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ORIGINAL ARTICLE

Down but not straight down: significance of lateral flow in the vadose zone of karst terrains

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Abstract Karst terrains exhibit some of the most heterogeneous and anisotropic subsurface properties of any geologic media. The vadose zone, and especially the epikarstic portion of that zone, is often important in detaining and laterally transporting contaminants in the subsurface. The epikarst, which is the interval between the regolith and rock in soluble rock landscapes, is routinely poorly characterized due to its vast heterogeneity and generally inadequate understanding of its importance in the subsurface movement of water and contaminants. At waste sites in karst, the traditional approach of measuring water table elevations at several wells, contouring these data, and inferring groundwater flow directions often fails to adequately characterize the subsurface movement of contaminants. This simplistic view of the subsurface presumes that infiltrating water and contaminants will move vertically from the surface to the water table. Lateral flow within the vadose zone, and especially in the epikarst, can produce radically different infiltration pathways than anticipated under the traditional vertical infiltration conceptual model. The horizontal extent of flow in the vadose zone is summarized from four case histories. The complicated connectivity of openings in the vadose zone, coupled with often variable infiltration from the surface, not only creates an unpredictable groundwater recharge regime at any one point in time but also a flow regime that can change under varying hydrologic conditions. Smith (Tenth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, ASCE Geotechnical Special Publication, vol 17, pp 154–160, 2005) studied two landfills in karst portions of Tennessee. He found that landfill contaminants were distributed roughly radially around the landfills and even up-gradient monitoring wells were impacted. Smith (Tenth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, ASCE Geotechnical Special Publication, vol 17, pp 154–160, 2005) suggested groundwater mounding beneath the landfills, but a more likely explanation is lateral flow in the vadose zone. A case history of an Alabama (Aley in Hydrogeologic assessment of ground water and surface water contamination resulting from the Florence, Ala., Municipal Landfill, p 35, 2010) landfill illustrates the practical implications of substantial lateral transport through the vadose zone. An additional case history of petroleum leakage contaminating a nearby water supply well in Arkansas (Aley in The engineering geology and hydrogeology of Karst Terranes, Balkema, Rotterdam, pp 207–211,1997) illustrates rapid transport of contaminants through a vadose zone with thick residuum.

Keyword Lateral groundwater flow · Epikarst · Contaminant migration

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Introduction

A common monitoring approach at waste sites—regardless of whether or not they are in karst landscapes—is to drill one well up-gradient and three or more wells down-gradient into the aquifer and monitor these for a selection of water quality parameters. Site selection for the wells is based largely on surface topography and a presumption that the water table will be a subdued reflection of surface topography. The typical site selected for the planned up-gradient well is in a location where two conditions are expected to be met. First, the elevation of the top of the water table must be higher than the water table elevation at the other wells. Second, the location should be desirable for detecting any off-site contaminants moving into the waste site of concern. All of the down-gradient wells are typically located relatively close to the wastes to hopefully maximize the chance of detecting aquifer contamination and detecting it in a timely fashion. The up-gradient well is routinely located near the wastes for a variety of reasons including property boundaries and a desire to have a monitoring system that is tightly focused on the waste site.

Many of the contaminants at waste sites, and especially sites in karst landscapes, originate at the surface at elevations substantially above the water table. At karst sites they are often in the epikarstic zone. An implicit assumption in the typical monitoring well strategy is that any contaminants leaking from the waste area will move more or less vertically down to the water table. In karst areas, and perhaps in some other hydrogeologic settings, this is a risky assumption that is sometimes—and perhaps often—incorrect. The lateral movement of contaminants for substantial distances in the vadose zone has been documented in karst areas and in the following examples. The frequency of lateral water and contaminant migration over substantial distances in the vadose zone is unknown but is probably common.

Lateral flow distances in the vadose zone

A primary challenge in determining lateral flow distances in the vadose zone is finding sites where they can be credibly measured. One effective approach has been to introduce tracer dyes at or near the surface of the ground and sample for them at ceiling drippage zones in nearby caves. This approach has been used in the following four case studies.

Case 1. Blanchard Springs Caverns, Arkansas

In 1971, the U.S. Forest Service was developing Blanchard Springs Caverns as a show-cave and had constructed a paved parking area higher in elevation than the cave passages. The parking lot was not directly above any known portions of the cave, but drainage from the pavement had been directed into pits filled with gravel. The pits, excavated into residuum, were up to 3 m deep and were located beneath the pavement. Water entered the pits through grated drains. The rationale for the pits was to maintain near-natural flow of water into the vadose zone near the cave so that the drippage of water onto speleothems (cave formations) would not be impeded. However, after the pits had been installed and the parking area paved, the agency became concerned that the pits could introduce poor quality water into the cave.

