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Hydrogeologic investigations of contaminant movement in karst aquifers in the vicinity of a train derailment near Lewisburg, Tennessee

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Abstract A train derailment near Lewisburg, Tennessee, in October 1990 prompted two series of groundwater investigations. The first was to determine the subsurface flow route of chloroform and styrene that sank into the underlying karst aquifer. The second was to determine the source of contamination for two nearby residential wells which were found to be contaminated with trichloroethylene (TCE). Water-sample analysis and a dye trace performed at the time of the train derailment indicated groundwater flow to Wilson Spring. A dam was constructed to contain the entire discharge from the spring so that it could be treated before being discharged into Big Rock Creek. Three springs and three water wells were contaminated with chloroform and styrene. Dye traces were performed to determine groundwater flow directions in the vicinities of the TCE-contaminated wells and in the vicinities of potential sources. At the train derailment, the chloroform and styrene sank into the Upper Ridley Karst Aquifer and pooled on top of the Lower Ridley Confining Layer. An exploratory well revealed a layer of chloroform (a Dense Non-Aqueous Phase Liquid DNAPL) on the bottom, a layer of groundwater in the middle, and a layer of styrene (a Light Non-Aqueous Phase Liquid LNAPL) on top. Groundwater with relatively low levels of chloroform and styrene in solution was carried by a small cave stream southeast along the strike to Wilson Spring. Chloroform product moved by gravity southwest down-dip along weathered bedding planes. Treatment of contaminated groundwater from Wilson Spring and recovery wells at the spill site has occurred continuously since October, 1990.

Key words Contamination — Karst — Train derailment

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Introduction

Two series of karst groundwater investigations for US EPA were conducted in the Lewisburg, Tennessee, area located 72 km south of Nashville, between October 1990 and April 1992 (Fig. 1). The objective of the first investigation was to determine the subsurface flow route and destination of approximately 56,775 l of chloroform and 15,140 l of styrene that were spilled from a train that derailed about 4.8 km north of the town of Lewisburg. The spilled chloroform and styrene immediately sank into the underlying karst aquifer. Several contaminated residential water wells were identified through sampling and analysis conducted pursuant to the spill. However, two of these wells were found to be contaminated with trichloroethylene (TCE) rather than chloroform or styrene. This discovery prompted a second groundwater investigation for the purpose of determining the source of the TCE.

Karst hydrogeology research procedure

The research procedure used for both investigations is one which Crawford has used to trace the flow of groundwater in karst aquifers on numerous occasions since 1970. It consists of the following:

Karst hydrogeologic inventory

This includes locating all springs, caves, cave streams, karst windows, significant sinkholes (usually those that are deep with steep sides), sinking streams, and lineaments (usually a line of sinkholes).

Installation of background dye receptors

The passive dye receptors used are: (1) small packets of activated coconut charcoal contained within fiberglass

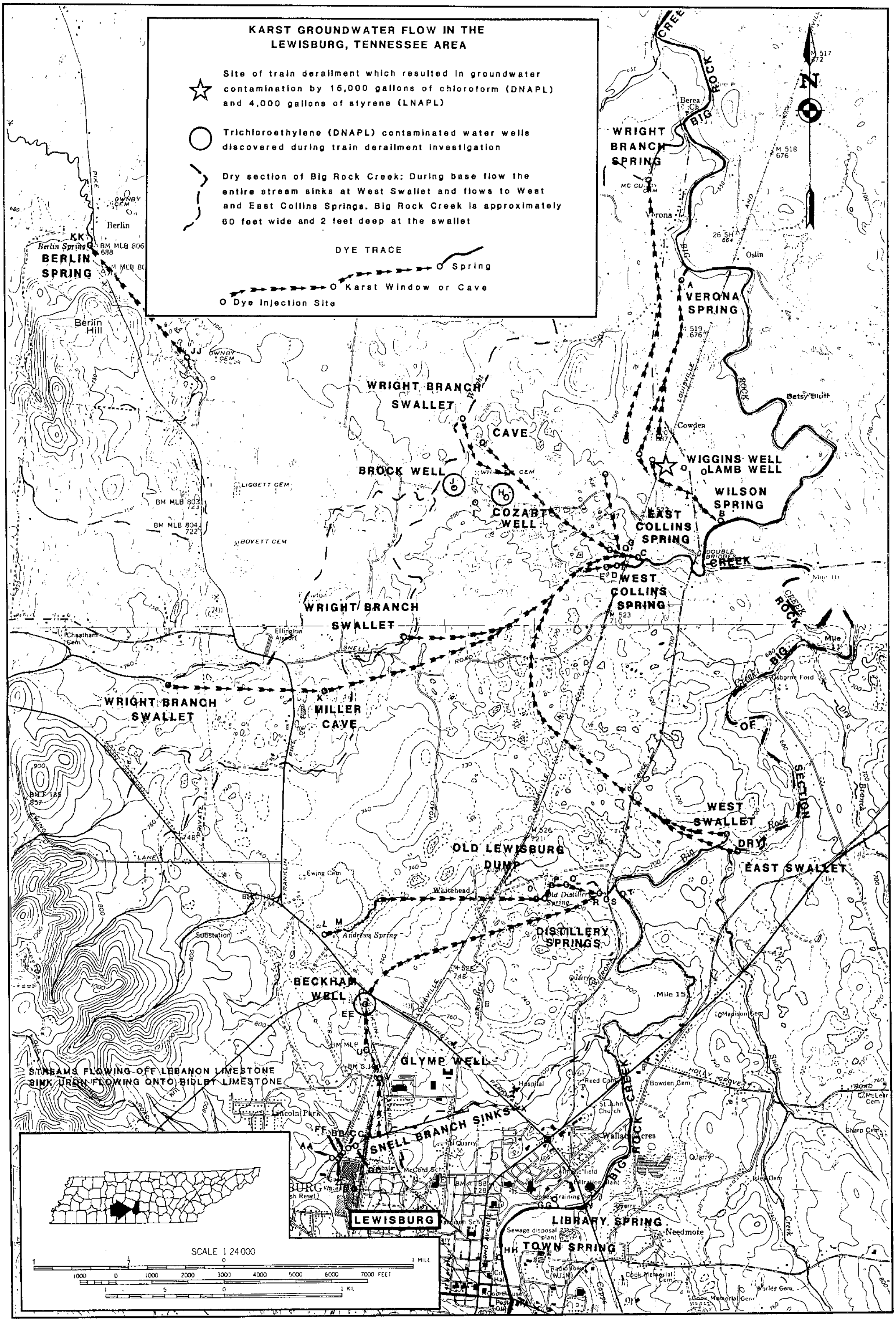


Fig. 1. Dye traces of karst groundwater flow in the Lewisburg, Tennessee area

screen mesh and (2) 5 × 10-cm bundles of unbleached cotton. These are placed in all springs, cave streams, karst windows, surface streams, and selected water wells and left for approximately one week. They are then replaced with new receptors, and the background receptors are analyzed in the lab, along with water samples collected at each site, for background fluorescence.

