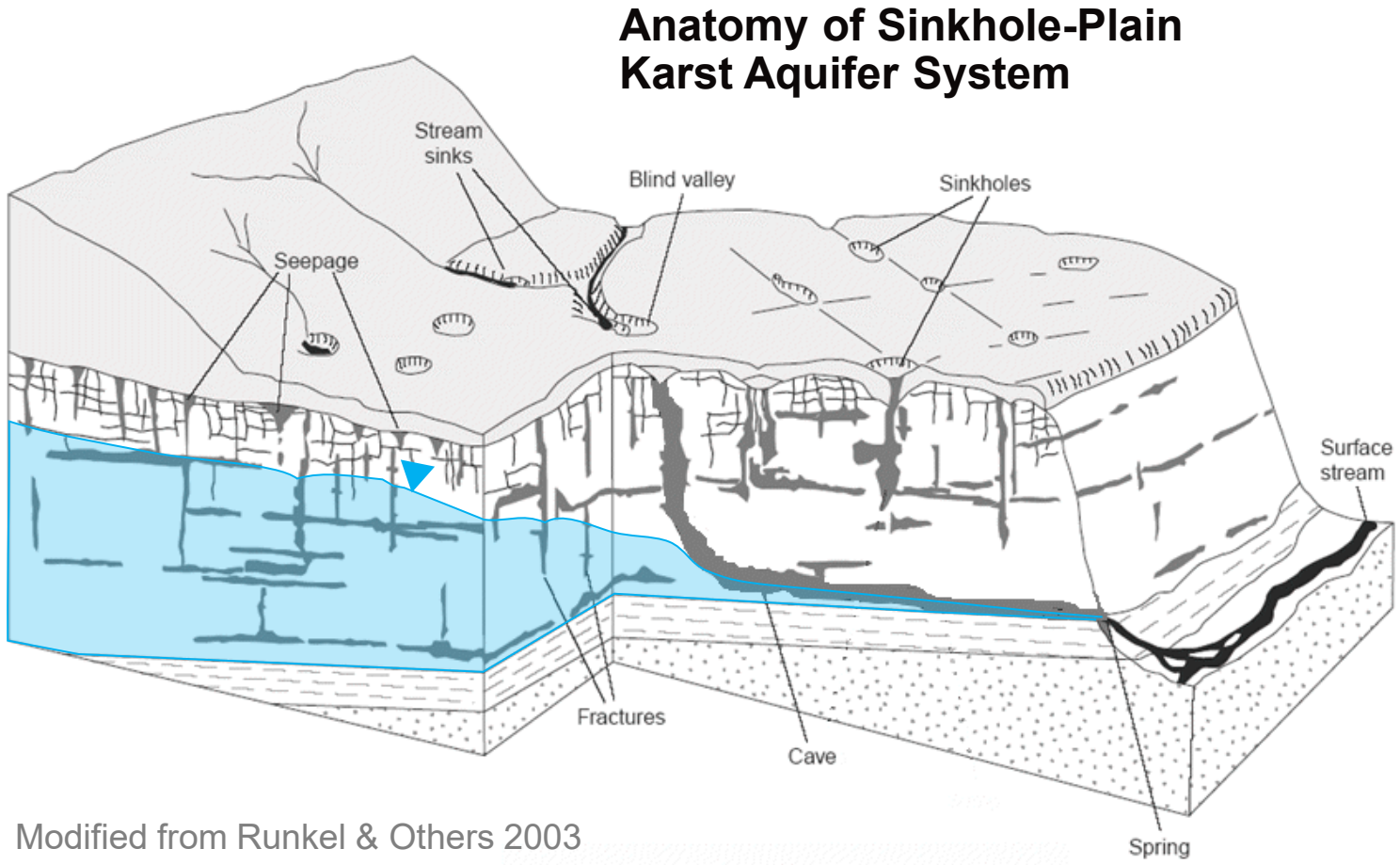
OTV Image of a void in Frederick Formation limestone, Maryland (depths in feet)

How about Vapor Extraction?

- Many karst aquifers have significant vadose zone porosity
- Source mass is often trapped in the surficial zone (epikarst)
- Conduits create highly efficient vapor pathways
- Capturing and treating vapors can be easier than groundwater

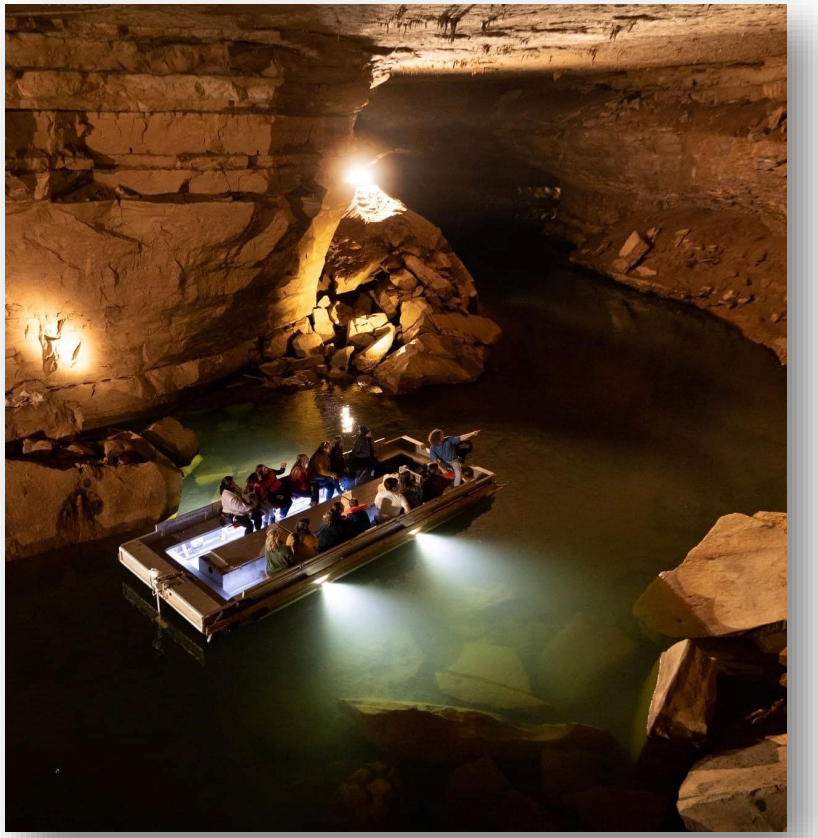


The Sometimes-Copious Karst Vadose Zone



Modified from Runkel & Others 2003

Lost River Cave, Bowling Green, KY



Friends of the Lost River, Inc.
(www.lostrivercave.org)

Bowling Green Toxic Fumes Incident 1983-1985

Park City Daily News, March 18, 1983

Polluted

Volatile chemicals in underground river system may be health hazard

By DEBI WADE
Daily News Staff Writer

Industrial pollution found in the underground river system below Bowling Green includes some highly volatile chemicals that could pose a health hazard.

Concentrations of benzene and methylene chloride have been found in the fast flowing water of Lost River and enter the river from an underground tributary that flows beneath Industrial Park, according to Dr. Nick Crawford, a hydrologist with Western Kentucky University's geography and geology department.

"Both are toxic substances and both of them are volatile at a low temperature," Crawford said. "Benzene will go into gas at 12 degrees Celsius." The cave temperature is 14.7 degrees Celsius, according to Crawford.

Two cavers discovered the spill almost seven months ago. Crawford said he and four other people, including Bob Adams, engineer for the Bowling Green office of the state Natural Resources and Environmental Protection Cabinet Division of Water, had gone back into the cave three times to secure water samples for analysis.

Pools of scum three inches thick and a diesel fuel-like substance were distributed throughout at least 2,000 feet of the river, Crawford said. The river flows past that point, but the cavers couldn't get past a breakdown of rocks to see if the pollution flowed past them as well. A smell similar to that of paint thinner permeated the cave air.