Fluorescein dye (Acid Yellow 73) and about 380 l of water were introduced into each of four of the parking lot drains. By the next day, the dye was detectable in two sampled drippage zones in the cave. The lateral distance from the nearest dye introduction point to a dye detection zone where water fell from the ceiling in the Cathedral Room of the cave was 239 m. Dye subsequently was detected at several points in the elevator shaft; this shaft is 195 m from the nearest dye introduction point. The elevational difference between the dye introduction points and the points where dripping water entered the cave was between 37 and 46 m. The parking lot was in a relatively level area underlain by deep residuum. The cave passages lay directly beneath a hillside. The bedrock in the area is relatively flat-lying limestone of the Boone Formation of Mississippian age. As a result of the tracing study, the Forest Service recognized that lateral water movement in the vadose zone would directly and rapidly convey poor quality stormwater runoff into the Caverns. The drainage pits were sealed and stormwater was re-routed.

Case 2. GB Cave, England (Smart and Friederich 1986)

Cave passages are located up to 140 m below ground surface. Dye was introduced at a single point on the surface of the ground and detected at 30 drippage stations in the cave. First dye arrival times at the drippage stations were within 5 days of dye introduction. The detection points in the vadose zone radiated outward from the dye introduction point; maximum distances to detection sites from the dye introduction point were scaled from a map in the paper and were approximately as follows: 75 m to the north; 34 m to the east; 70 m to the south; and 75 m to the west. Soils in the area were shallow and the authors concluded that the most extensive lateral water movement in the vadose zone occurred in the epikarst.

Case 3. White Scar Cave, Yorkshire, England (Bottrell and Atkinson 1992)

This cave is located in the horizontally bedded Great Scar Limestone. Fluorescent dyes were used to trace water movement through the 45–90 m thick vadose zone of limestone overlying the cave system.

A total of eight dye introductions were made at points below the soil cover. Two of these used the same dye introduction location with one of the introductions being made under flood conditions (Trace 6A) and the other under drought conditions (6B). The lateral distances traversed by the descending waters in the eight dye introductions were scaled from a map in the paper (Table 1). In all cases, the first arrival of the dyes at the sampling stations occurred within 24 h of dye introduction and the peak

Table 1 Lateral distances traveled through the vadose zone above White Scar Cave

Trace number	Lateral distance (m)	Lateral distance (ft)	Trace number	Lateral distance (m)	Lateral distance (ft)
1	38	125	6A	131	430
2	37	120	6A	30	100
2	50	165	6A	46	150
3	35	115	6A	35	115
3	107	350	6B	46	150
4	53	175	7	27	90
4	58	190	7	35	115
5	27	90	Maximum	131	430
5	30	100	Minimum	27	90
5	69	225	Mean	52	171
5	81	265			

The 6A traces were conducted under flood conditions and the 6B traces were conducted under drought conditions (Bottrell and Atkinson 1992)

dye concentrations arrived between 48 and 72 h after dye introduction. Subsequent precipitation events produced smaller peaks in dye concentrations.

Case 4. Tumbling Creek Cave, Missouri (Aley 2003)

Tracer dyes were introduced into a small epikarstic sinkhole about 2 m in diameter and 2 m deep on a hillside near mapped portions of Tumbling Creek Cave. Under low flow conditions, the dyes were detected in ceiling drippage at points located 143, 186, and 192 m lateral distance from the dye introduction point and at elevations about 15 m below the dye introduction point (Fig. 1). Under high flow conditions dye was not detected at any of these three sampling stations but was detected in water discharging from the epikarst at the surface 152 m laterally from the dye introduction point. The distance between the most distant detection sites was 271 m (Fig. 1).

The bedrock in this study area is flat-lying dolomite and chert assigned to the Cotter Formation of Ordovician age. Soil and residuum in the area are cherty clays. This trace has been replicated several times and travel time from dye introduction to initial dye detection at the identified sampling stations is typically less than 24 h.