Mapping of potentiometric surface of the uppermost karst aquifer

All accessible water wells and monitoring wells in the area are measured during a dry period and the depth to water subtracted from the ground surface elevation, which is usually estimated from a 3.05-m contour interval 7.5-min USGS topographic quadrangle map. Some of the well elevations were determined by leveling from benchmarks. A water table map was prepared for the train derailment area, but the water table had such a low gradient it was of little value in predicting groundwater flow directions. Dye traces were essential in this area for determining groundwater flow directions.

Dye injection

After the completion of the hydrogeologic inventory, the potentiometric surface map, the analysis of the background dye receptors, and the placement of dye receptors in all springs, karst windows, cave streams, and surface streams, dye is injected directly into a sinking stream, sinkhole, well, or hole excavated in the soil. Water from a hose or a water truck is used to flush the dye past the soil into a bedrock crevice, which leads to a cave stream. Usually about 1893 l of water are injected into the hole to make sure that is drains sufficiently and to wet the soil so that less dye will be sorbed by clays. The dye is then injected and flushed with at least 7570 l of water. Usually three or four dye traces can be performed simultaneously by using different dyes. The dyes used for this investigation are: (1) fluorescein—color index: acid yellow 73; (2) optical brightener—tinopal 5BM GX, fabric brightening agent 22; (3) rhodamine WT—color index: acid red 388; and (4) direct yellow 96—diphenyl brilliant flavine 7GFF. These are standard dyes often used for dye traces in karst aquifers. They are safe for this purpose in the concentrations used both for human consumption and aquatic life.

Dye receptor analysis

Usually within four to ten days (depending on weather and other factors) the dye receptors are replaced, and the ones collected are then analyzed for dye. The activated charcoal is washed and then half is treated with a 5:2:3 mixture of 1-propanol, concentrated ammonium hydroxide, and distilled water (Smart 1972) to elute the fluorescein and rhodamine WT to the surface of the charcoal. Green fluorescein and/or red rhodamine WT is then observed, if present, under a bright light. If there is any question concerning the interpretation of a charcoal dye receptor, the elutant is compared with elutant of the background receptor on a Turner fluorometer or a Shimadzu spectrofluorophotometer. The unbleached cotton dye receptors are washed to remove as much mud as possible and then tested for optical brightener and direct yellow 96 under a long-wave ultraviolet lamp. Optical brightener, if present, will glow a blue–white, and direct yellow 96 will glow a pale yellow.

Quantitative dye traces

This involves installing ISCO automatic water samplers at the hypothesized spring or springs. The collected samples are then analyzed on a Shimadzu spectrofluorophotometer or Turner fluorometer. This provides a graph of the complete dye breakthrough curve at the spring or springs. ISCO samplers were installed at Wilson (B) and Verona (A) springs during the dye traces for the train derailment site investigation (Fig. 1).

The three residential wells identified as contaminated with TCE (H, J, and EE) were monitored throughout the TCE investigation dye tracing activities using ISCO automatic samplers. Each well was continuously pumped during the dye traces at a rate that maintained a drawdown of 3–4.6 m. A fourth ISCO automatic water sampler was placed at Collins Creek downstream from East (C) and West (D) Collins springs since this was apparently the resurgence for many sinking streams in the area (Fig. 1).

Often detectable levels of dye are present in spring discharge for several days or even several weeks. A grab water sample is always collected as dye receptors are changed. This permits the direct analysis of the grab samples for dye on the fluorometer or spectrofluorophotometer. This does not permit the construction of a dye breakthrough curve, but it does provide quantitative support of the interpretation of the passive dye receptors.

Report and map of groundwater flow

Maps were prepared showing the following: (1) groundwater elevations of all water wells measured; (2) potentiometric surface of the water table aquifer; (3) all springs, cave streams, karst windows, and sinking streams in the research area; (4) generalized groundwater flow routes through the aquifer as determined from dye traces and water table data.

Hydrogeology of the Lewisburg area

The karst hydrogeology of this portion of south-central Tennessee is extremely complicated and had not been studied prior to this investigation. This research has contributed considerably to characterizing the hydrogeology of the Lewisburg area. The study area consists of the northern portion of the Lewisburg topographic quadrangle and the southern portion of the Verona topographic quadrangle. The stratigraphy of the study area is similar to the Snail Shell Karst-Overall Creek area, located 48 km northeast of Lewisburg. This area was investigated by Crawford (1982, 1988) as part of the hydrogeologic investigation for Tennessee's proposed site for the superconducting super collider (Thompson and others 1989). Therefore, the hydrogeology and typical cavern development scenarios were hypothesized to be similar.

The Ordovician Lebanon Limestone tends to form uplands in the Lewisburg area. It has numerous thin shale beds that reduce karstification and the downward movement of groundwater. It therefore acts as a caprock above the Ridley Limestone. As surface streams flow off the Lebanon onto the Ridley Limestone, they sink into the Upper Ridley Karst Aquifer. There are several good examples of this northwest of Lewisburg (Fig. 1). Cave streams in the Upper Ridley appear to be flowing upon the Lower Ridley Confining Layer. This confining layer, first identified in the Snail Shell Karst area, consists of numerous thin beds of alternating shales and limestones. In the Snail Shell Karst, this layer is only about 4.6 m thick, but in the Lewisburg area, this confining layer appears to be about 9.1 m thick and contains some fairly thick beds of limestone. It appears that in some cases, cave streams have breached the upper part of this confining layer and are flowing through caves that have formed in limestone beds within the confining layer. However, it does not appear that any cave or surface streams have breached the entire Lower Ridley Confining Layer anywhere in the Lewisburg vicinity.