An analysis of the river water, not the scum itself, conducted by state officials in the Division of Water revealed a 91 micrograms per liter (parts per billion) concentration of benzene and a concentration of 51 micrograms per liter of methylene chloride, according to Crawford.

Benzene is a carcinogen and appears to be more dangerous when people chronically come into contact with it, according to information from N.I. Sax's "Dangerous Properties of Industrial Materials" supplied to Crawford by Dr. David Hartman, a chemist at Western.

Benzene is rated high on a toxic hazard rating code for ingestion, inhalation and skin absorption, according to the book. Methylene chloride is more dangerous from a heavy dose at one time than from long-term exposure to a smaller amount. It ranks high in a toxic hazard rating code for inhalation after a one-time heavy dose.

"Methylene chloride is hazardous and is used as an anesthesia in Europe," Crawford said. He said he thought he and the other cavers who gathered water samples were probably lucky not to have passed out when they were in the cave.

"It's not good for people to go back into the cave because it's (methylene chloride) so concentrated in there," he said.

There is an entrance to the Lost River system behind Bowling Green Mall near where the tributary from Industrial Park enters it, according to Crawford. He said he has often seen children playing around the entrance and in the water.

"I've talked to chemists and biologists who don't think the levels of benzene in the water will have an effect on kids on a one or two time exposure," Geary Schindel, a Western graduate student who helped collect water samples, said. But Schindel said breathing the fumes from the

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Column 3, This Section

(Staff Photo by Mark Workman)

A WATER SAMPLE from Lost River has a layer of fuel-like liquid on top of scum. Water in Lost River ran clear prior to an industrial spill sometime last fall, according to Dr. Nick Crawford (in background), a hydrologist with Western Kentucky University's geography and geology department.

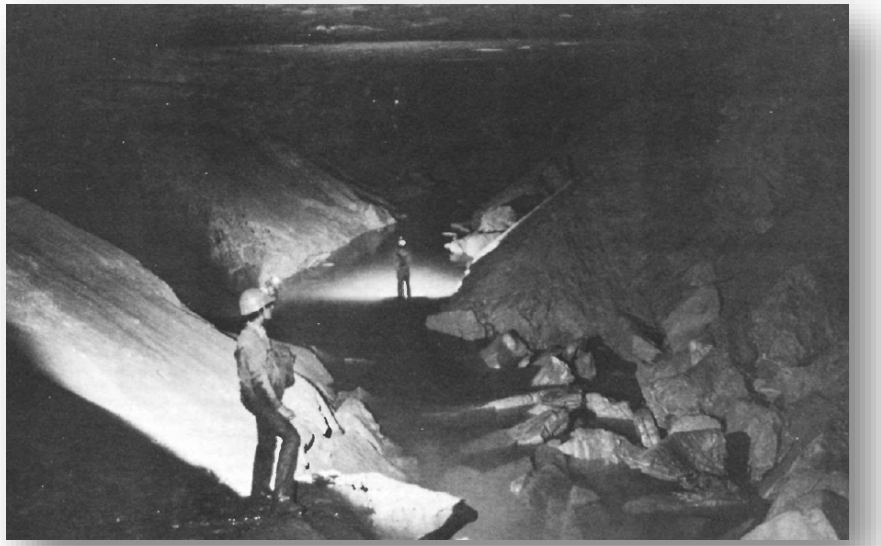
- Toxic and explosive vapors found in two schools and over 50 homes
- Vapors found to be migrating up from cave system below
- EPA rushes to map caverns and identify sources

The Response

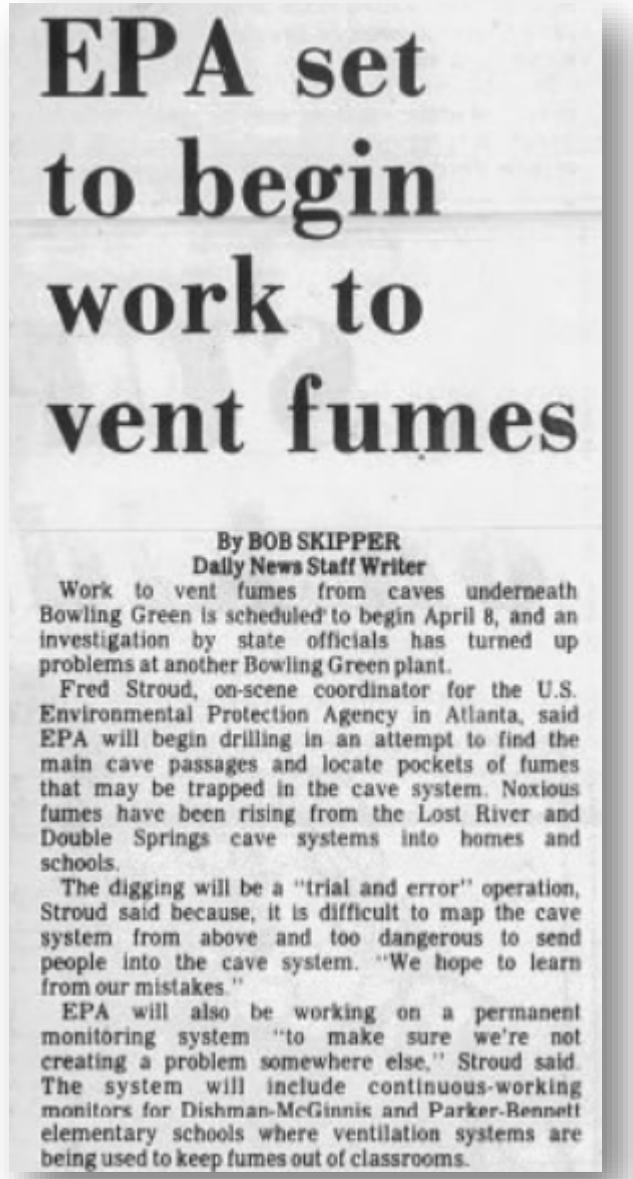
- Ad hoc ventilation pipes attached to bedrock crevices at effected buildings
- Vapors “easily” controlled to protect receptors
- Identifying and addressing sources took years

TESTING FOR CONTAMINATION: Worker emerges from 33-foot well drilled into Lost River cave after collecting air, water and sediment samples.

Atlanta Journal & Constitution May 12, 1985



EPA Journal July/August 1985



EPA set to begin work to vent fumes

By BOB SKIPPER
Daily News Staff Writer

Work to vent fumes from caves underneath Bowling Green is scheduled to begin April 8, and an investigation by state officials has turned up problems at another Bowling Green plant.

Fred Stroud, on-scene coordinator for the U.S. Environmental Protection Agency in Atlanta, said EPA will begin drilling in an attempt to find the main cave passages and locate pockets of fumes that may be trapped in the cave system. Noxious fumes have been rising from the Lost River and Double Springs cave systems into homes and schools.

The digging will be a "trial and error" operation, Stroud said because, it is difficult to map the cave system from above and too dangerous to send people into the cave system. "We hope to learn from our mistakes."

EPA will also be working on a permanent monitoring system "to make sure we're not creating a problem somewhere else," Stroud said. The system will include continuous-working monitors for Dishman-McGinnis and Parker-Bennett elementary schools where ventilation systems are being used to keep fumes out of classrooms.