Role of the epikarstic zone

The epikarstic zone is the interface zone between soil and regolith and rock in soluble rock landscapes (Jones et al. 2004). Thicknesses are commonly on the order of 10 m but are highly variable (Ford and Williams 1989). An introduction to a symposium on the epikarst (Jones et al. 2004) described the epikarst as including "…solid carbonate rock, wholesale openings in the rock, and unconsolidated sediments, including soil, regolith, silt, clay, trapped rock rubble, and trapped vegetative debris, thereby making it

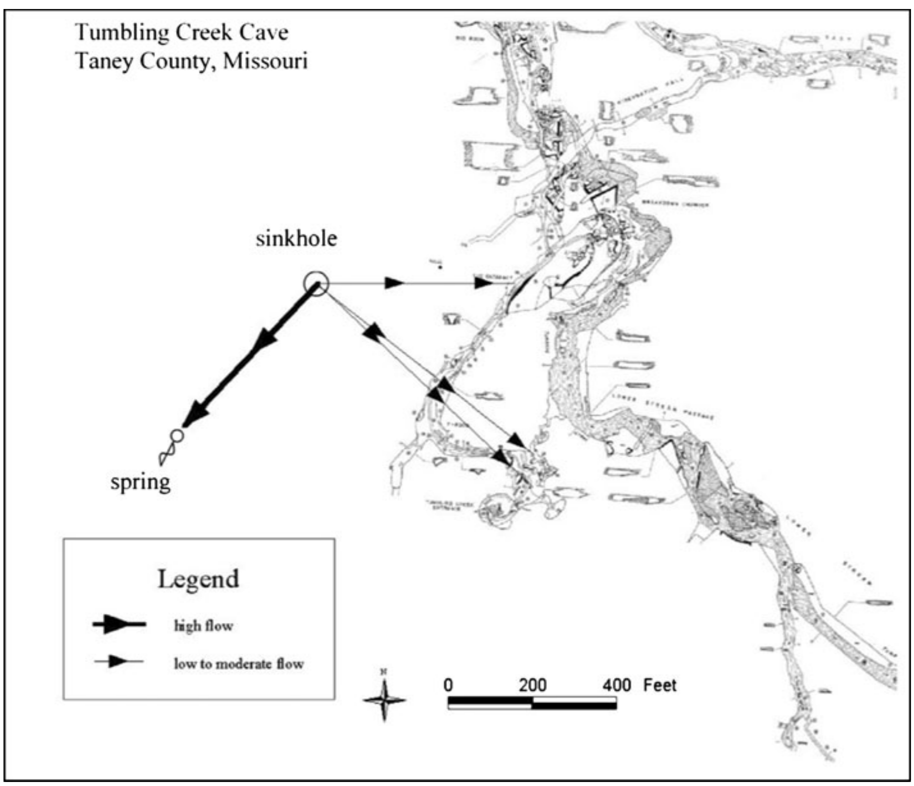

Fig. 1 Variable flow directions from an epikarstic sinkhole toward different cave passages under low to moderate flow and to a surface spring under high flow conditions (Aley 2003)

highly physically heterogeneous." White (2004) includes some sketches showing highly variable epikarstic conditions resulting from features such as shaley limestone, massive limestone, barrier layers, and dipping beds. In addition, experience has shown that the nature and extent of epikarstic development can vary dramatically over short distances.

The epikarstic zone is where much of the lateral water movement is observed in karst areas. Both vertical and horizontal permeabilities are routinely greater in the epikarstic zone than in the underlying rock mass that has been less affected by dissolution. This commonly results in ponding of water and lateral movement along preferential flow routes to localized features and zones where the water can flow to lower elevations. This in turn helps explain why the distances traversed by lateral water movement sometimes increase between low and high flow conditions. It also explains why the direction of flow may change between low and high flow conditions.

A major groundwater tracing study that included 46 new dye introductions and utilized results from 39 previous introductions was conducted in a sinkhole plain area of Perry County, Missouri (Aley et al. 2010). The area is underlain by Ordovician dolomite and limestone with a regional dip of about 1.5°. One of the primary purposes of the study was to delineate recharge areas for important springs and caves. The majority of the water that enters the cave stream passages of the study area does so in highly localized areas often substantial distances from each other. As a result, lateral water transport in the epikarstic zone and other unsaturated portions of the rock mass overlying these passages is appreciable. In some cases, tracer dyes introduced into sinkholes almost directly above mapped cave stream passages did not enter those streams but instead flowed to more distant cave streams. This suggests that many of the sinkholes in this area are directly connected to the epikarst and only indirectly connected to deeper conduits.