In the Snail Shell Karst, most large cave streams have breached the Lower Ridley Confining Layer and formed caves in the 10.4-m thick massively bedded limestone below. These cave streams are flowing within what Crawford has called the Lower Ridley Karst Aquifer directly upon the Pierce Confining Layer. This confining layer is actually the Pierce Limestone, which is about 6.1 m thick and consists of thin alternating beds of shale and limestone. The principal cave stream in the Snail Shell Karst flows within the Lower Ridley Karst Aquifer, upon the Pierce Confining Layer, from Upper Snail Shell Cave to Wallace Spring on the West Fork of Stone River, a distance of over 22.5 km.

All dye traces conducted for the investigations in the Lewisburg area were within the Upper Ridley Karst Aquifer. The Lower Ridley Aquifer appears to be confined everywhere in the study area. The Lower Ridley Confining Layer and the Pierce Confining Layer are both thin-bedded shaley limestones, which are almost identical. The authors believe that in many cases the Lower Ridley Confining Layer has been mapped as the Pierce Limestone on the geologic quadrangles for the Lewisburg area. The authors are confident that the areas along Big Rock Creek at Double Bridges and at Verona, which have been mapped as the Pierce Limestone on the Verona Geologic Quadrangle, are actually the Lower Ridley Confining Layer. This conclusion is based on a well that was cored through both of the confining layers into the Murfreesboro Limestone near the derailment site.

Groundwater investigation in the vicinity of the train derailment

Dye traces of groundwater flow

Dye traces were performed to determine groundwater flow directions in the vicinity of the train derailment (Fig. 1). Water-sample analysis and a trace performed at the time of the train derailment in October indicated groundwater flow to Wilson Spring (Fig. 2). A dam was constructed to contain the entire discharge from the spring, and it was then treated by air stripping and activated carbon before being discharged into Big Rock Creek. Dye traces performed during wet-weather conditions, however, revealed groundwater flow to two additional springs in separate groundwater basins.

The spill occurred near the drainage divides of four karst groundwater basins (Fig. 1): (1) Wilson Spring (B), (2) Verona Spring (A), (3) Wright Branch Spring, and (4) East Collins Spring (C). The karst aquifer in this area is believed to be similar to that in the Snail Shell Karst. Even during base flow, the cave streams flowing through the Snail Shell Cave System resemble a braided stream, with the pattern greatly influenced by jointing. Cave streams frequently divide and then eventually flow together again as much as a mile downstream. Therefore, during high discharge, groundwater may follow different routes through the karst aquifer and may even flow to additional springs. Dye traces revealed that groundwater flow routes in the area of the derailment are directly related to the volume of surface water that recharges the karst aquifer. A dye trace from the wreck site performed in October 1990 indicated that groundwater flow was only to Wilson Spring (B). However, during the winter months when discharge was high, contaminants also flowed to Verona Spring (A) and Wright Branch Spring.

Analytical data for springs in the area of the derailment support the theory that groundwater flow routes vary with discharge. Chloroform was not detected at Verona Spring (A) and Wright Branch Spring until three months after the derailment. In a porous-media, laminar-flow aquifer, one might conclude that the contaminant migrated slowly to these springs. However, dye traces in the area of the derailment revealed that it was due to a change in groundwater flow directions during high discharge.

Fluorescein injected into a sinkhole to the west of the derailment site flowed to Wright Branch Spring but not to Verona Spring (A). Dye injected into a different sinkhole nearby flowed to Verona Spring (A), but not to Wright Branch Spring. Using a cored well at the derailment site as a reference, the two springs discharge near the contact

