Carbonates Evaporites (2013) 28:55–66
DOI 10.1007/s13146-013-0152-7

ORIGINAL ARTICLE

An investigation of monitorability issues for groundwater in the Zachs Knob syncline area, Northeast Tennessee, USA

Randy M. Curtis · Thomas J. Aley · R. Keith Barnhill · Shiloh L. Kirkland

Accepted: 3 February 2013 / Published online: 2 March 2013

Abstract A dye trace was conducted in 2007 to verify a site conceptual model for groundwater monitorability near an orphan landfill in Sullivan County, Tennessee. The old landfill is in the Valley and Ridge physiographic province. Multiple tracing efforts in this area dating back to 1980 were either unsuccessful or yielded ambiguous results, causing the site to be deemed un-monitorable. Available geologic information, water chemistry data, and subsurface investigation results were compiled to produce a site conceptual model for about 120 ha of land, including the old landfill area. Eosine dye was used as a mimic for potential contamination effects in order to document the monitorability of the local aquifer as part of a hydrogeologic report for a new disposal facility permit. The site exhibits characteristics of a youthful karst setting at the surface. Overflow conduits left behind from a geologically older hydrologic system were found after detailed investigation. These remnant karst features were adjusted to a higher baseflow regime and act as a constraint to the maximum water table elevations in the present hydrologic system. Eosine dye was chosen as the best surrogate leachate after background water and bench scale leachate/dye interaction tests were done. The eosine injection was conducted in a variety of ways across the site to mimic potential leachate release scenarios from the proposed liner system for a new solid waste disposal facility. Eosine was visually detected in local springs and positively detected in some domestic supply and monitoring wells. Subsurface drainage patterns indicated two main groundwater basins in the area of study. Follow-up dye traces with simultaneous injections of pyranine and sulforhodamine B were conducted in 2009 to comply with the request of State regulators. The inferred drainage patterns were confirmed with dye detections at proposed monitoring points for each of the two main groundwater basins.

Keywords Eosine · Conduit · Monitor · Springs · Diffuse flow

R. M. Curtis (✉) · R. K. Barnhill
Gresham, Smith and Partners, Nashville, TN, USA
e-mail: heimdall@blomand.net

T. J. Aley · S. L. Kirkland
Ozark Underground Laboratory, Protem, MO, USA

Site description

The site is approximately 3 km northwest of the town of Blountville and is bordered by Interstate 81 to the south, US Route 11W to the north, State Highway 394 to the east, and Barger Hollow Road to the west. For the purposes of this report, the term, "Hollow" generally refers to a broad valley between two high ridges; the north ridge is the edge of the Pulaski thrust fault, and the south ridge marks the edge of the Dunham Ridge fault (DeBuchanne and Richardson 1956) (Fig. 1).

The bulk of the study area is within a syncline in the Pulaski thrust sheet that strikes northeast–southwest and plunges to the southwest, with some intrasheet thrust faulting and some cross-strike structural elements that were identified during the course of detailed investigations within the study area. The bedrock units are of Cambrian/Ordovician age and are mainly dolomitic limestones and shales.

Regionally, the surface streams form a modified trellis drainage pattern typical of the Valley and Ridge Physiographic Province. The study area is in a headwater or interfluve area where numerous small springs form perennial streams that follow strike until they reach water gaps in the north ridge. Because these streams are only first order

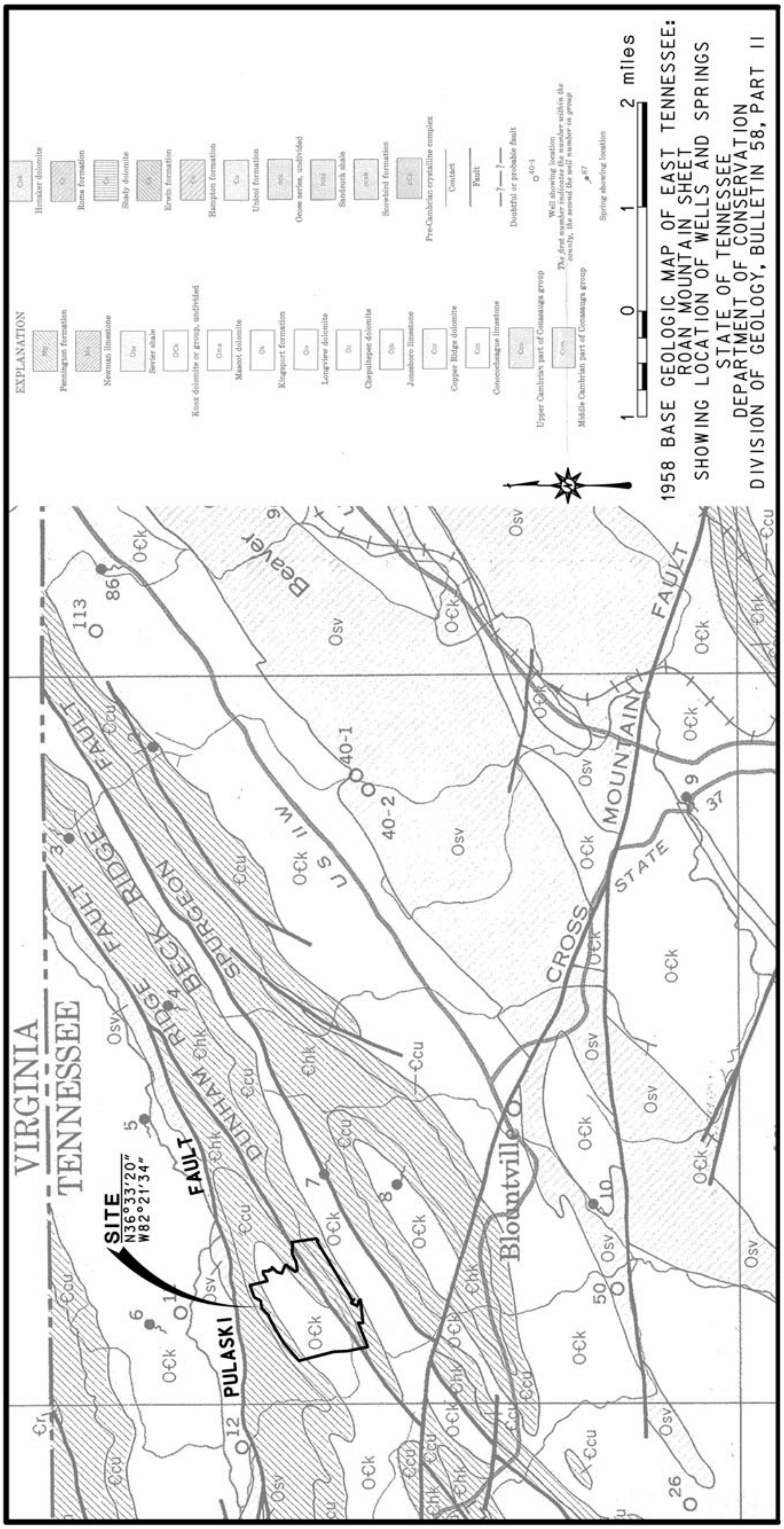

Fig. 1 Study area Barger Hollow

tributaries of Reedy Creek, they are not named on the topographic maps. For this report, the stream flowing through the water gap southwest of the injection points was called Barger Creek and the stream paralleling State Highway 394 northeast of the study area was called Hunters Trail Creek.