Park City Daily News, March 28, 1985

Networked Karst Drainage “Plume” Zones

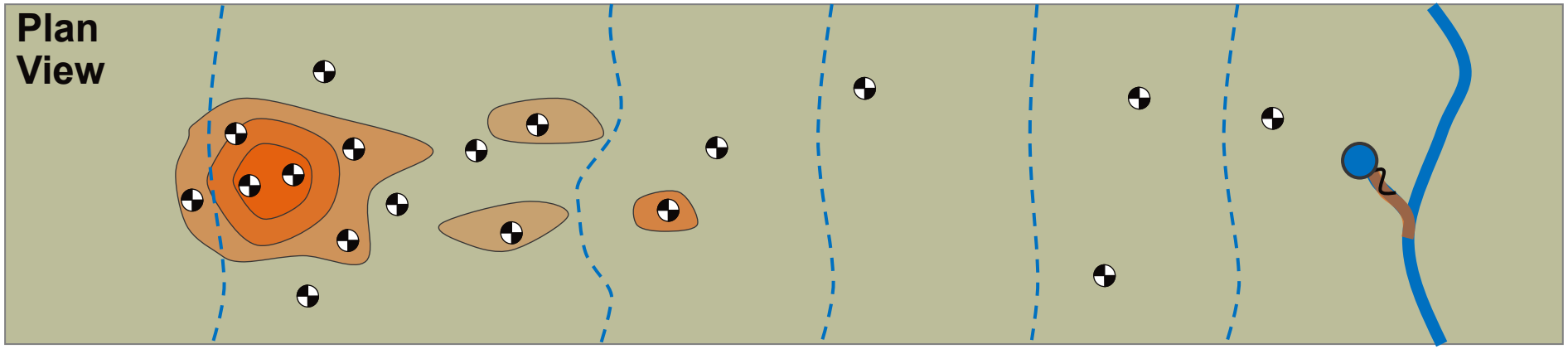
Modified from Parker & Others 2012

Near Source
“Pseudo Plume”

Mid-Field
“Spotty Plume”

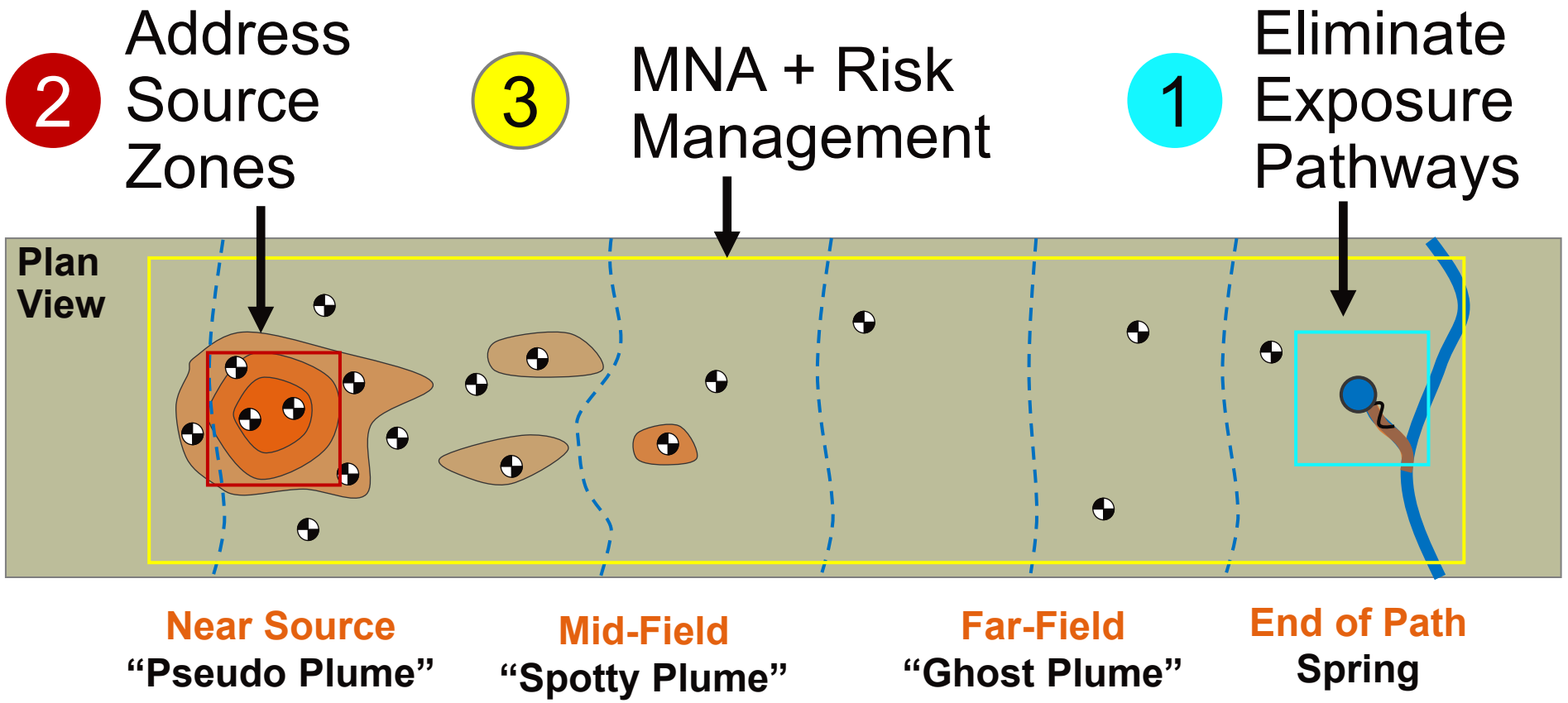
Far-Field
“Ghost Plume”

End of Path
Spring



A Karst Remediation Approach

Not as easy as 1, 2, 3



The Epikarst Sponge

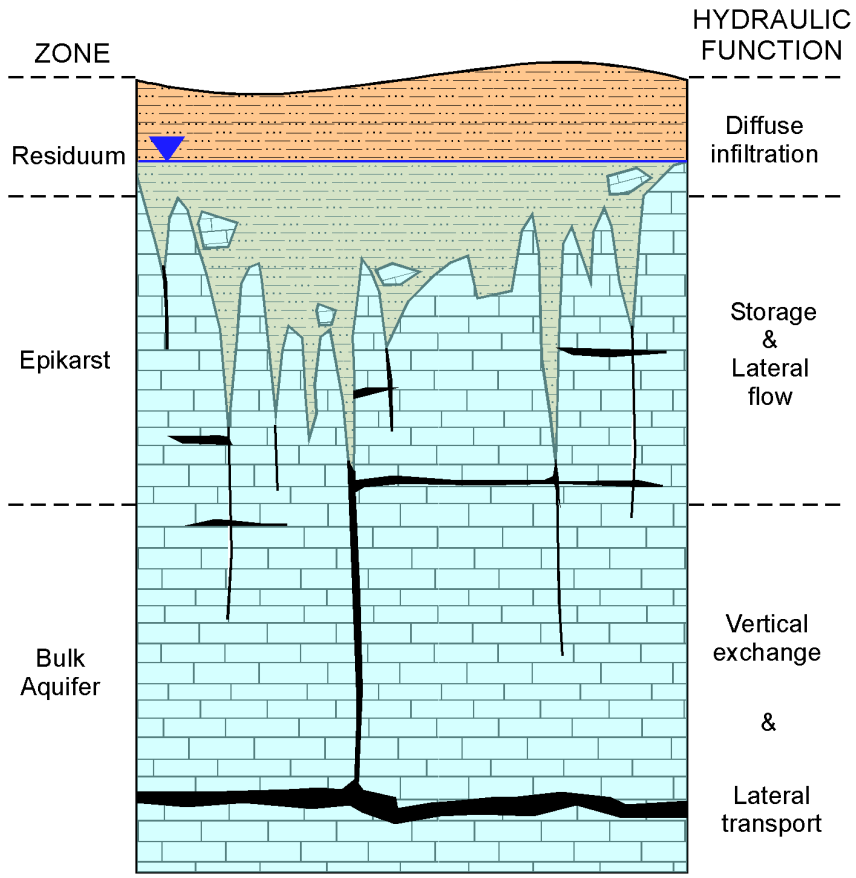
Where the source resides often

- A zone in the uppermost portion of the bedrock
- Often a “swiss cheese” of voids
- Developed on bedding planes, vertical joints, and other fractures
- The voids are complexly interconnected to each other; some are often sediment filled
- Connected to the deeper bedrock at discrete points