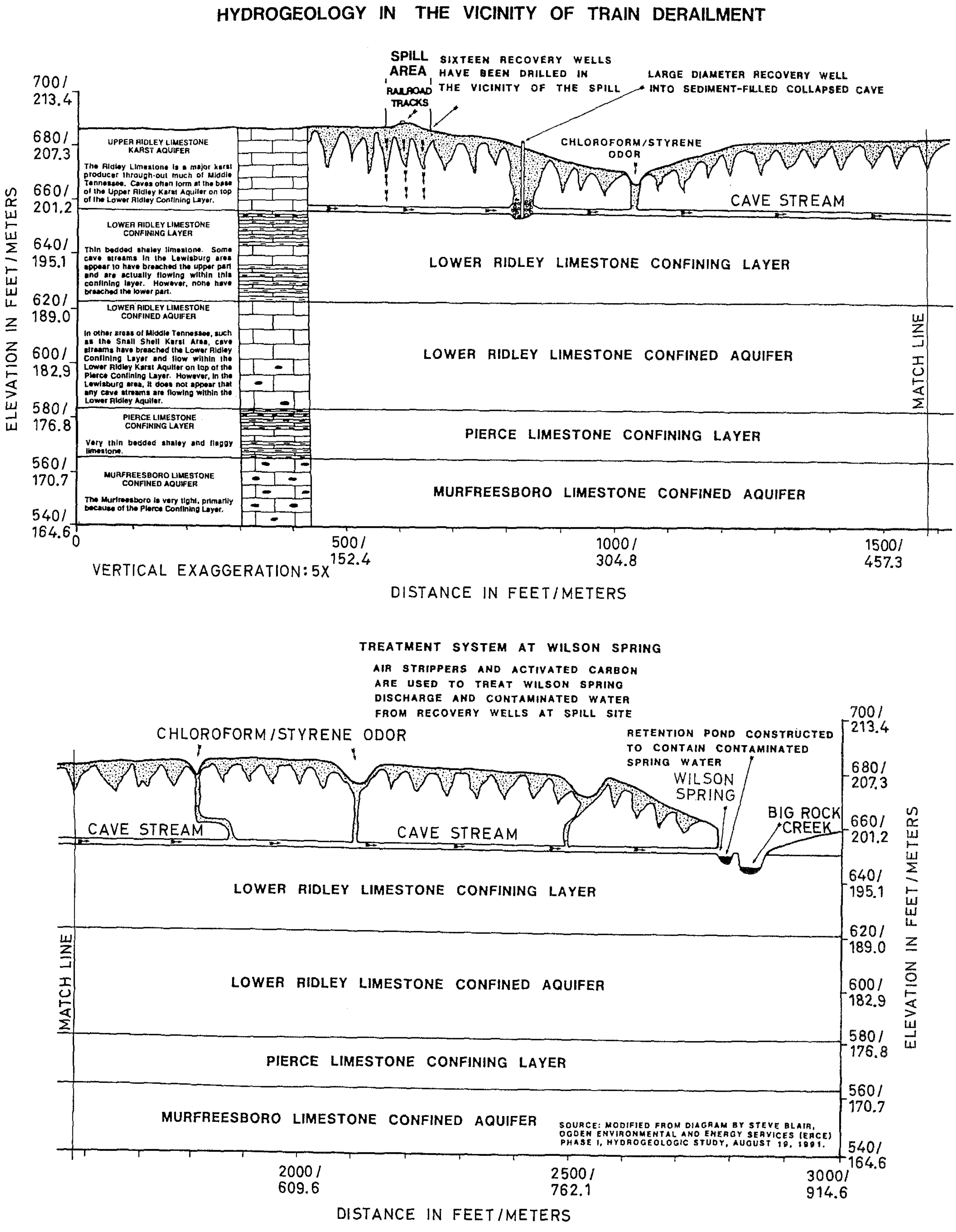


Fig. 2. Hydrogeology in the vicinity of train derailment. Chloroform and styrene in solution were carried by a small cave stream to Wilson Spring on Big Rock Creek. During high discharge, low levels of chloroform in solution also flowed to Verona and Wright Branch springs

of the Upper Ridley Karst Aquifer and the Lower Ridley Confining Layer at approximately the same elevation of 198 m. It is possible that one flows within the Upper Ridley Aquifer and the other flows through a conduit within the Lower Ridley Confining Layer. It is also possible that these parallel cave streams flow within the same aquifer but are not hydrologically connected.

Contaminant movement and recovery

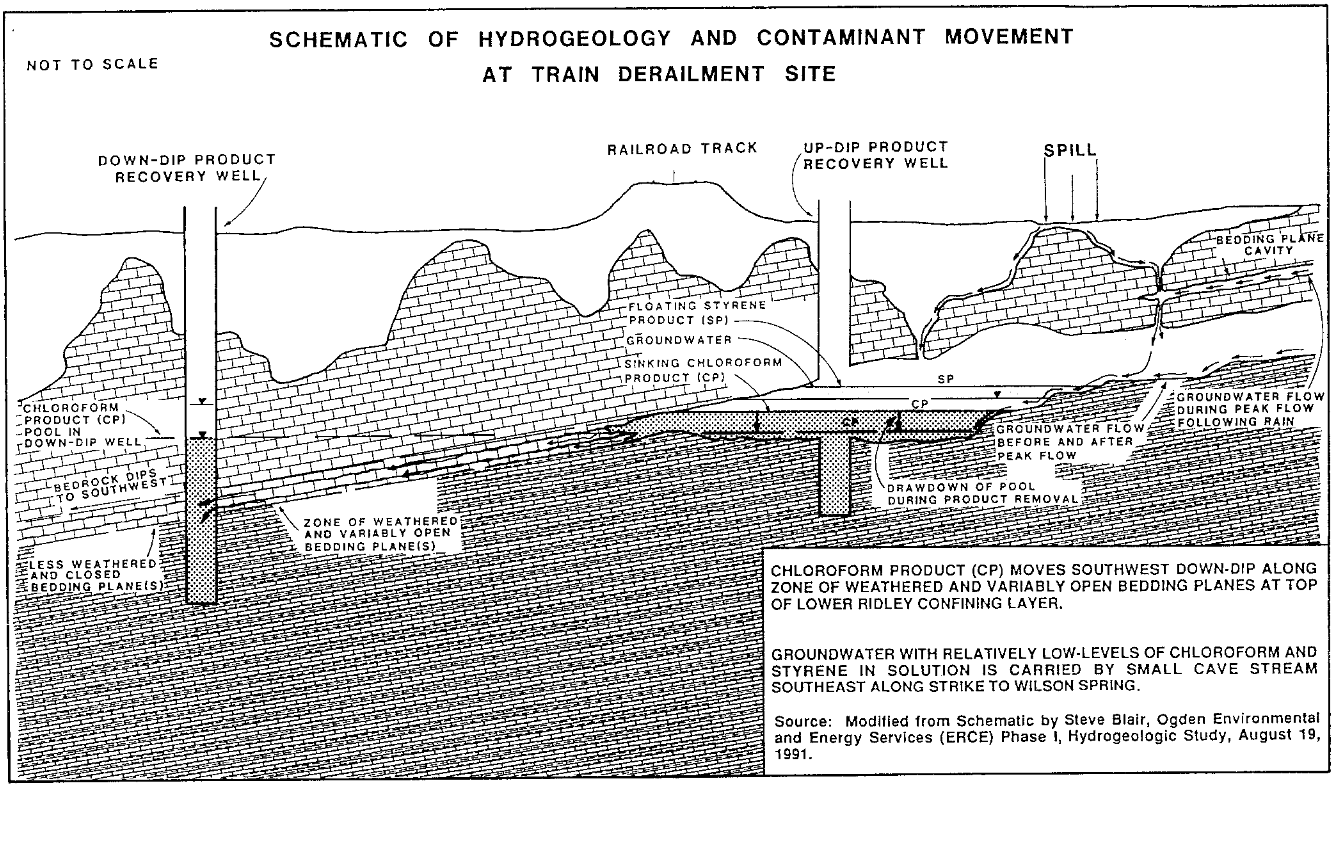
At the site of the train derailment, the chloroform and styrene sank into the Upper Ridley Karst Aquifer and pooled on top of the Lower Ridley Confining Layer. An exploratory well revealed a layer of chloroform (a DNAPL) on the bottom, a layer of groundwater in the middle, and a layer of styrene (a LNAPL) on top (Fig. 3). Groundwater with relatively low levels of chloroform and styrene in solution was carried by a small cave stream southeast along the strike to Wilson Spring. Small globs of styrene product were flushed out at the spring during large storm events. Chloroform product moved southwest down-dip along weathered bedding planes. With depth, these bedding planes are less weathered and actually appear to be very tight, thus preventing the chloroform from migrating farther down-dip. Sixteen chloroform product recovery wells have been drilled at, and down-dip from, the spill site. Over 15,150 l of chloroform product have been recovered, and pumping continues (Fig. 3).

Although the dense chloroform flowed southwest down-dip, the groundwater at the site flows southeast along the strike. Lineament analysis and microgravity were used to locate a small cave stream about 61 m down-gradient of the spill site (Fig. 4). An excavator was used to dig a pit into the sediment-filled cave where the roof had collapsed. The sediment was removed from the pit and a large-diameter recovery well installed. Although pure chloroform product was not recovered from this well, large quantities of chloroform-contaminated groundwater have been, and continue to be, pumped from this well.