Practical implications

Smith (2005) discussed two landfills in karst in Tennessee. Linear groundwater flow directions had been drawn normal to potentiometric contours based upon water table elevations in monitoring wells. Smith (2005) showed that these flow directions were inconsistent with the locations of a number of monitoring wells where contaminants attributable to the landfills had been detected. He showed that landfill contaminants were distributed roughly radially around the landfills and that even up-gradient wells were impacted.

Smith (2005) concluded that the radial patterns of landfill leachate contamination around the two landfills resulted from mounding of the water table beneath the landfills. If that were to occur, then the total volume of water infiltrating through the landfill cap and into the buried trash would be greater per unit area than in adjacent lands where no trash had been buried. While the permeabilities of clay caps on closed landfills are often orders of magnitude greater than when they were installed, it seems unlikely that the infiltration rates over landfills would exceed those on adjacent lands. A more likely explanation for the observation of a relatively wide contaminant halo around the landfills is lateral movement of water and contaminants in the vadose zone. Such a halo is consistent with the flow patterns in the vadose zone as shown in case histories 2 and 4.

Smith (2005) notes that contaminants specific to the two landfills provide a tracer that is introduced over many acres of land for a long period of time. As a result, sampling for landfill constituents can help delineate the lateral extent of contamination in the vadose zone.

An example of the practical implications of substantial lateral water movement in the vadose zone is provided by a currently operating municipal landfill at Florence, Alabama (Aley 2010). The landfill occupies an area of about 30 hectares and is located in the lower Tuscumbia Limestone and upper Fort Payne Chert. The landfill basically fills a small, steeply sloping valley tributary to Cypress Creek. A dye trace conducted from the channel of the valley stream prior to the opening of the landfill demonstrated flow for approximately 700 m to springs in a valley south of the one now used for waste disposal. A more recent dye trace has shown groundwater flow of about 375 m from a leachate contaminated monitoring well adjacent to the landfill to springs in a valley north of the one used for waste disposal (Fig. 2). The monitoring well used for the dye introduction had been viewed as an up-gradient well for the landfill. Landfill leachates are now discharging from the springs where dyes have been detected and from other springs along Cypress Creek southeast of the landfill.

The landfill began operating in 1987. Leachate constituents were first detected in one of the monitoring wells in 1990. There are currently one up-gradient, one cross-gradient, and six down-gradient monitoring wells around the Florence Landfill. Elevated organic chemical parameters associated with landfill leachates have been detected in six of the seven monitoring wells including both the up-gradient and side-gradient wells. Potentiometric mapping of the top of the water table by the City's consultants has routinely shown south to east flow directions without evidence of flow toward the up-gradient and side-gradient wells. Based upon this mapping, consultants to the City have concluded that the source of contamination in wells

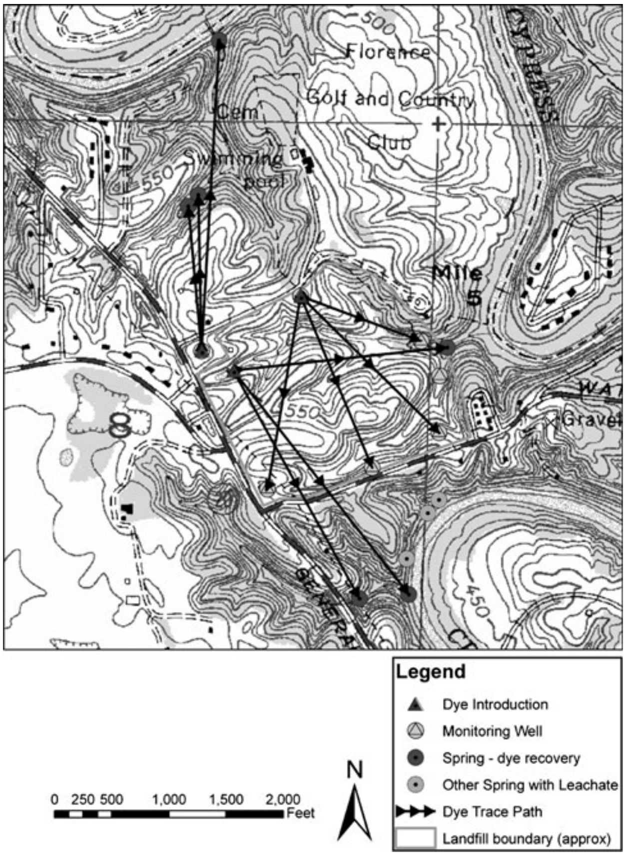

Fig. 2 Dye tracing results from Florence, Alabama landfill. No true up-gradient or cross-gradient wells exist (Aley 2010)