The local structural elements in the bedrock consist of low-angle thrust faults and a regional right-lateral cross-fault. The Zachs Knob syncline consists of steeply dipping Cambro-Ordovician calcareous shales, limestones and dolostones on the flanks of a southwest plunging syncline within the Pulaski Thrust Sheet. Detailed subsurface investigation indicates that the hinge of the syncline has been disrupted by a fault which has thrust the southeastern flank of the syncline upward, with concomitant cross-strike structural features such as lineaments, zones of weakness, and high-angle faults. The Dunham Ridge Fault Sheet thrusts similar age rocks over the southern flank of the syncline and footwall rocks in the Pulaski Thrust Sheet. The additional structural detail was one of the keys for the successful implementation of a dye trace for this area.

Historical background

Most of the prior tracing history for the study area was related to operations and proposed expansions of a solid waste landfill. The landfill was privately owned and it operated on leased land. When the owner died, the landfill became the State's Division of Solid Waste Management (DSWM) responsibility under the orphan landfill program. The orphaned landfill's fill area is about 12 ha (30 acres) and contains about 1.5 million cubic meters of municipal and industrial waste (over two million cubic yards of waste and cover soil). It was an unlined landfill which depended on a thick natural clay barrier to contain any solid waste constituents. The first indications of groundwater problems were noted about 6 months after the initial operation began in 1979. Surface water indicators of contamination in Hunters Trail Creek include discoloration, strong odor, and detectable volatile organic compounds in laboratory samples at several small springs. The facility has groundwater monitoring wells and water level data for about a dozen wells in the study area that provided data for the period dating from 1989 to 2009.

Dye trace attempts began about a year after the spring contamination was noticed (Fig. 2).

The first recorded attempt consisted of an injection of about 13,250 l (3,500 gal) of water mixed with green food coloring into a sinkhole covered by the landfill access road in 1980. The intent of this injection was to document that the landfill area was not responsible for the spring contamination by showing that no colored water would be visually detected at the contaminated springs about 365 m (1,200 ft) away along strike. About 2 years later, in October 1983, an unknown quantity of Formulab® green-yellow fluorescent dye was injected into a water supply well associated with the landfill. The target again was the contaminated springs though this time they were about 730 m (2,400 ft) away along strike. Positive indications were reported, and the well was abandoned because it still had yellow-green dye in it 14 months later.

The landfill continued operations until the mid 1990s, when there were a series of dye traces associated with contamination monitoring or proposed vertical or horizontal expansion permit requests. In August and October of 1990 there were two rhodamine WT injections into a sinkhole between the contaminated springs and the original food dye injection point. Some positive indications were reported for springs about 275 m (900 ft) away along strike. These injections were followed by a fluorescein injection into the abandoned water supply well in November 1990. Fluorescein was reported from a contaminated spring about 730 m (2,400 ft) away along strike.

In 1992 fluorescein was injected into a borehole on the southwest side of the drainage divide between Hunters Trail Creek and Barger Creek; the objective was the spring at the head of Barger Creek and indications of the dye were reported at very low levels but it was concluded that they were not above background.

In July 1994 an attempt was made to trace from a contaminated monitoring well about 1,100 m (3,600 ft) southwest of the landfill, along strike, to a series of springs along Barger Creek about 460 m (1,500 ft) further southwest. Some very low level rhodamine WT detections were reported.

Tracing water from injection points to local springs up and down strike was considered essential for the site characterization for a lateral expansion or a new landfill permit adjacent to the old landfill. The old site was closed in 1995, and the request for a new permit was held up by the perceived failure of the applicant to demonstrate monitorability.

In 1998, another attempt was made to trace water to the spring at the head of Barger Creek, this time using rhodamine WT injected into a sinkhole about 730 m (2,400 ft) north northeast of the spring. Positive detections were reported for monitoring wells at the old landfill and contaminated springs northeast of the sinkhole, but not at the target spring for the lateral expansion characterization effort. The only detections at this large spring at the head of Barger creek were some ambiguous positive fluorescein detection in 1992/1993.

2007 Study background

In 2004 a new applicant wished to re-visit the issue of monitorability in order to move forward with a permit application for properties adjacent to the old landfill. The