Contamination of a deep confined aquifer

In this area of Tennessee, water well yields are very low unless by chance a good conduit in the Ridley Limestone is intersected. Consequently, many of the wells in the area penetrate the Pierce Confining Layer and extend through the usually very tight Murfreesboro Limestone and Wells Creek Formation into the Knox Dolomite Confined Aquifer. Knox wells in the Lewisburg area range from 152 to 305 m in depth. Once a well is drilled into the Knox, the water will rise from the confined aquifer in the well for hundreds of feet. In some cases it will rise above the water

Fig. 3. Schematic of hydrogeology and contaminant movement at train derailment site. Chloroform, a DNAPL, sank to the top of the Lower Ridley Confining Layer and then moved southwest down-dip along a zone of weathered and variably open bedding planes. Styrene, a LNAPL, floated on top of a layer of groundwater. Groundwater with relatively low levels of chloroform and styrene in solution was carried by a small cave stream southeast along the strike to Wilson Spring



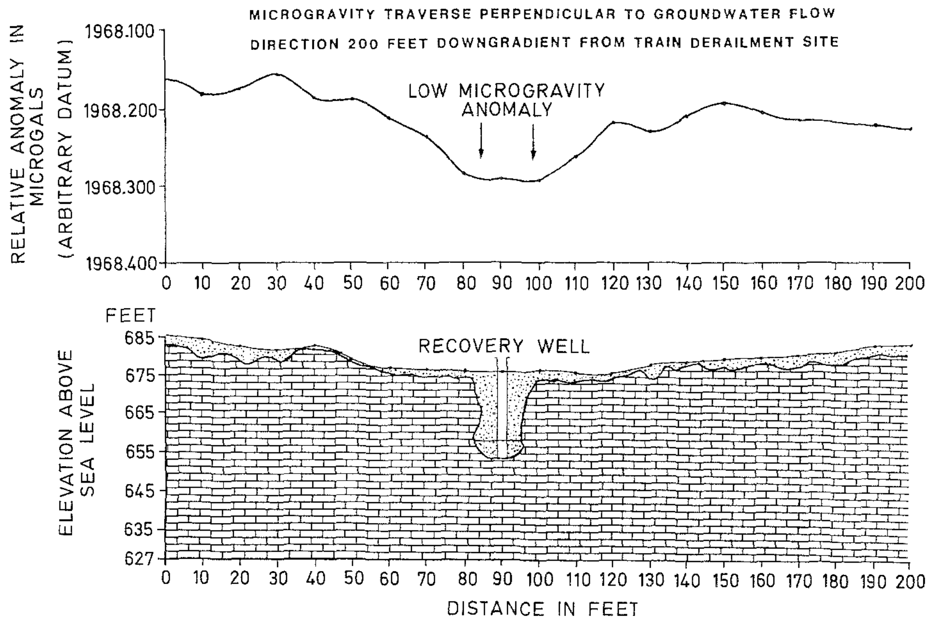
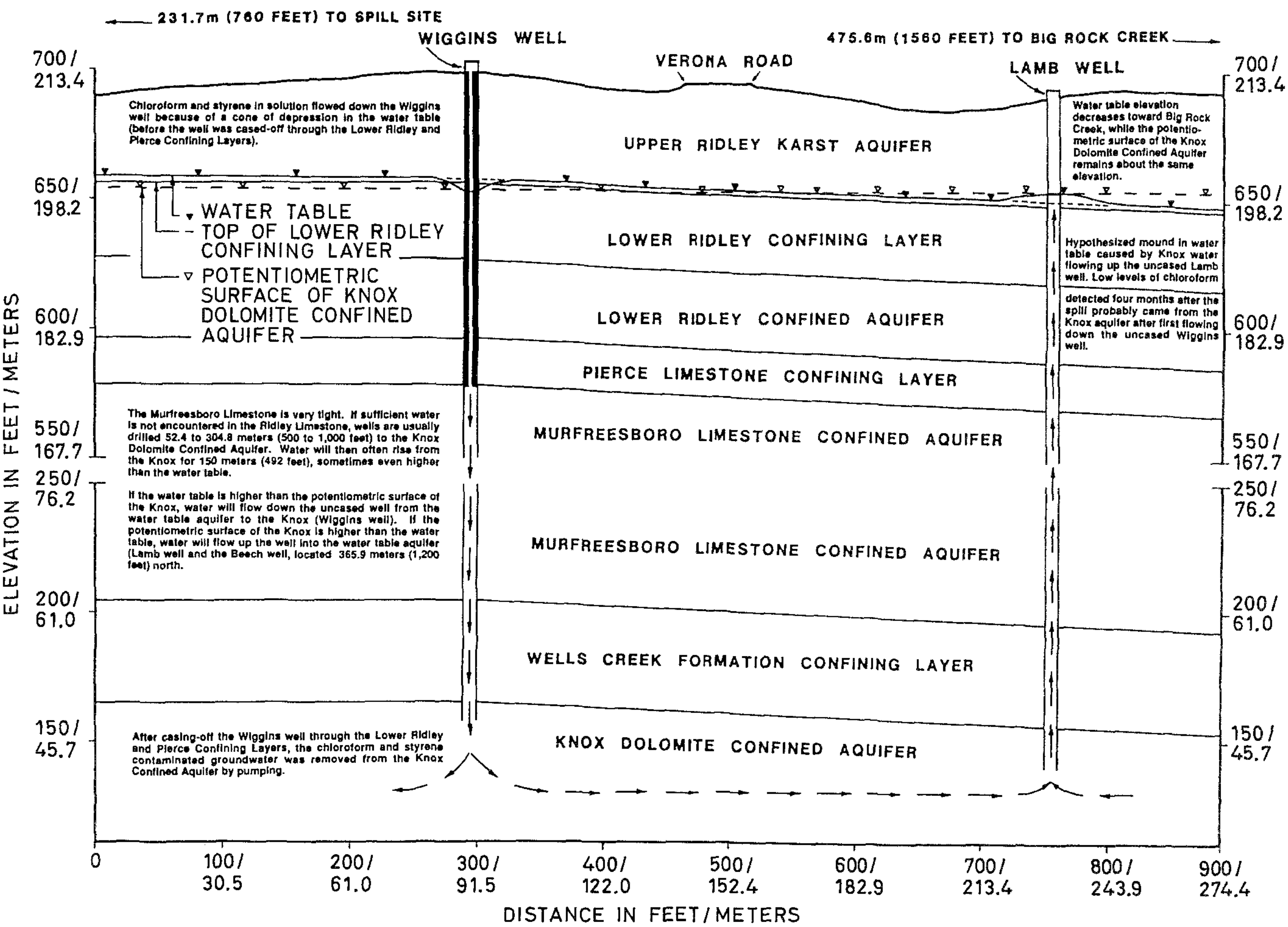