Karst Aquifer Storage Zones

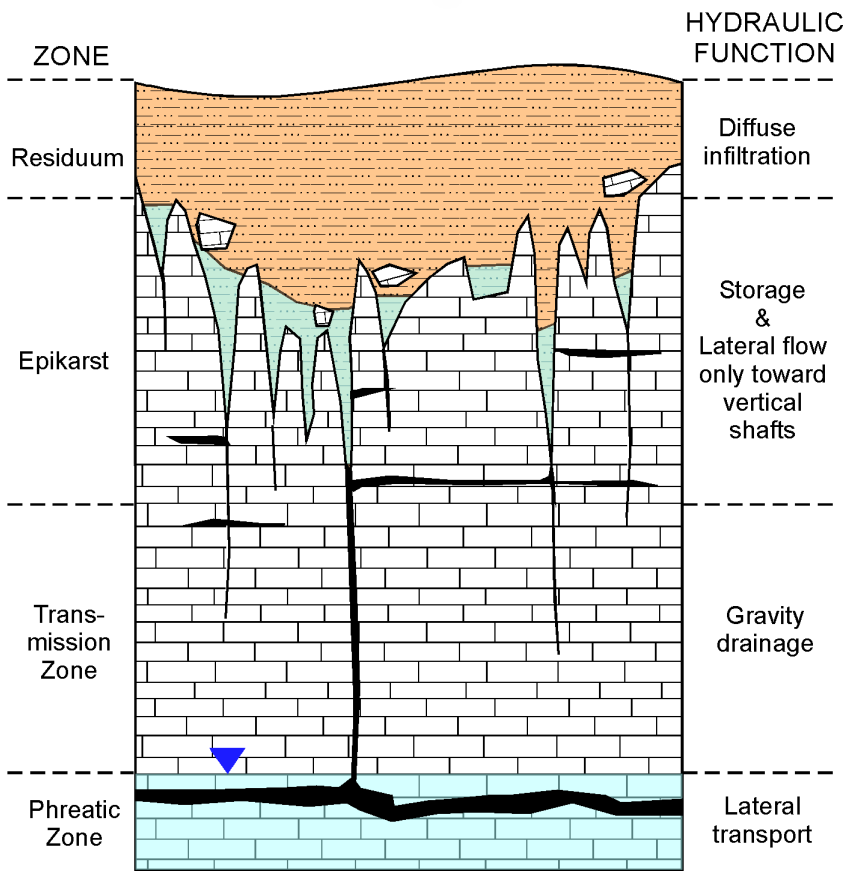
ARCADIS

Saturated Epikarst



The domain of challenging hydraulic remedies

Vadose Epikarst

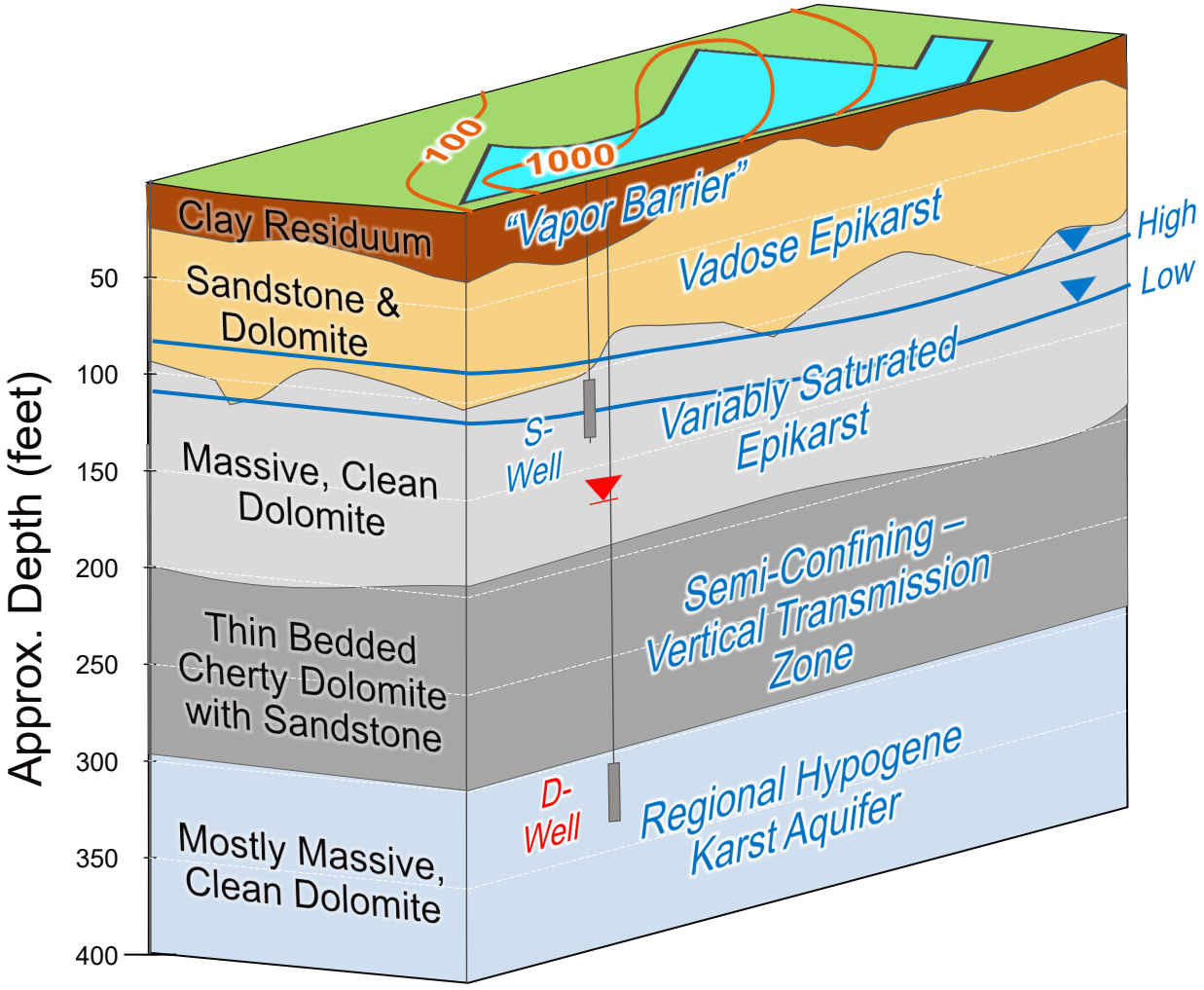


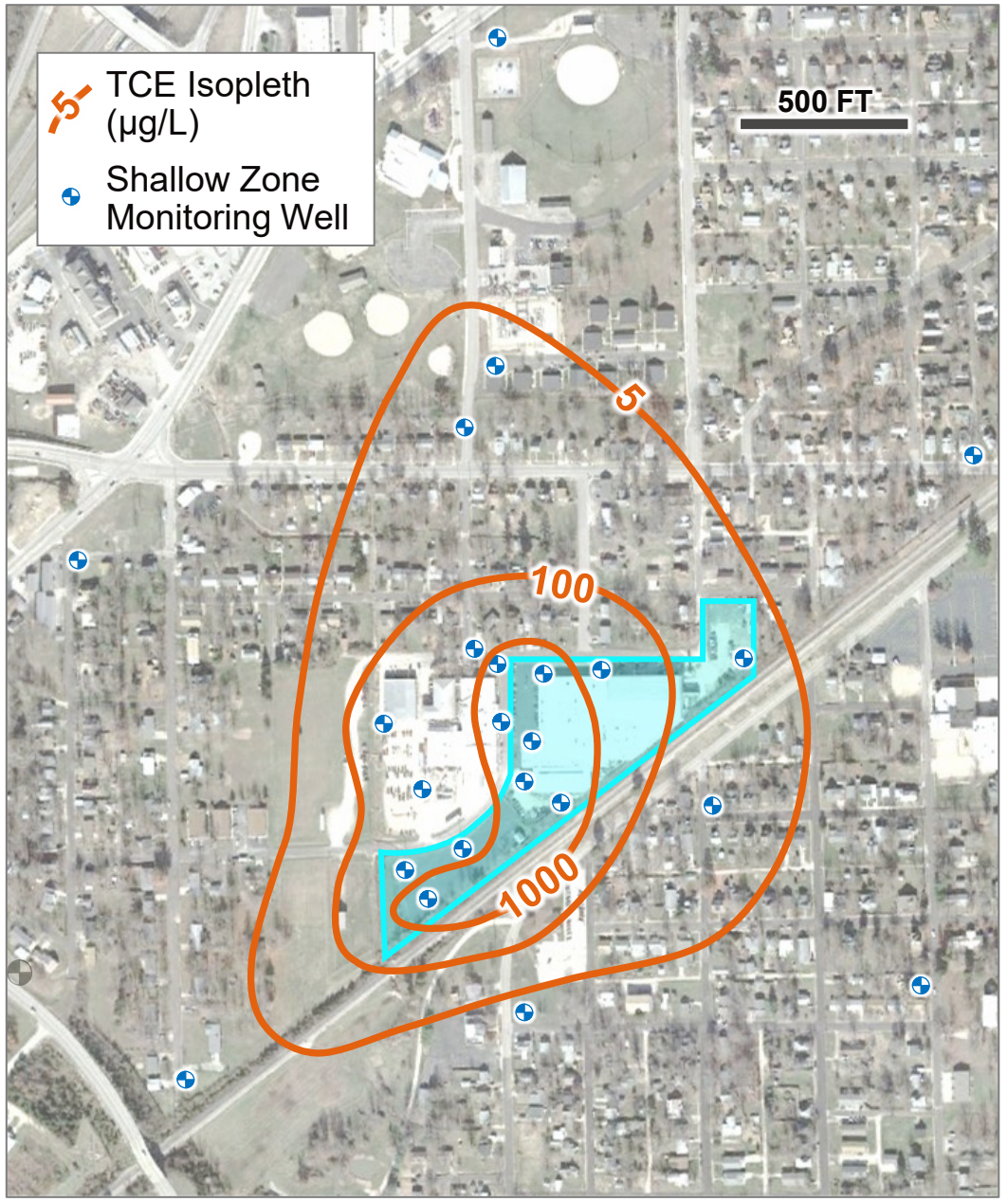
A vapor-phase remedial opportunity!