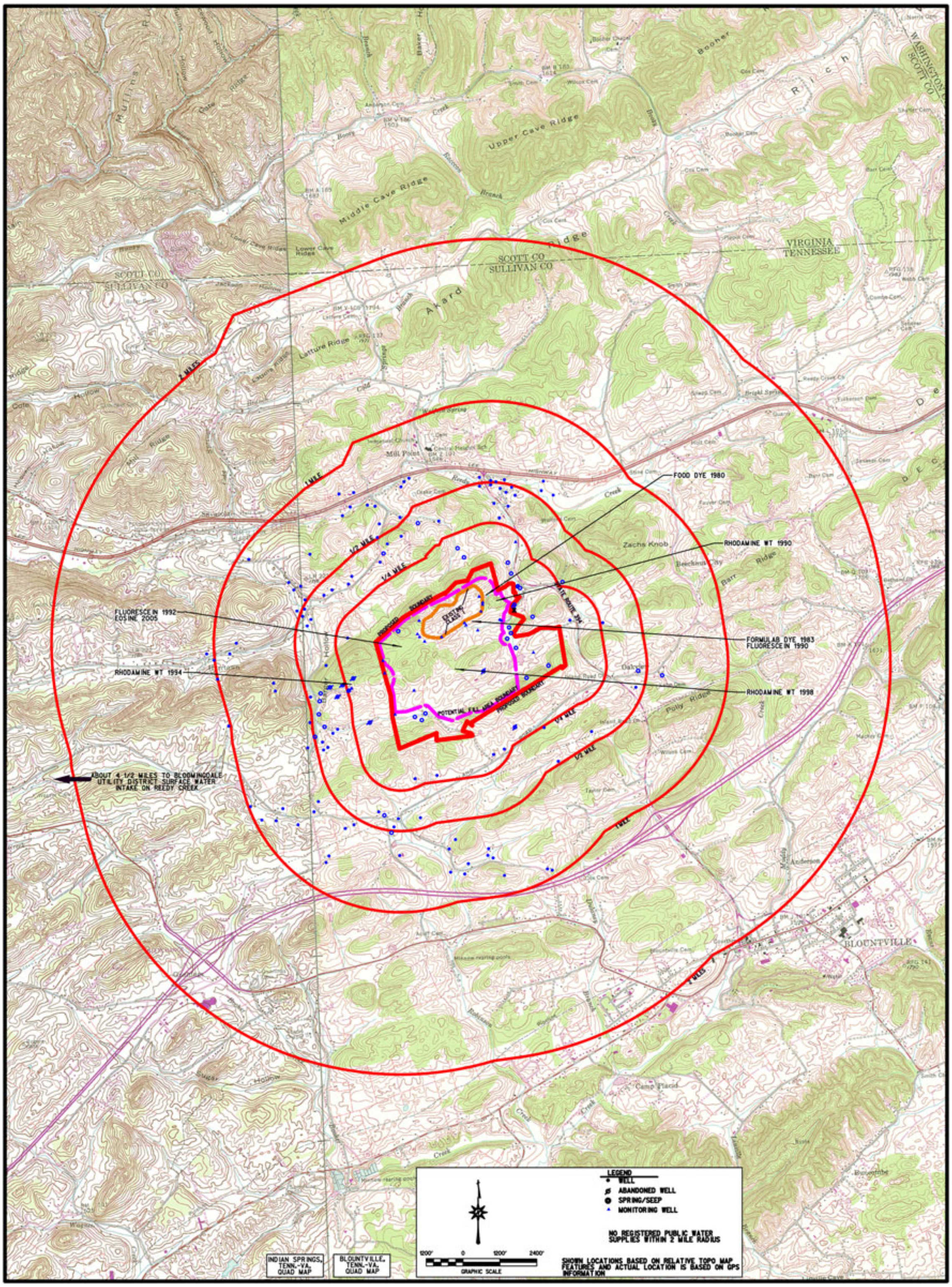

Fig. 2 Pre-2009 injection history

logical starting point was the potential positive results from the 1992 fluorescein injection event. A new regolith collapse sinkhole had been found near the 1992 fluorescein injection borehole and a statistical evaluation of the charcoal packet fluorescein results indicated a relatively short travel time to the spring at the head of Barger Creek, about 640 m (2,100 ft) away to the south southeast. Two large totes of 1,892 and 3,785 l (500 and 1,000 gal) capacity were moved to the new sink to determine if the hole would receive water and at what rate. The small hole at the bottom of the sink accepted water as fast as it would gravity drain through a 5 cm (2 in.) line.

In February 2005 a dye trace was done using 5.44 kg of eosine dye (75 % dye equivalent powder) mixed with 50 gal of water, in general accord with the procedures outlined in the groundwater tracing handbook (Aley 2002). The 1992 ambiguous fluorescein trace had used 5 l of dye solution (332 gm/l uranine sodium fluorescein) from 12/18/92 that was followed for 55 days at 14 monitored locations, ending 02/11/93. The 2005 eosine trace followed several weeks of background charcoal packet rotations at multiple spring, creek, and well sampling points. Criteria for a positive eosine trace were established as at least 3× background. The injection was timed to coincide with the high range of the seasonal water table variation for the site.

No positive eosine detections were detected in the study area between the ridges at Barger Hollow, although strong indications (<3× background) were seen about 1.5 miles away in a creek that starts near the Cross Mountain Fault, a regional cross-fault in the Valley and Ridge (Gresham et al. 2005). However, because multiple dyes were scanned for in the elutant from the charcoal packets, strong positive fluorescein detections were noted in springs up and down strike from the eosine injection point. Because these detections appeared to be related to precipitation events >2 cm (0.75 in.) in a day, and because it had been 13 years since any known fluorescein injection in the study area, two possibilities had to be incorporated into the water flow conceptual model: (1) fluorescein was hung up in the subsurface in such a way that large precipitation events mobilized some, but not all of it; or, (2) the fluorescein was an incidental component of leaking landfill leachate, and