Fig. 4. Lineament analysis and microgravity traverses were used to locate a sediment-filled cave about 61 m downgradient from the train derailment site. Sediment was excavated at a place where the cave roof had collapsed and a large-diameter recovery well installed. The cave, with bedrock roof still intact, was visible at bottom of excavation extending northwest toward the spill site

Fig. 5. Cross-contamination between aquifers due to uncased water wells. At the 165-m-deep Wiggins well, the water table was higher than the potentiometric surface of the Knox Dolomite Confined Aquifer. This resulted in a cone of depression around the well as water flowed down the well from the water table aquifer to the Knox Aquifer. Chloroform and styrene in solution were carried down the well into the Knox. The well was cased through the Lower Ridley and Pierce Confining layers and the contaminated groundwater was removed from the Knox by pumping. Low levels of chloroform were detected in the Lamb well about four months after the spill. It is hypothesized that it came from the Knox Aquifer after first flowing down the Wiggins well



table, while in others, the potentiometric surface of the Knox will be below the water table.

Unfortunately, nearly all water wells in the Lewisburg area are cased only to bedrock. The open hole through the bedrock provides a direct route for cross-contamination between aquifers. If the water table is higher than the potentiometric surface of the confined aquifer, water will continuously flow down the well into the confined aquifer. If the potentiometric surface of the confined aquifer is higher than the water table, water will continuously flow up the well into the water table aquifer.

After the derailment, chloroform and styrene in solution were detected in the Wiggins residential well located about 232 m east of the spill site (Figs. 1 and 5). The Wiggins well, 165 m in depth, extends into the Knox Dolomite Confined Aquifer. Because the water table is 0.9 m higher than the potentiometric surface of the Knox at this location, water had been going down this well since it was drilled approximately 30–40 years ago. The cone of depression in the water table around the Wiggins well pulled chloroform and styrene in solution to and then down the well, resulting in low levels of contamination in the Knox Confined Aquifer. The Lamb well, located about 137 m east of the Wiggins well, is also a Knox well. The water table is lower at this well because it is closer to Big Rock Creek, while the potentiometric surface of the Knox Confined Aquifer is at about the same elevation. Therefore, with the potentiometric surface of the Knox higher than the water table, water has been flowing up the Lamb well from the Knox since it was drilled 30–40 years ago (Fig. 5).

Approximately four months after the derailment, low levels of chloroform were detected in the Lamb well. It is hypothesized that this chloroform-contaminated water went down the Wiggins well into the Knox and was then pulled to and up the Lamb well. Very little chloroform actually went down the Wiggins well, and the problem is believed to have been corrected. The Wiggins well was cased through the Lower Ridley and Pierce Confining Layers and then pumped to remove the contaminants from the Knox Aquifer. Subsequent sampling of the Wiggins and Lamb wells suggests that the contamination has been removed from the Knox Confined Aquifer.

Approximately 18,925 l of chloroform have been removed from the aquifer since the train derailment in October 1990. All of the discharge from Wilson Spring continues to be treated along with contaminated groundwater pumped from recovery wells at the spill site. Ogden Environmental and Energy Services (1991) is still investigating the site, and additional wells are to be installed in the near future.

Groundwater investigation in the vicinity of trichloroethylene (TCE)-contaminated water wells

Forty-three water wells within a 1.6 km radius of the train derailment site were tested for contamination. Although three wells were found to have low levels of chloroform and styrene, two wells were contaminated with TCE. Since TCE was not involved in the train derailment, an investigation was initiated by the EPA to determine the source. An additional TCE-contaminated well was found during this investigation. Dye traces were performed to determine groundwater flow directions in the vicinities of the contaminated wells and in the vicinities of potential sources.

The two residential wells initially identified as contaminated with TCE were the Brock well (J) and the Cozart well (H) (Fig. 1). Persistence of TCE in the residential wells over a two-year period suggested that the source was probably a substantial leak or spill. Distance from the contaminated wells was not considered to be an important factor in looking for potential sources because of the nature of groundwater flow in karst aquifers. Therefore, all potential sources upgradient of the wells were considered. This extended the search area to include the town of Lewisburg, located about 5 km south of the contaminated wells, and all of the area to the west in the vicinity of Wright Branch.

Potential sources

Several potential sources for the TCE groundwater contamination were considered. The four most likely sources considered are as follows:

1. A manufacturing facility in the town of Lewisburg, which had a spill of approximately 15,140 l of TCE in the early 1980s. Samples collected several years after the spill from deep groundwater monitoring wells at the facility contained up to 4300 ppm TCE. Residential well sampling for this investigation identified a TCE-contaminated well less than 1.6 km to the north of the facility, the Beckham well (EE) (Fig. 1).
2. The Old Lewisburg Dump, an abandoned limestone quarry used as a landfill, which is now on the National Priorities List (NPL). Significant concentrations of TCE have not been detected in monitoring wells for the landfill. However, monitoring wells into karst aquifers, rarely intersect the conduit that contains most of the groundwater flowing from a site. For this reason, wells are usually not reliable for detecting or monitoring contamination in most karst aquifers.
3. Ellington Airport, a municipal airport that may have used degreasing agents for airplane engine maintenance.
4. An auto salvage yard located near Berlin to the west of the contaminated wells. Degreasing agents, like TCE, may have been used to clean engine parts at this location.

Snell Branch

Dye trace investigations for the contaminated residential wells were initiated at the manufacturing facility in Lewisburg because of a known TCE groundwater contamination problem at that location. The three residential wells identified as contaminated with TCE. (H, J, and EE) were monitored throughout dye tracing activities for the TCE investigation using ISCO automatic samplers. Each well was continuously pumped during the dye traces at a rate that maintained a drawdown of 3–4.6 m. A fourth ISCO automatic water sampler was placed at Collins Creek downstream from East (C) and West (D) Collins springs since this was apparently the resurgence for many sinking streams in the area (Fig. 1). Passive dye receptors (activated coconut charcoal and unbleached cotton) were placed at all springs, karst windows, cave streams, surface streams, and water wells indicated by letters on Fig. 1.