Example Case 1

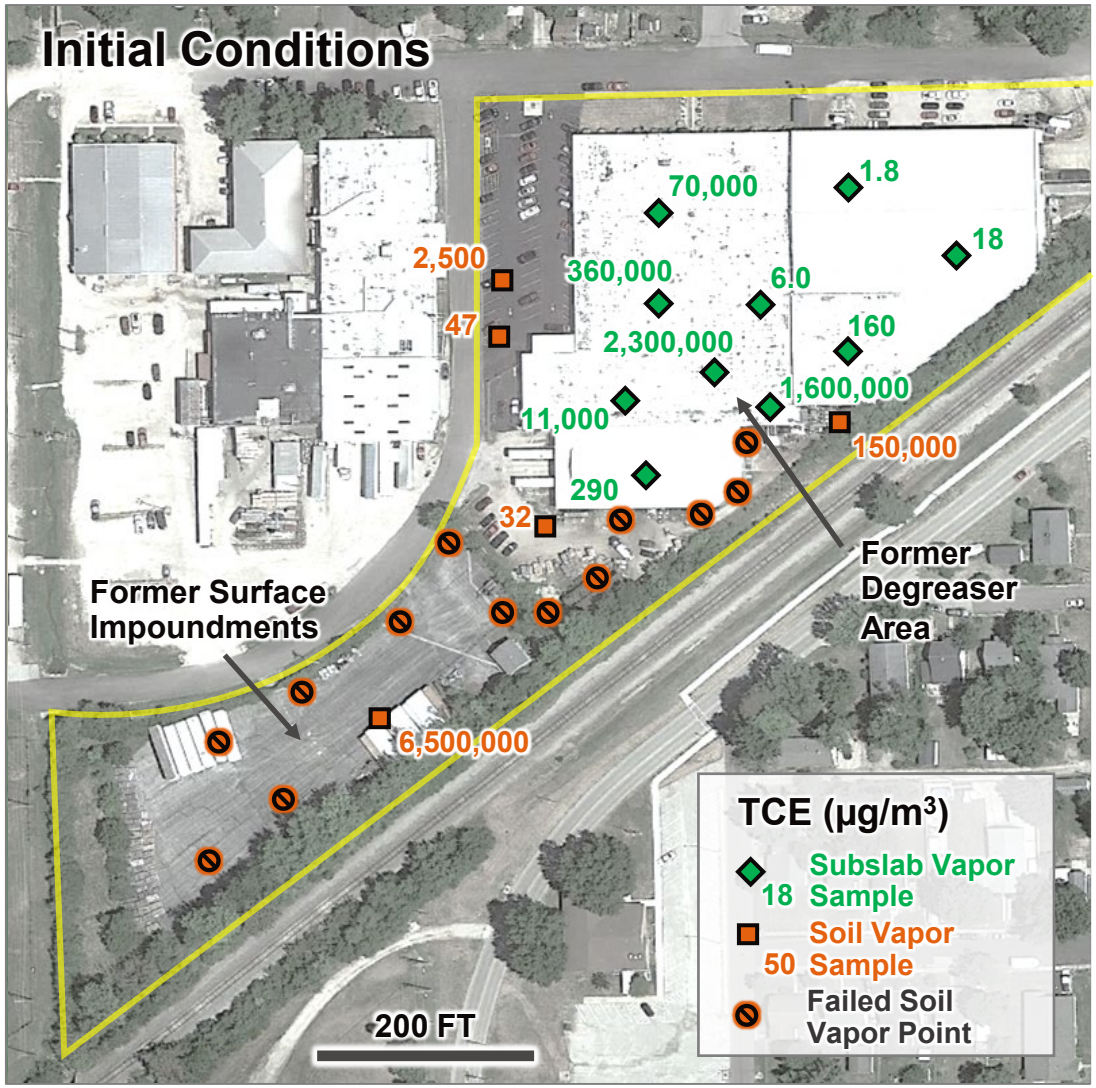
Addressing a TCE Pseudoplume

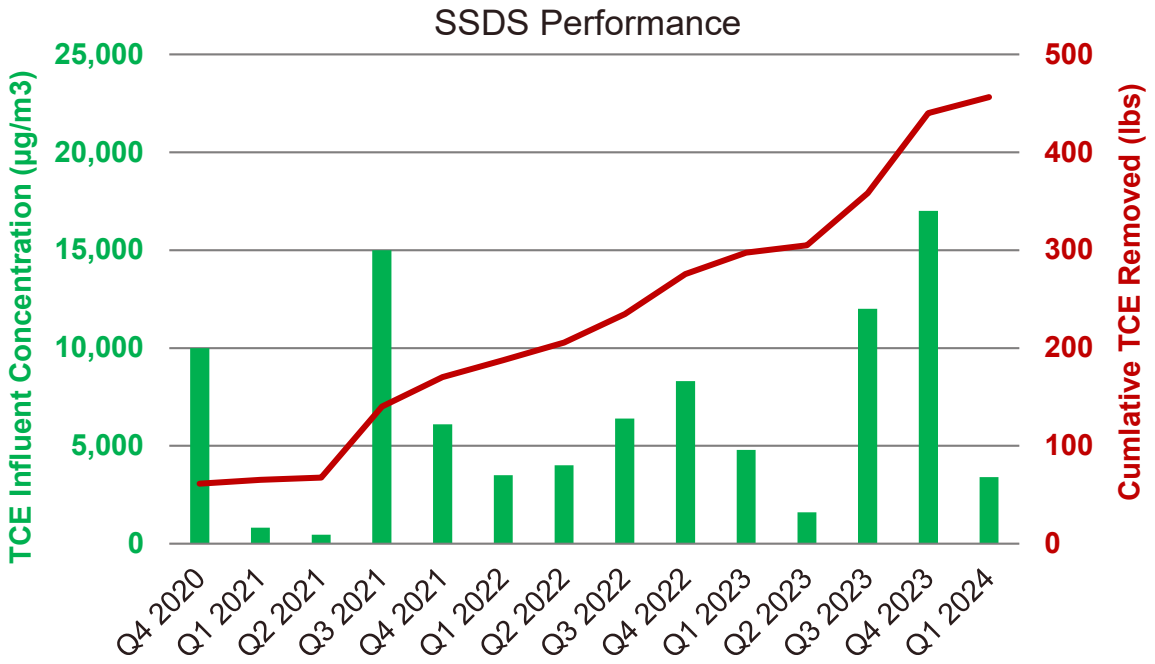
Industrial facility in Midwest, United States