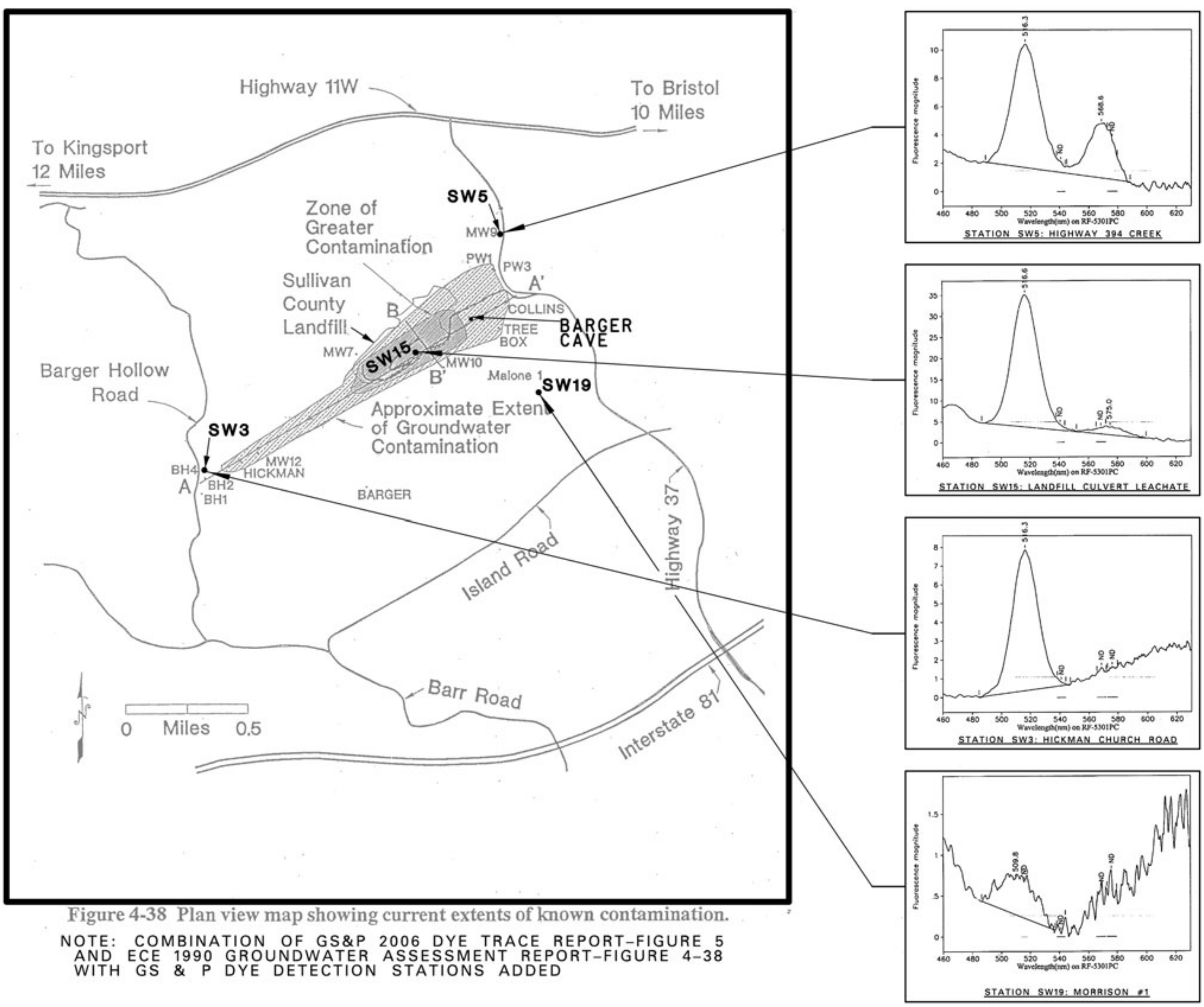

Fig. 3 2005 dye stations and leachate contamination

the detections were related to landfill contamination (Fig. 3; Environmental Consulting Engineers 1990; Gresham et al. 2005).

2007 Eosine injection preliminary work

While the February 2005 attempt was no more successful than its predecessors in detecting the targeted dye, the strong non-targeted signals provided insight into the nature of the hydrologic system. Signals not seen in the course of baseflow monitoring were detected in the aftermath of relatively heavy rainfalls. In order to achieve positive results with the next and hopefully final tracing attempt, several preliminary actions were taken. Charcoal packets were placed in stormwater ditches at the old landfill to evaluate the potential for common dye fluorescence signatures if there were leachate impacts to the groundwater. Undiluted leachate samples were taken for bench scale tests for potential leachate induced alterations in common tracing dyes. Field parameter and water chemistry data was acquired to evaluate the utility of leachate impact as a tracing mechanism, (Baker 2005; Mazor et al. 1985; Meisler and Becher 1967) and continuous field parameter measurements were taken to evaluate precipitation-induced changes at the large spring feeding Barger Creek. The ultimate goal was unambiguous dye detections in springs and monitoring wells around the properties to be used for a new landfill footprint, inclusive of the old landfill area.

An In Situ Inc. Troll® 9500 continuous recording unit was deployed to monitor pH, specific conductance, and temperature at the head of Barger Creek for 3 weeks in October 2006. The continuous field indicator measurements recorded by the Troll® 9500 unit documented clear diurnal variations in temperature and, after two intense precipitation events, significant variation in specific conductance values (Fig. 4).

The specific conductance values at the head of Barger Creek increased rapidly after more intense precipitation events in the 3 week span. This indicated a piston effect in the recharge feeding the spring, whereby the internal stormflow recharge displaced stored water (White 1988). A re-evaluation of a historical series of continuous field indicator measurements northeast of the old landfill (October/November 1991) showed a similar but more gradual response to precipitation events.

Other field activities in late 2006 included multiple borings to confirm suspected cross-strike structural elements and a hypothesized fault in the core of the syncline, and to establish monitoring wells, observation points, and targeted injection points. The area is classified as a youthful karst setting (White 1988), with a few sinkholes on-site and some caves within the drainage basin. On-site sinks, including the injection points for the 1998 rhodamine WT and the 2005 eosine injections, were excavated with a track hoe and subsurface conditions were evaluated. For safety reasons these excavations could not be left open, so small diameter steel pipes were salvaged and placed at a shallow angle in such a way that backfilled trench material would surround them but not bend or crush them. These were intended to provide methane monitoring locations and to serve as potential direct routes for future dye injection.

Preparations were complete by February 2007 for the implementation of a follow-up eosine trace to document monitorability of the site with wells and surface water/spring monitoring stations. The intent was to use eosine

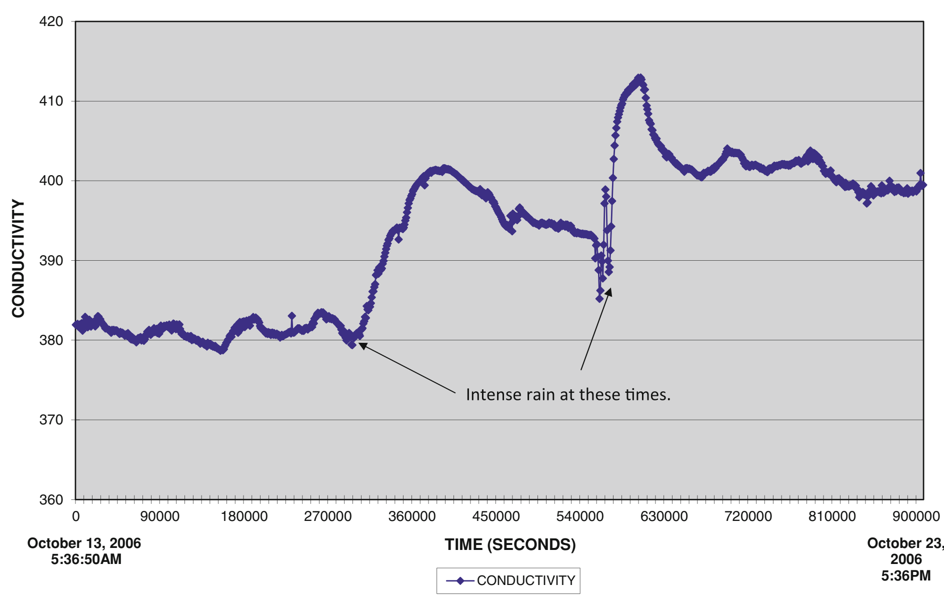

Fig. 4 Time series of measurements at the head of Barger Creek

dye as a mimic for possible leakage scenarios if a new lined landfill was permitted. Accordingly, ten injection locations were identified that would represent the gamut of injection techniques, from ground surface dry sets and animal burrow liquid injection at rock outcrops, to sinkhole and subsurface injections, with and without pre-injection wetting and chasing slugs of water.