One of several monitoring wells at the manufacturing facility was chosen for dye injection. This monitoring well is screened through the entire Ridley Limestone and completed at the contact with the underlying Pierce Limestone. The Lower Ridley Confining Layer was unaccounted for when the monitoring well was drilled, and as a result, the relative concentrations of TCE within the Upper and Lower Ridley aquifers remain undetermined.

Dye injected into the monitoring well at the facility was expected to discharge quickly from both the Lebanon and the Upper Ridley Aquifer. However, the Upper Ridley Aquifer appears to be confined in the vicinity of the manufacturing facility. In this area, the overlying Lebanon Limestone has numerous thin shale beds that act as a caprock for the underlying Upper Ridley Aquifer. Nevertheless, some dye discharged slowly into Snell Branch, which bounds the facility to the north, but the majority of the dye remained caught up in the confined Ridley aquifers on-site. The facility is using a recovery well to remediate the groundwater in the Ridley aquifers, and most of the dye was pumped from this well.

As previously indicated, some of the fluorescein injected into the monitoring well discharged from the Lebanon into Snell Branch in spite of the fact that the dye had been injected into the underlying Ridley aquifers. Using potentiometric surface data for monitoring wells at the facility, it was deduced that the potentiometric surface of the Ridley Confined Aquifer in the vicinity of Snell Branch is higher than the water table aquifer. Therefore, contaminated groundwater could leak upward into the Lebanon Limestone through the confining layer and discharge into Snell Branch from springs near the Lebanon–Ridley contact.

The Lebanon Limestone has numerous thin shale beds that reduce karstification. Consequently, few sinkholes have developed in the Lebanon in this area, and most streams flow on the surface. As these streams flow off the Lebanon onto the Ridley Limestone, they usually sink into solutionally enlarged conduits. Snell Branch flows off of the Lebanon Limestone and sinks into the Upper Ridley Aquifer downstream of the facility. During base flow, the entire discharge of Snell Branch sinks upon flowing off the Lebanon onto the Ridley.

The subsurface Snell Branch was traced to a residential well about 1.6 km to the north of the facility, the Beckham well (EE) (Fig. 1). This well is completed in the Upper Ridley Aquifer. The Beckham well (EE) had been previously identified as contaminated with TCE and was therefore continuously monitored throughout the investigation. The Glymp residential well (V) was also positive for dye from Snell Branch. The Glymp well (V) is no longer in use and was monitored by placing a passive dye receptor directly in the well.

Distillery Branch springs

Surface water in Snell Branch, which sinks into the Upper Ridley Aquifer, flows north to the Beckham well (EE) and then east to a spring on Distillery Branch near Verona Road (R). This was the only spring flowing in the Distillery Branch area during this particular dye trace. It is hypothesized that during high discharge, the trace would have been positive at other springs and karst windows in the Distillery Branch area (N, O, P, and Q). This hypothesis is supported by the fact that a dye trace of the sinking stream downstream from Andrews Spring (M), which was performed while all these springs were flowing, was positive at all of them.

The springs and karst windows in the Distillery Branch area (N, O, P, Q, and R) appear to be perched on top of, or flowing within, the Lower Ridley Confining Layer (Fig. 1). Many of the cave streams in the Ridley Limestone are flowing upon this confining layer. It appears that some cave streams in the Lewisburg area have breached the upper part of this confining layer and are flowing within conduits that have formed in limestone beds within the Lower Ridley Confining Layer. However, the complete unit does not appear to have been breached at any location in the Lewisburg area. Therefore, the major karst conduits in the Lewisburg area are within the Upper Ridley Aquifer.

Collins springs

The Collins springs (C and D) are two of the largest springs in middle Tennessee (Fig. 1). Both springs discharge from the Upper Ridley Aquifer into Collins Creek, which then flows upon the Lower Ridley Confining Layer to its confluence with Big Rock Creek at Double Bridges Road. Because of their size, it was hypothesized that they must be resurgences for most of the Wright Branch Groundwater Basin. This hypothesis was confirmed through tracing of all three major swallets along Wright Branch. Even when the entire Wright Branch Groundwater Basin is included, the base-flow discharge from these interconnected springs is still much larger than one would expect. This led Crawford, while working on the groundwater flow in the vicinity of the derailment site, to hypothesize that some of the groundwater flow from these springs was from Big Rock Creek (1991). Consequently, an unsuccessful attempt was made to locate a swallet along Big Rock Creek at the location where the stream swings against a bluff downstream from its confluence with Distillery Branch. Prior to initiating the residential well dye trace investigations, all springs in Big Rock Creek were inventoried. While conducting this inventory, it was discovered that, during base flow conditions, the entire discharge of Big Rock Creek sinks into a swallet on the west side of the creek near its confluence with Snake Creek (Fig. 1: West Swallet). At the West Swallet, Big Rock Creek is approximately 18 m wide and 0.6 m deep as it drops about 1.5 m into a cave along the west bank. During base flow, a dry stream bed continues beyond the West and East swallets for about 4 km to Double Bridges Road where Collins Creek flows into Big Rock Creek. During high flow conditions, some of the discharge of Big Rock Creek overflows these swallets and flows down the usually dry stream bed.

According to a draft geologic structure map prepared by Wilson and modified by the authors, the top of the Lower Ridley Confining Layer is at the same approximate elevation as the East and West swallets on Big Rock Creek. Therefore, it appears that at least the top part of this confining layer has been breached along a prominent joint at this location. Crawford (1982, 1988, 1991; Thompson and others, 1989) observed in the Snail Shell Karst area that in upstream sections the Lower Ridley Confining Layer often acts as a perching unit for cave streams. These streams frequently breach this confining unit and drop through vertical shafts into caves in the Lower Ridley Karst Aquifer. In downstream sections where caves in the Lower Ridley Karst Aquifer are completely filled with water, the Lower Ridley Confining Layer acts as a leaky confining layer. However, data suggest that in the Lewisburg area the sinking Big Rock Creek did not breach the entire confining unit at this location and that the subsurface Big Rock Creek is actually flowing within the Lower Ridley Confining Layer to Collins Springs. The Lower Ridley Confining Layer is only 4.6 m thick in the Snail Shell Karst area but 9.1 m thick in the Lewisburg area. Therefore, caves may have formed in some of the thicker limestone beds in the middle of this confining unit.
the middle of this confining unit.