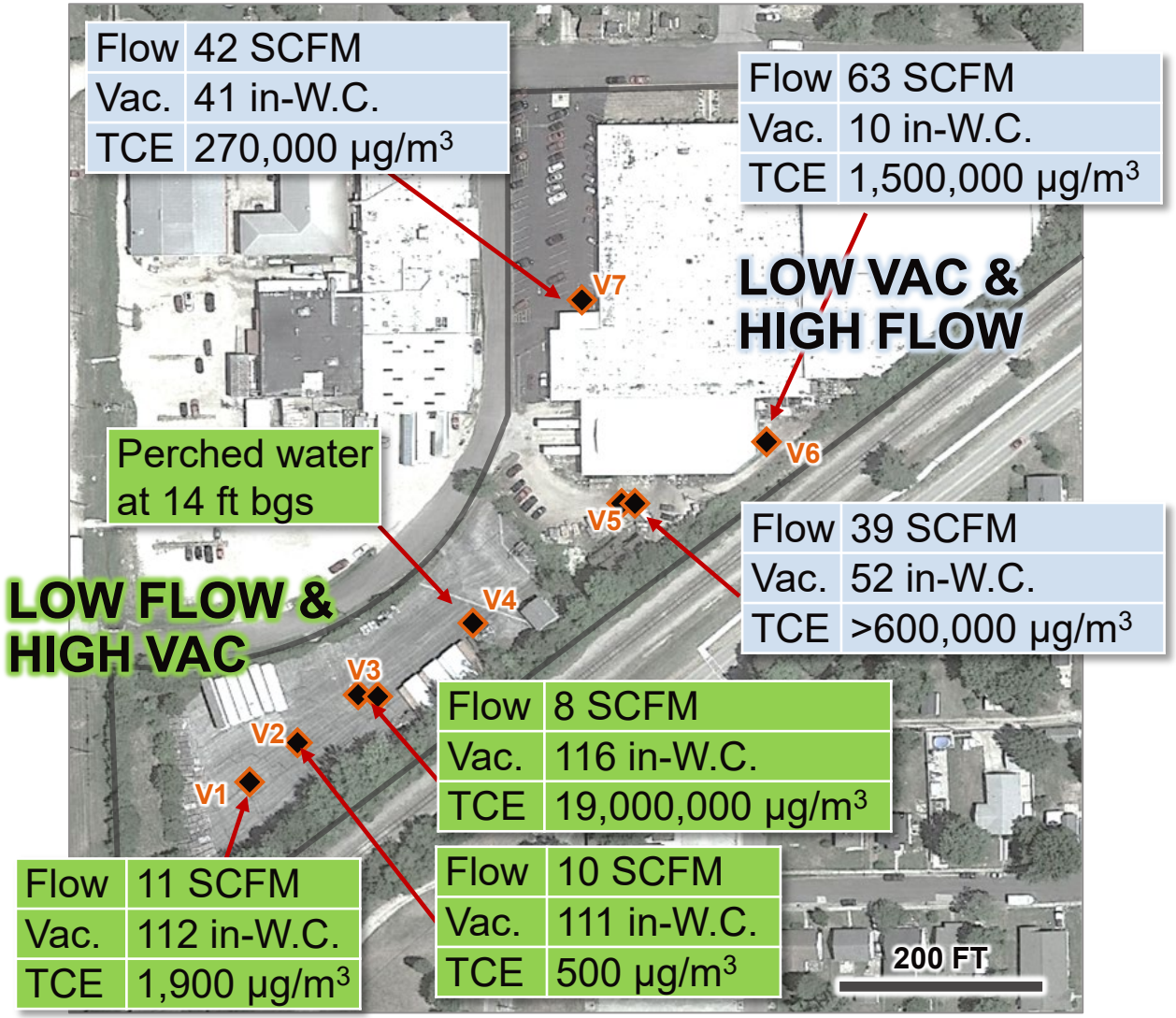
SSDS as Prelude to Vapor Extraction





No. Suction Points	15
Ave. Total Airflow	580 SCFM
Ave. Inlet Vacuum	20 in. W.C.
Average Mass Removed	10 lb/month TCE