Successful eosine dye trace, February 2007

The eosine (Acid Red 87 Eosine OJ,) totaled of 54.4 kg (120 pounds) of 75 % by weight dye mixture split evenly between 10 injection points across the approximately 121 ha (300 acres) of the proposed site. Figure 5 shows the 2007 injection points. Six carboys, pre-mixed, with 75 % by weight eosine in 18.9 l (4.5 gal) of water, were used to quickly set up on the initial sites on the first day, and then new wet dye mixtures were produced at a dye mixing station set up at the old landfill maintenance shed. The shed was about central to the injection locations and could easily be kept under control in terms of housekeeping. Water was supplied from a local water well driller who had a domestic well several miles removed from the site. Wilson Drilling's water truck had a 7,500 l (4,000 gal) capacity steel tank. An all-terrain back-up for the water truck was a 5,700 l (1,500 gal) capacity plastic tank mounted on a hay wagon pulled by a farm tractor. This was filled with water from a nearby spring-fed farm pond and was used for sinkhole injection slug water. There was also a smaller 3,000 l (800 gal) capacity plastic tank available and a 280 l (75 gal) capacity barrel that could be mounted on a mechanical 'mule' all-terrain vehicle.

New background determinations were undertaken because eosine had already been used in the area 2 years earlier. After notifying the Tennessee Division of Water Supply of the intended amounts and tentative locations for the replication of the eosine trace, background charcoal packets and water samples were acquired at springs, domestic wells, surface waters, and landfill groundwater monitoring wells. Doubled charcoal samples were placed on the first day, 2/6/2007, and half of them were replaced on 2/13/2007. On 2/19/2007, while the injection team was setting up, a sample team placed new packets and began picking up background samples. This yielded two 1-week interval background samples and one 2-week interval background sample. Anything over 10× background dye concentration would be regarded as a positive result. Reported dye concentrations were based on the eosine mixture used and were not adjusted for the dye equivalent weight.

The dye injections took nearly 2 days, starting at 11:00 a.m. local time on 2/21/2007 and ending at 10:10 a.m. on 2/22/2007. There was visible dye in the large spring forming the headwaters of Barger Creek on the western side of the site by late afternoon on February 22, 2007 (52 h after first injection on the west side). The flow in Barger Creek was traced downstream far enough to confirm

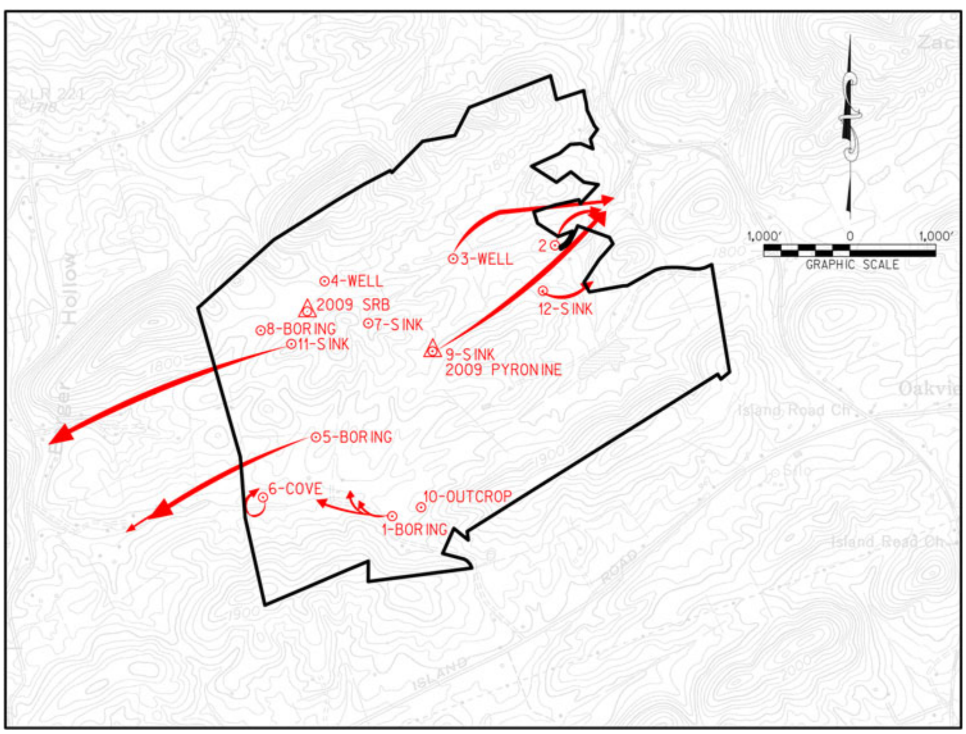

Fig. 5 2007 eosine injection points

that Reedy Creek was not receiving significant color. Visible dye was seen in Hunters Trail Creek on the eastern side of the site the following afternoon, February 22, 2007 (30 h after the last injection on the east side). The visual detection limit for eosine dye in water under field conditions is around 135,000 parts per billion, while the minimum detection limit for eosine in lab conditions with instrument analyses is between 0.008 ppb for water and 0.035 ppb for elutant containing eosine (Aley 2002).

Because the intent of the trace was to document monitorability of the eosine dye as a leachate mimic, the charcoal packet rotation schedule was not altered because of the visual water detections. Packets were changed weekly for 3 weeks, then at intervals of 2, 3, and 4 weeks until May, 2007. Selected points received an additional examination in June 2007. Charcoal elutions were done on some replicate samples as part of the quality assurance/quality control program, and water samples were taken and examined whenever the charcoal yielded dye detections. Dye was still being detected in the creeks 124 days after the last injection. Eosine dye was also detected in two domestic wells near the southwestern corner of the proposed project area (Fig. 5).

Site conceptual model

A site conceptual model was developed, based both on where the dye was detected and where it was not detected (Fig. 6). The soil on site consists of residual and transported components. The thickest soil areas appear to be related to alluvial or colluvial augmentation of existing residual soil columns. The uppermost soil layer near steep slopes appears to contain a great deal of colluvial material; the thickest soils on site consist of a topmost colluvial layer, a bottom residual layer, and a middle layer where illuviation processes have transported clay at a colloidal particle scale into pre-existing stormwater infiltration pathways.