During base flow conditions, Snake Creek sinks upstream of its confluence with Big Rock Creek. During higher discharge, it flows into Big Rock Creek and then sinks (along with water from Big Rock Creek) into the East Swallet (Fig. 1). A dye trace performed during high discharge when most of Big Rock Creek was overflowing the West and East swallets revealed that water flowing into the East Swallet crosses under the creek and then joins the cave stream from the West Swallet without mixing with the surficial Big Rock Creek. Therefore, Snake Creek is part of the Collins Springs Drainage Basin and contributes to the large volume of water flowing from these springs.

Wright Branch

Wright Branch Creek is also part of the Collins Spring Drainage Basin. Wright Branch, in addition to most of the streams on the Lewisburg and Verona topographic quadrangles, is mapped as a perennial stream, when actually it is an intermittent stream. Wright Branch is almost always dry from its upstream swallet (Fig. 1) to its confluence with Big Rock Creek to the north of Verona. It only flows on the surface after very heavy rains.

There are three large swallets along Wright Branch and numerous small places where the stream sinks into the cave drainage system. All three of these swallets have been dye traced to resurgences at West and/or East Collins springs (Fig. 1). The middle Wright Branch Swallet was dye traced to East and West Collins springs during the derailment site investigation (Fig. 1). The middle and downstream swallets only receive water after very hard rains, while a spring-fed stream flows off the Lebanon Limestone into the upstream swallet most of the time. This is the headwater of the Subsurface Wright Branch Drainage System.

The only location where the subsurface Wright Branch can actually be seen is believed to be in Miller Cave (K). Miller Cave is flowing within the Upper Ridley Karst Aquifer. A relatively large stream can be followed in the cave for about 183 m. A flood occurred during the dye trace of upper Wright Branch Swallet, and when the water in Miller Cave lowered enough to retrieve the dye receptor, the cotton had been lost due to high discharge. However, there is little doubt that this stream is the subsurface Wright Branch.

Berlin Spring

The dye traces performed at the downstream Wright Branch Swallet and a nearby cave stream indicated that groundwater flow in the vicinity of the Cozart and Brock wells was from the northwest. An auto salvage yard, one of the four potential sources of TCE, is located to the northwest. A cave stream was located near the salvage yard, Pruitt Cave Stream (JJ), but it appeared to be flowing northwest toward Berlin Spring (KK). This was confirmed when direct yellow 96 dye injected at Pruitt Cave Stream (JJ) was detected only at Berlin Spring (KK) (Fig. 1).

Big Rock Creek

All surface streams and sinking streams in the Upper Ridley Aquifer within the study area are part of the Big Rock Creek Drainage Basin (Fig. 1). Under high flow conditions, most of the discharge of Snell Branch does not sink downstream of the facility but flows on the surface to its confluence with Big Rock Creek. From this location, Big Rock Creek meanders in a northerly direction to its confluence with Distillery Branch (T). Snake Creek discharges into Big Rock Creek between the West and East swallets. Collins Creek discharges a considerable volume of water from West and East Collins springs into Big Rock Creek at Double Bridges Road. Several small springs are located along the banks of Big Rock Creek in the Verona area, including Wilson Spring (B) and Verona Spring (A). Just to the north of Verona, Wright Branch discharges into Big Rock Creek during high flow conditions.

Source(s) of TCE contamination in wells

The dye trace investigation identified the probable source and flow route of the TCE contamination in the Beckham well (EE). Although the general area upgradient from the Brock (J) and Cozart (H) wells was identified by dye tracing, a probable source within that area has not been found.

The Cozart (H) and Brock (J) wells, like virtually all the wells in the area, are cased only to bedrock. It is possible that TCE contamination of these wells is from a confined aquifer rather than the uppermost karst aquifer. This scenario might explain the persistence of the contamination. The Brock well has a strong odor of hydrogen sulfide, which is usually indicative of water coming from a confined aquifer. The well is 49.7 m deep and extends through the Lower Ridley and Pierce Confining Layers into the Murfreesboro Limestone. It is interesting that the highest levels of TCE are coming from a well that is obviously pumping at least some water from a confined aquifer. By placing inflatable packers in the Brock well at the confining layers, it would be possible to sample each aquifer independently. This could identify the contaminated aquifer or aquifers. It is possible that contaminated groundwater might be flowing from the Murfreesboro Aquifer into the Lower Ridley Aquifer at the Brock well and then being pulled to the Cozart well. Isolating the individual aquifers and then attempting to determine the potentiometric surface and contaminant concentration for each of the aquifers might help to confirm or disprove this hypothesis.

Chlorinated solvents, such as TCE and chloroform, are DNAPLs with relatively high densities and low viscosities. This type of DNAPL is more likely to find its way through fractures or interconnecting features in hydrogeological aquitards than less dense and more viscous DNAPLs (US EPA 1992). The TCE in the Ridley Aquifer at the manufacturing facility and the chloroform in the Knox Aquifer at the Wiggins and Lamb wells demonstrate that DNAPLs can get into confined aquifers in this area. Therefore, the possibility exists that the source of the Cozart (H) and Brock (J) wells' contamination is from a confined aquifer.

Recently, a fourth residential water well has been found to be contaminated with TCE in the Lewisburg area. This well is located in the area identified as being upgradient from the Cozart and Brock wells and may therefore facilitate the identification of the source.

Conclusions

1. Chloroform and styrene spilled at the train derailment site sank into the Upper Ridley Karst Aquifer to the top of the Lower Ridley Confining Layer. Chloroform product, a DNAPL, moved by gravity southwest downdip into weathered and variably open bedding planes, while groundwater carried chloroform and styrene in solution southeast along the strike to Wilson Spring. The spill occurred near the drainage divide of four karst groundwater basins. The low-gradient water table resulted in contaminated groundwater flowing to two additional springs in separate groundwater basins during periods of high discharge.
2. Contaminated groundwater from the manufacturing facility leaks into Snell Branch and then sinks downstream of the facility. It is possible, if not probable, that this facility is the source of the TCE contamination in the Beckham residential well (EE). The source of the TCE contamination in the Cozart (H) and Brock (J) wells was not identified by this investigation. However, the recent discovery of a fourth TCE-contaminated well located in the area identified by dye traces to be upgradient from these wells may facilitate the identification of the source.

Disclaimer

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