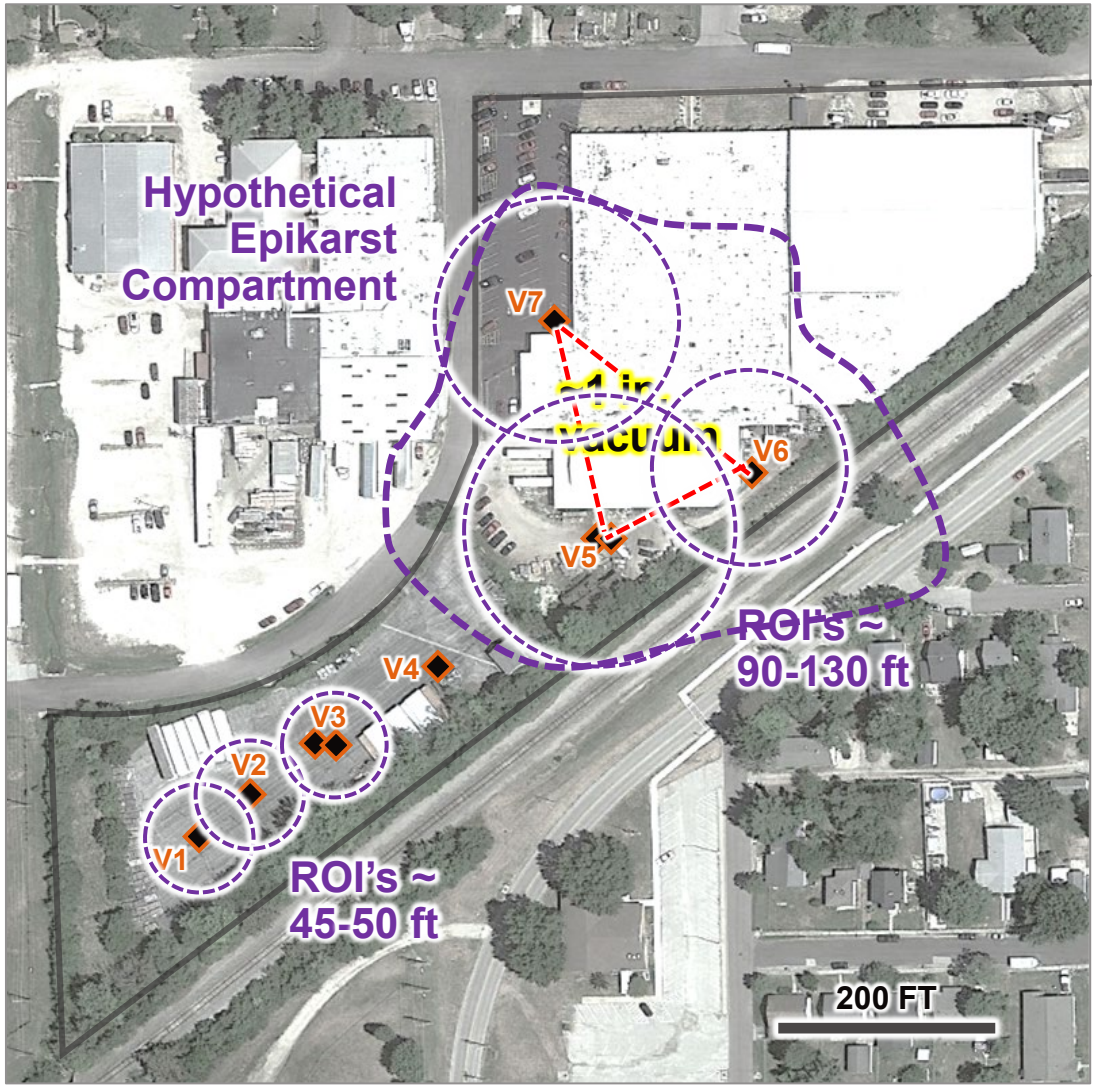
Vapor Extraction Pilot Test



Airflow in Standard Cubic Feet per Minute (SCFM)
Applied Vacuum in inches of water column (in. WC)
TCE at end of test in micrograms per cubic meter (µg/m^3)

- Extraction & observation wells installed at 7 locations, each to approximately 50 ft bgs
- Pilot tests completed at each well individually (3 HP blower, 8-12 hours)
- Highly variable results underscore heterogeneity of epikarst

Vapor Extraction – Going Full Scale



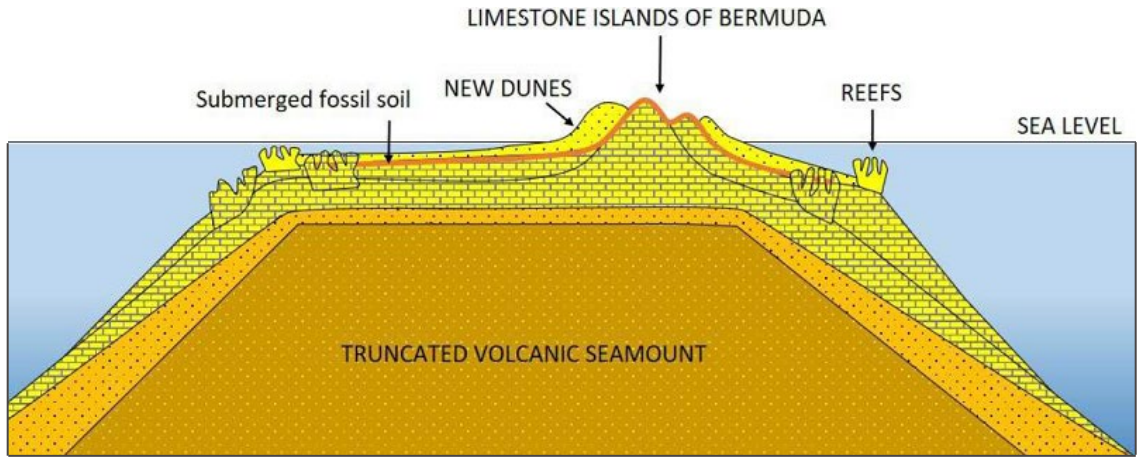
- Radii of influence estimated using porous media approach (3 percent porosity, 2 daily pore-exchanges)
- Calculations only so useful...
- Northern points each connected within networked epikarst compartment
- Rotating extraction among points expected to flush pathways
- Southern area to be addressed more conventionally

Example Case 2

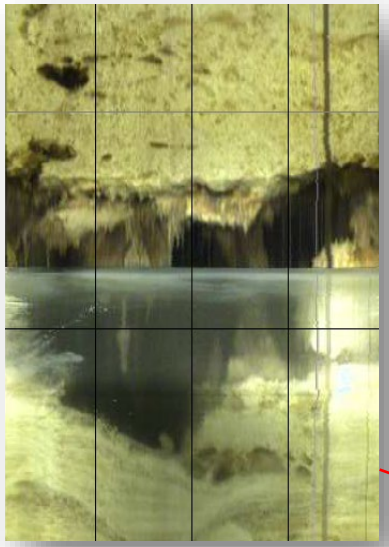
Rapid Response to a Tank Failure

Petroleum storage facility in Bermuda

- 3/17/2017 – gasket failure released 17,200 gallons of gasoline to the surface
- Gasoline seeped into the bedrock; reaching the water table in <48 hours
- Vac deployed initially to extract vapors from existing well
- Six vapor extraction wells installed and robust extraction system started 1 month after release