Precipitation water at the site can travel very quickly in colluvial soils or residual soils with macropores developed due to shrink–swell and rootlets. Areas of exposed bedrock on the site tend to be impermeable due to selection, i.e., any permeable rock has probably been dissolved into a cutter already. Rock exposures are remnants able to withstand direct infiltration, probably with more permeable pathways off to one side into the epikarst. The thickness of the unsaturated zone at Barger Hollow is 0–60 ft, with soil being entirely absent in some places and groundwater issuing from the ground at some points along the topographic lows. The saturated zone is mostly in the fracture matrix; with some solutionally enlarged fractures and some relatively isolated pockets of groundwater developed in sandy soils or in primary porosity sandstones.

Most of the groundwater flow is fracture controlled, with a few fractures preferentially enlarged to conduit size interconnected with the slow, matrix flow. Some lithologic units are more susceptible to dissolution than others, but the majority of observed solution voids appear to be the result of mixing corrosion at the time of a shift in baseflow

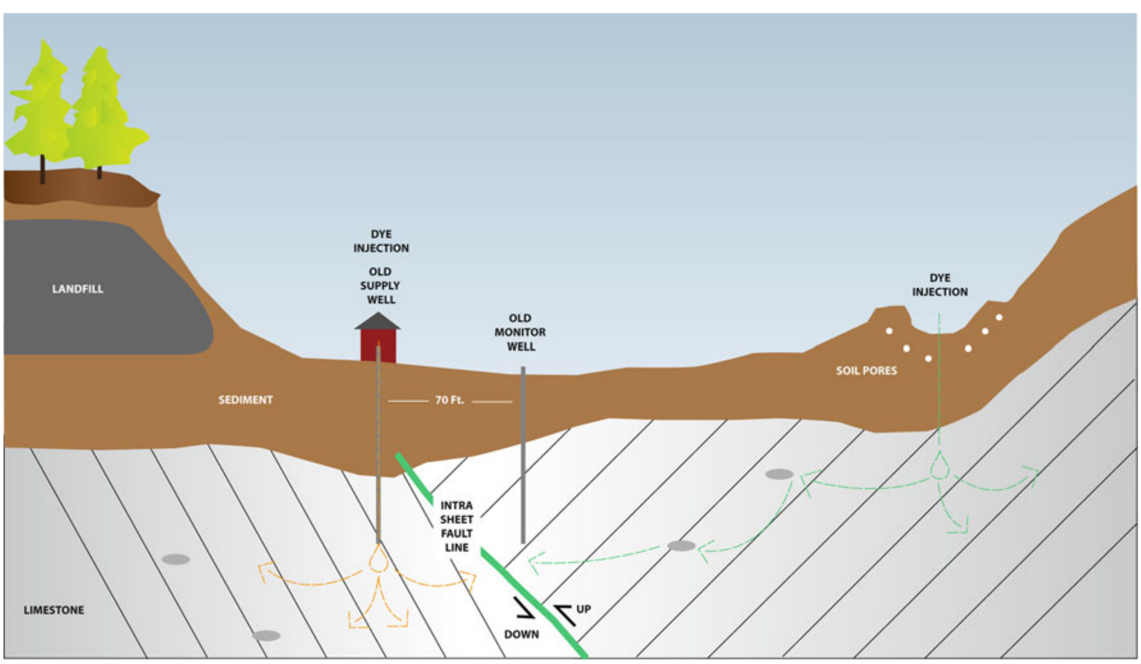

Fig. 6 Site conceptual model

conditions from an ancient higher level to those found in the present topography. The closest mapped caves to the site contain elements of relic high-velocity groundwater flow in the form of venturi-tube shapes at the head of keyhole shaped cross-sections aligned with strike and joint set directions. Larger rooms in those caves are sealed with mud/cobble/rock fragment debris on the up-plunge ends. This old high-velocity paleo-conduit level is an upper constraint on the degree of water table fluctuation due to intense precipitation events; strong rains quickly infiltrate the available fracture permeability in the bedrock and begin to raise the hydraulic head within the aquifer while flowing toward the local baseflow discharges. Excessive rains raise the water table to remnant paleo-conduits which were capable of handling water flow from an earlier environment (Bartholomew and Mills 1991; Driese et al. 2005; Kiraly 2002). That flow is dispersed to upper bedrock fractures or formerly preferred baseflow discharge points. Flow is predominantly along strike, with interruptions brought about by faults or deformation zones.

The faults or deformation zones are not uniformly barriers or pathways. The fault zone core may be impermeable, but there may be significant flow through in areas with less micro-tectonic fault gouge and breccia and more of a bedrock to bedrock contact exists at the fault. This potential for flow through makes the piezometric heads upgradient and downgradient of faults interdependent (Celico et al. 2006; Fairley et al. 2003).

Relation of trace results to the conceptual model

The fault hypothesized to account for the abrupt transition in dips near the core of the study area is projected to run between the old landfill supply well used for past injections in 1983 and 1990 and its intended replacement, MW#3, located just at the foot of the slope off the orphaned landfill site. The slope is inferred to mark the trace of the fault because MW#3 did not have any eosine detections, despite the 2007 eosine dye injection into the old water supply well being only about 24 m (80 ft) away up the hill towards the old landfill. The eosine powder at that location was poured into the old supply well casing and chased with about 6,400 l (1,700 gal) of potable water at a rate of nearly 112 l (30 gal) per minute.

There were only two groundwater monitoring wells with eosine detections at the old landfill, MW#7 and MW#2. Only MW#2 had a positive detection according to the pre-injection criteria of 10× background; 2,210 PPB dye equivalent was recorded between 4/18/2007 and 5/23/2007. The wells at the old landfill are sampled using a micropurge technique which only removes a few liters of water per sample event. MW2 had been sampled on 4/15/2007. In order to evaluate potential purging effects, the dye monitoring wells installed to test monitorability for the proposed new landfill had been left to natural water table variations during most of the 2007 eosine dye trace. On May 16 and 17, 2007, DMW-3 and DMW-4 were subjected to standard groundwater monitoring well purging practices to see if dye in slow-flow, fracture-fill groundwater could be induced to enter the well screens by artificially altering the hydraulic head. The site conceptual model was for recharge water to flow fast in conduit-based, turbulent flow after major recharge precipitation events, with corollary slow, non-turbulent flow in saturated small fractures and joints in the bedrock in the period between large rainfall events. After pumping, dye was detected in DMW-3 and DMW-4, confirming that micropurge techniques could miss the eosine contaminant mimic in monitoring wells within 24 m (80 ft) of an injection point because micropurge does not induce sufficient head change to sample the fractures in the saturated zone near a well for a few tens of meters.