around the landfill is not from the landfill but instead from an unknown waste source. A nearby service station that experienced minor leaks has been suggested as a potential source even through the detected contaminants in the landfill monitoring wells are indicative of landfill leachates rather than petroleum hydrocarbons. As a result of reliance on the potentiometric mapping and the attribution of detected contaminants to an unknown source, until this year, no action has been taken to correct problems that have now been evident for almost two decades. Leachate with heavy deposits of iron bacteria and oil sheens now discharge from springs in three different topographic basins other than the one in which the landfill is located. Failure to recognize that lateral water movement in the vadose zone was the source of contamination in the up-gradient and cross-gradient wells has been critical to the inaction by the City and the Alabama Department of Environmental Management. The inaction has been changing in the last year, but necessary remediation efforts now will undoubtedly be much more costly than if all parties had promptly understood and accepted the likelihood of substantial lateral movement of water and contaminants in the vadose zone.

In some karst areas, the epikarst is overlain by substantial thicknesses of unconsolidated materials in which some of the lateral flow can occur. This was the case at a service station in Lakeview, Arkansas (Aley 1997) where the thickness of the soil and residuum ranged from 16 to 20 m over a relatively thin epikarstic zone. Petroleum leaked from a buried storage tank and concurrently petroleum constituents were detected in a water supply well 13.7 m away. The typical depth to water in this well was 43 m, total well depth was 66 m, and the casing was probably set only a meter below top of rock. Four borings that bottomed in the epikarstic zone detected no petroleum constituents in the residuum or in the epikarst. One of these borings was between the tank pit and the well. No water was encountered in the epikarstic zone, yet one of the consulting firms indicated that the epikarstic zone sloped away from the well and thus any petroleum hydrocarbons reaching that zone would flow away from the well. Laboratory permeability for a sample of the clayey residuum was measured at 10^{-6} cm/sec which led one of the consulting companies to argue that petroleum compounds could not have moved rapidly enough through this material to reach water in the well. There is, of course, little relevance of laboratory permeability values to unmodified natural materials.

On behalf of the well owner, 900 g of a fluorescein dye mixture and slightly less than 379 l of water were introduced into the tank pit. The amount of water used was constrained by attorneys for the service station and state regulators—it amounted to a depth of approximately 2.5 cm across the floor of the tank pit. The well was pumped at a rate approximately equal to its previous pre-pollution rate. Dye first arrived in the well within 20 h of introduction in the tank pit and the peak dye concentration occurred 9 days after dye introduction. The previous assessment work had failed to detect the preferential flow routes that led from the tank pit to the well. While nearly vertical flow through the vadose zone might have occurred, lateral flow within the vadose zone is probably more likely.

Groundwater tracing with fluorescent dyes has been critical in demonstrating substantial lateral water movement in the vadose zone. Introducing these dyes on the surface or directly into the epikarstic zone is important in determining the full extent of the area that is impacted by current waste sites in karst. However, groundwater tracing studies at waste sites in karst where the dyes are introduced directly into the water table through monitoring wells cannot assess the extent of lateral water and contaminant movement within the vadose zone.

At waste sites in karst, trenches or borings are commonly constructed that terminate in the epikarstic zone and introduce tracer dyes and flush water into these features. These routinely work well. Utilizing this approach is particularly important when water table elevations are well below the epikarstic zone and where much of the wastes are in or above the epikarst.

Summary

The case histories discussed in this paper demonstrate that lateral flow in the vadose zone of karst areas can traverse appreciable distances. The longest lateral distance reported was 239 m. The transport in the vadose zone is usually rapid with first dye arrival travel times of a few days or less. The movement of dyed water from a single point of introduction at or near the surface is often multi-directional, and different flow routes, and even different flow directions, may exist between high and low flow conditions.

Lateral flow in the vadose zone may result in the production of a halo of contamination surrounding waste sites. As a result, many to all monitoring wells for a site, including up-gradient wells, may show contaminants derived from the site even if contouring of the water table based upon water level elevations in the monitoring wells suggest that it is unlikely or impossible for site contamination to have reached the wells.

If dye tracing studies are to fully assess the karst area impacted by a waste site, consideration should be given to introducing the tracer dyes at or near the surface or near the top of the epikarstic zone rather than through a well at the water table. The importance of this consideration increases with the thickness of the vadose zone.

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