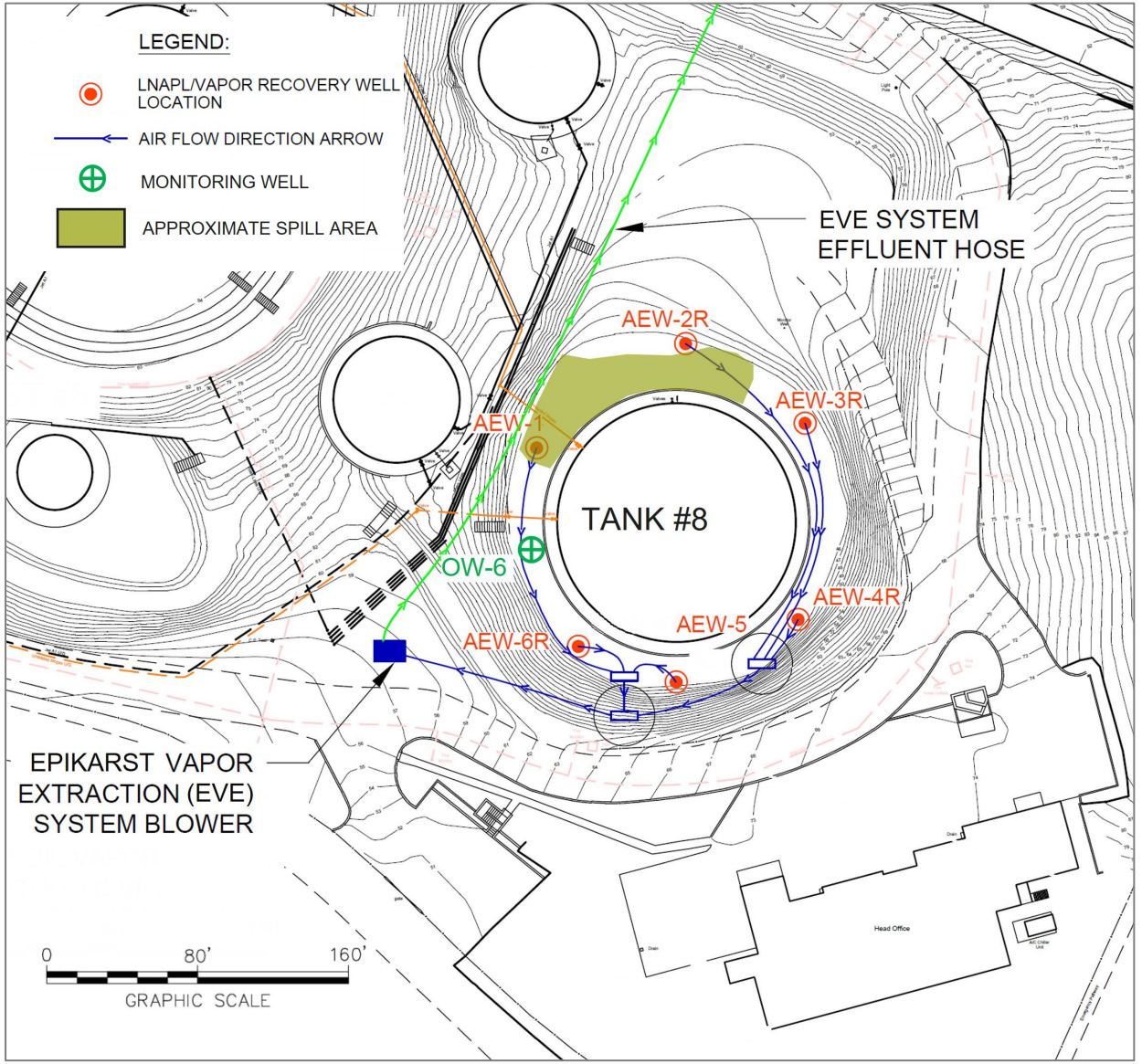


LNAPL Conceptual Model

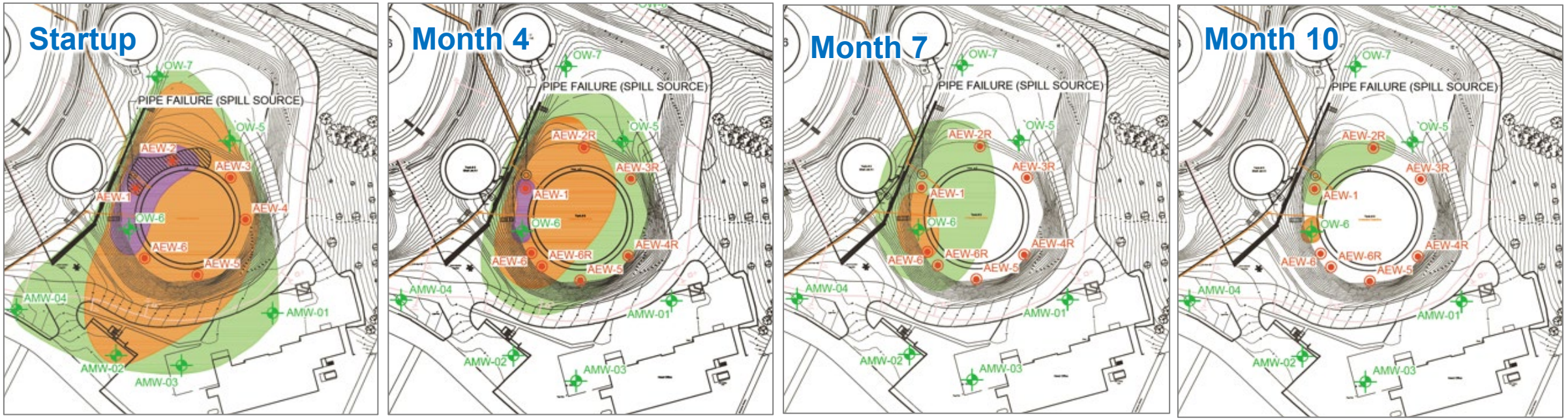


Vapor Extraction System

- Six “open-hole” vapor extraction wells
- Terminate 5 feet into water table; installed depths range from 40’ to 60’
- 15 HP regenerative blower and air/water separator
- Full system operated at approximately 350-480 SCFM, with only 1 to 4 in WC wellhead vacuum
- Area of influence estimated to span the entire Tank #8 area and extend to the southeast, including most of the facility office building
- LNAPL skimming at OW-6 and AEW-1



Vapor Extraction Performance



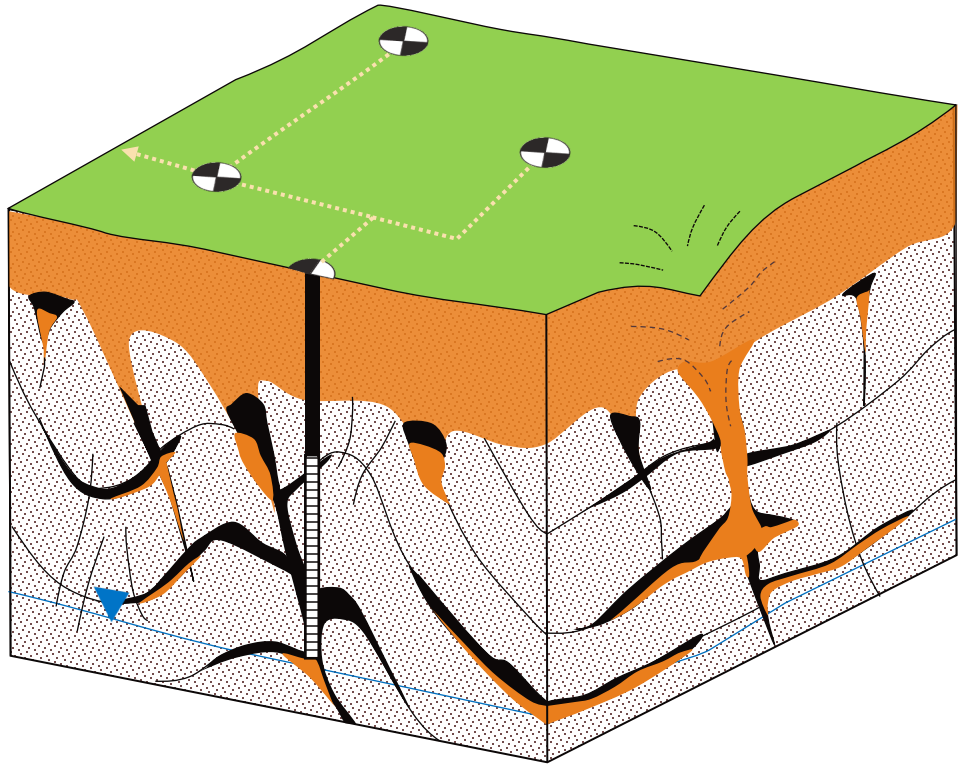
LEGEND:

- MONITORING WELL LOCATION
- OFFSITE WATER WELL LOCATION
- LNAPL/VAPOR RECOVERY WELL LOCATION
- APPROXIMATE LNAPL LIMITS
- APPROXIMATE DISSOLVED IMPACT LIMITS (INFERRED)
- APPROXIMATE VAPOR PLUME LIMITS (INFERRED/BASED ON WHERE VAPORS HAVE BEEN CONSISTENTLY MEASURED)
- SURFACE IMPACT OF SPILL

- System operated for 18 months
- Recovery rates up to 30 lbs/hr in early months
- Gasoline mass removed calculated to be equivalent to 6,500+ gallons
- Active system shut down in July 2018
- After one further year of monitoring, site granted NFA

Vapor Extraction in Karst: The Takeaways

- Performance will not conform to traditional SVE models
- A powerful tool to reduce source mass, if conditions are right
- Lower in cost and complications than nearly all other remedial options



Thank you!

Questions? Please reach out to:

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Also catch:

Eating the Elephant
Development of a Remedial Strategy in a Complex Karst Bedrock Setting

Whitney Sauvé, Arcadis U.S., Inc.

Monday 3:55 A2. Challenges and Lessons Learned in Remediating Sites with Complex Geology

Breaking the Uncertainty Logjam
Leveraging CSMs to Make Remedial Progress in Bedrock Aquifers

Urvi Tulsiani, Arcadis U.S., Inc.

Tuesday 12:10 A5. Process-Based Conceptual Site Models (CSMs) for Informing Remediation