On May 23, 2007, a slim line bailer was used to acquire water samples from five injection points in order to see how much dye remained 3 months after the injections. Observation Well 1 had 463,000 PPB dye mixture. The old landfill supply well took water as fast as it could be released at the time of injection and had 2,800 PPB left in the groundwater in the well bore. Observation Well 2 also took water very quickly and had 755 PPB dye left in it. The Core 1 injection point took chase water very slowly but had a deep water column and 27,700 PPB dye left. The Core 3 point received the 10 gal of liquid dye mixture but no other chase water; this was one of the last points scheduled to receive a chase slug of potable water and the visual dye in Barger Creek was seen as the creek was crossed going to Core 3. Because visual dye was in the target point, Core 3 was left alone as a check for the degree of dilution attributable to natural water table variation. Core 3 had a dye mixture of 1,490,000 PPB remaining 92 days after the injection.

Another item of note was the lack of eosine detections in DMW-2. This well was emplaced near the southwestern boundary of the proposed site and did not fully penetrate to the uppermost aquifer. Features typical of the epikarst zone (Kiraly 2002) were noted at this location at the time of drilling, so the well was screened above the zone of saturation. Water levels in this well were detectable only after storm events. The packet for this well detected fluorescein but not eosine. It is located approximately 670 m (2,200 ft) from the 1992 fluorescein and 2005 eosine injections, and about 304 m (1,000 ft) from the closes 2007 eosine injection.

Of 532 charcoal packet analyses from 73 locations over a period of 5 months, 116 eosine detections were reported (including duplicates). Not all of these met the standard of proof of 10× background for a positive result. The objective of the monitorability study was to introduce an artificial pollutant mimic into the environment to simulate a potential leak of leachate from a proposed new landfill into the uppermost aquifer. The eosine dye was quickly detected in the closest surface water bodies and the larger springs adjacent to the proposed landfill site. The dye detections continued over a period of several months indicating the dye was present in both conduit flow and slow fracture flow areas in the saturated zone. Dye was not positively detected in monitoring wells until purging induced a change in hydraulic head, demonstrating that monitoring wells not screened directly in conduits are capable of detecting contaminant releases via the diffuse flow in the saturated portion of the uppermost aquifer. Dye persisted at very high levels in the water in some of the injection points 3 months after injection. Eosine will probably persist in the Barger Hollow area for a significant period of time. This should be considered by the Tennessee Division of Water Supply in the evaluation of any future requests for dye registration in the vicinity of the study area covered in this report.

Based on the available data, including the positive results from the 2007 eosine dye trace, the hydrologic system at the Barger Hollow site was determined to be monitorable with a combination of traditional wells penetrating the uppermost aquifer and groundwater discharges into perennial streams east and west of the proposed landfill site. The eosine dye, as a leachate mimic, demonstrated that detectable dye flowed quickly to the streams as water in transit under increased hydraulic head conditions, but was persistent for several months due to the slow-flow component of groundwater in storage in the fracture systems in the bedrock. The enlarged fracture/small conduit pathways and the associated fracture/joint systems are intermingled and amenable to monitoring by wells as long as conventional purging protocols are applied. Failure to appreciate the slow fracture flow component's predominance over stormwater macropore flow in the regolith and conduit transit flow in the bedrock were contributing factors in a succession of less-than-successful historical tracing attempts. The interconnection of fast and slow-flow groundwater pathways effectively buffers slugs of dye in this setting by diverting chase water anytime the conduit constricts fluid from a free-flowing condition. The amount of chase water must be sufficient to offset a tendency for high-head storage in the fine fractures that ordinarily feed water into the enlarged fractures/conduits. High-head conditions reverse the gradient along conduit passages. As long as the gradient is maintained, the conduit can feed the adjoining fractures, however, when the gradient returns to normal, the fluid in the small fractures begins to push back into the larger pathways. Eosine may be expected to persist at this site for quite some time into the future.

2009 point-to-point confirmation traces

Although the site was deemed monitorable due to the eosine detections in the 2007 trace, the State regulators requested specific actions to demonstrate monitorability. Previously unused dyes were to be used to trace from injection locations chosen by the State regulators to detection monitoring wells placed on the proposed site perimeter. Additionally, the positive detections in the on-site wells were to occur before detections in off-site springs or creeks. The injection location chosen on the west side was near the 1992 fluorescein and 2005/2007 eosine injections, and the injection location chosen on the east side was near the 1998 rhodamine WT and 2007 eosine dry set sinkhole injections. A new injection point was drilled into a bedrock void and screened with a 10 cm (4 in.) diameter PVC pipe for the western area of the site. A surface mixing and injection apparatus was set up near the sink for the eastern area. The injection system there consisted of a plastic water tank with an attached hose so that the dye could be mixed and chased with a slug of water, but slowly. The sides of the sink were soil and aggressive slugging could have induced a collapse if the soil was churned into mud. Two new monitoring wells were emplaced near the proposed perimeter on the northeast and southwest sides, respectively. These were spotted down strike of the injection points.

Background sampling was initiated on October 30, 2008 at the 25 stations identified within the initial work plan. Background sampling concluded on December 14, 2008. On December 15, 2008 at around 01:00 pm EST, 25 pounds of Sulforhodamine B (SRB) dry powder were mixed with water and injected into the PVC cased and screened injection boring, GSP-INJ-1. The boring had been pre-wetted with about 3,025 l (800 gal) of potable water, and the injected dye was followed with approximately 9,460 l (2,500 gal) of water on the day of injection, followed with an additional 21,570 l (5,700 gal) of water over the next 24 h.

On the same day and at about the same time, 4.5 kg (10 pounds) of pyranine dry powder was mixed with 756 l (200 gal) of potable water in a clean plastic tank; the liquid mixture was then routed via a 1-cm (2 in.) diameter discharge hose into the bottom of the swallet. This swallet hole had been pre-wetted with about 1,135 l (300 gal) of water supplied via a garden hose from the spigot at the nearby Sullivan County Sheriff's firing range training facility. The pre-wetting water was followed by 1,513 l (400 gal) of potable water using the same method the following day. In both instances, the dye mixing and injection were done by personnel who would not be involved in any of the subsequently scheduled monitoring. Additional water injection had been planned for GSP-INJ-

2, however, substantial rains the night of the injection and subsequent rain events over the next few days and weeks precluded the ability to access this sinkhole injection location with equipment (i.e. water truck).

After injection, on the SRB trace, hourly sampling of water from two wells and two springs on the western side of the groundwater divide was initiated. One sampling crew was responsible for the two new detection monitoring wells targeted by the SRB injection: one well was in the valley on-strike and the other was on a hill situated downgradient and down-dip. The second half of the 24/7 sample effort focused on two springs, one down strike below the SRB injection point, and the other located cross-strike of the SRB point at the head of Barger Creek. On the other, eastern side of the basin divide, daily pyranine samples were taken at springs and within Hunter's Trail Creek. These samples had to be adjusted to the correct pH before analysis. The sample schedule was not as frequent because the pyranine dye had not been pushed as aggressively.

Each afternoon samples were sent via Fed-Ex for rush analyses at the Ozark Underground Laboratory. One 24-h charcoal packet was sent with the 24-hourly water samples from each location. Duplicate, weekly charcoal packets were left in-place. The west side wells, DMW-6 and DMW-7 were pumped via dedicated Grundfoss Redi-flow pumps in each well. The spring water samples were taken as grab samples with a weekly packet remaining in-place. New disposable gloves were used by all personnel for each hourly sample at each point.

SRB was detected visually on the west side in DMW-6 in the water sample taken 42 h after the injection at GSP-INJ-1 about 800 ft up-strike. Subsequent laboratory data indicated the initial breakthrough started about 36 h after injection. After visual detection and confirmation by a DSWM representative, weekly sample tracking began utilizing the same tracking and shipping protocols. The SRB concentration in DMW-6 continued to rise until equipment breakdown precluded further sampling on the west side about 4 weeks after the initial detection. No SRB was detected in the closest off-site spring water samples in the same time frame as the well samples; the closest spring on the west side is located about 3,000 ft down strike of the GSP-INJ-1 location.

No pyranine was detected in the expected spring discharge points along Hunters Trail Creek on the east side of the proposed site for several weeks after the pyranine injection at GSP-INJ-2. After detection of SRB in DMW-6 on the western property boundary, sample rotation on the pyranine trace was also changed to weekly. As a check on dye progress, the intervening monitoring wells associated with the old landfill, MW-3 and MW-10 were checked for the presence of pyranine. These wells are generally on-strike between the sink, DMW-5 on the eastern property boundary, and the springs along Hunters Trail Creek further east. After pumping on January 28, 2009, pyranine detections in MW3 and MW10 water samples confirmed the pyranine dye front had traveled nearly three-fourths of the way from the sink towards the targeted eastside perimeter well and springs. Pyranine was indicated in the February 4, 2009 charcoal packets, and was confirmed above the 3× background criteria and 10× sampling cut-off criteria in the subsequent charcoal packets of February 16, 2009 for the springs and the charcoal packet for perimeter well DMW-5, indicating monitorability of the basins with typical monitoring wells and sample collection protocols.

Conclusions

It was once thought that reliable monitoring in a mature karst setting could not be done by an EPA-approved method (Quinlan and Ewers 1986), and while that might still hold true for areas where karstification has progressed to the mature stage and allowed consolidation of recharge waters, this study has shown that monitoring is feasible in a less mature setting. At the proposed Barger Hollow landfill site, the interconnection of pervasive diffuse flow in small fractures connected to relatively sparse master conduits means that the use of wells screened at appropriate depths will track potential contamination of the slow-flow network while the springs and creek monitoring stations can detect contamination in fast flow induced by intense stormwater off-site or potential liner failures on-site. A combined system of wells and springs would make monitoring more likely to be successful and protective. The thick residual clay soil, combined with relic paleo-conduit features in bedrock in upland/headwaters areas such as this site, can cause small dye impulses to be hung up in the unsaturated zone above the water table. The success of the traces done at Barger Hollow in 2007 and 2009 hinged on getting the dye mixture into the water with enough hydraulic impetus to reach pathways connected to a few monitoring points. The chances for successful, representative sampling in such a setting will be enhanced by purging protocols at groundwater monitoring well locations that induce some hydraulic head differences. Monitoring at the spring locations will need some regular monitoring of field parameters to ensure that normal variation due to rainfall events is accounted for.

References

Aley T (2002) Groundwater tracing handbook: a handbook prepared for the use of clients and colleagues of the Ozark Underground Laboratory. Ozark Underground Laboratory, Protem, Mo

Baker A (2005) Fluorescence tracing of diffuse landfill leachate contamination in rivers. Water Soil Air Pollut 163:229–244

Bartholomew MJ, Mills HH (1991) Old courses of the New River: its late Cenozoic migration and bedrock control inferred from high-level stream gravels, southwestern Virginia. Geol Soc Am Bull 103:73–81

Celico F, Petrella E, Celico P (2006) Hydrogeological behavior of some fault zones in a carbonate aquifer of Southern Italy: an experimentally based model. Terra Nova 18:308–313

DeBuchananne GB, Richardson RM (1956) Ground water resources of east Tennessee, Tennessee Division of Geology Bulletin, vol 58, parts 1 & 2. Nashville, Tn

Driese SG, Li Z-H, Horn SP (2005) Late Pleistocene and Holocene climate and geomorphic histories as interpreted from a 23,000 14C yr B.P paleosol and floodplain soils, southeastern West Virginia, USA

Environmental Consulting Engineers, Inc. (1990) Sullivan county landfill groundwater quality assessment report, vol 1, Figure 4–38

Fairley J, Heffner J, Hinds J (2003) Geostatistical evaluation of permeability in an active fault zone. J Geophys Res Lett 30(18):HLS 5-1–5-5

Gresham, Smith and Partners (2005) Report of dye trace work at Zach's knob, Tennessee in Sullivan county to support planning for a hydrogeologic report and groundwater assessment near a closed landfill. Submitted to Tenessee Division of Water Supply, Nashville, Tn

Kiraly L (2002) Karstification and groundwater flow, in evolution of karst: from prekarst to cessation. Postojna-Ljubljana, Zalozba ZRC, pp 155–190

Mazor E, Vuataz FD, Jaffe FC (1985) Tracing groundwater composition by chemical, isotopic and physical parameters-example: Schinznach, Switzerland. J Hydrol 76:233–246

Meisler H, Becher AE (1967) Hydrogeologic significance of calcium-magnesium ratios in ground water from carbonate rocks in the Lancaster quadrangle, Southern Pennsylvania, United States Geological Survey Professional Paper 575-C, pp C232–C235

Quinlan JF, Ewers RO (1986) Reliable monitoring in karst terranes: it can be done, but not by an EPA-approved method. Ground Water Monit Remediat 7(1):4–6

White WB (1988) Geomorphology and hydrology of karst terrains. Oxford University Press, Oxford, pp 200–210