Spatial and Temporal Variability in Seepage Between a Contaminated Aquifer and Tributaries to the Ohio River

by Alan E. Fryar, Eric J. Wallin, and David L. Brown

Abstract

Although ground water discharge can limit plume migration and transfer contaminants to streams, interactions among ground water, rivers, and tributaries in contaminated watersheds have received relatively little attention. We used multiple methods to delineate seepage along Little Bayou and Bayou Creeks, tributaries to the Ohio River in McCracken County, Kentucky, from July 1996 through July 1998. The Paducah Gaseous Diffusion Plant (PGDP) lies between the creeks. Trichloroethene (TCE) and technetium-99 plumes within the underlying Regional Gravel Aquifer (RGA) extend several kilometers from PGDP toward the river. Both creeks tend to gain flow where they are incised into the RGA or contiguous strata in the Ohio flood plain. Bayou Creek also gains flow upstream of PGDP; other reaches of both creeks tend to lose flow. Local storms, river floods, and seasonal dry periods caused temporary changes in seepage rates and reversals in hydraulic gradients. Gaining conditions were indicated by seeps, springs, and boils, by upward hydraulic gradients from bank wells and bed piezometers to the stream, and by mixing models using chloride and oxygen-18. Mixing models and downward hydraulic gradients from the stream to wells indicated losing conditions. Annual ranges of stream, bed, and bank temperatures tended to be narrower, bed and bank temperatures in summer and early autumn tended to be cooler, and maximum values of specific discharge measured by seepage meters were greater along gaining than along losing reaches. Estimates of specific discharge from stream gauging and one-dimensional flow modeling did not conclusively identify losing and gaining reaches, but absolute values of those estimates fell within the range of seepage-meter measurements. Contaminants discharging to Little Bayou Creek were diluted downstream by uncontaminated ground water. Volatilization, biodegradation, or sorption probably removed TCE from stream water. These results indicate that discharge to tributaries can limit seepage of contaminants to rivers.

Introduction

Understanding interactions among ground water, rivers, and tributaries is potentially important for assessing pollutant mobility. Ground water can carry significant loads of nonpoint source pollutants (e.g., pesticides and nutrients) to streams (Squillace et al. 1993; Böhlke and Denver 1995; Job and Simons 1996). Industrial point sources can also contaminate alluvial aquifers or discharge directly to rivers or tributaries (Winter et al. 1998). Surface water contaminants can move into alluvial aquifers with bank storage during floods, then return to streams under base-flow conditions (Squillace et al. 1993). However, contaminants can be naturally attenuated in riparian or hyporheic zones if residence times are sufficiently long and geochemical conditions are suitable (Lowrance 1992; Böhlke and Denver 1995; Lorah et al. 1997). Concerns about water quality in alluvial aquifers and the impacts of ground water contaminants on surface water ecosystems are motivating researchers and regulators to examine contaminant fluxes from an integrated (watershed) perspective (Job and Simons 1996; Ward 1996; Winter et al. 1998).

Multiple techniques are available for assessing ground water/stream interactions. Examples include physical methods (seepage meters and piezometers in stream beds, numerical models, and geophysical surveys), hydrochemical (e.g., isotope) methods, and hybrid methods (near-stream ground water sampling and

Pages 129–146

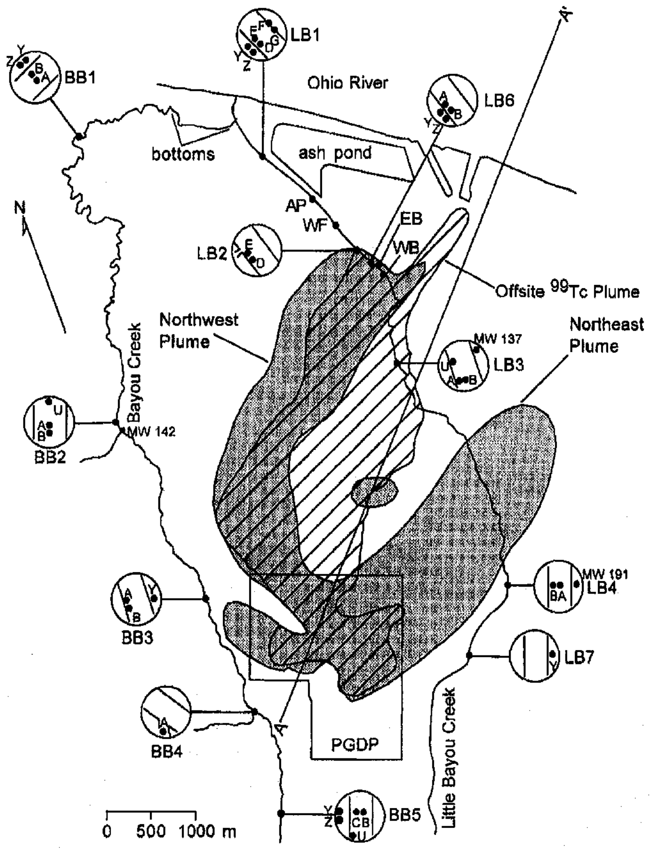

Figure 1. Site map with plume outlines from Jacobs EM Team (1998), approximate line of cross-section (A-A′) shown in Figure 2, and monitoring locations for this study. Stippled areas denote TCE concentrations ≥ 5 µg L^{-1} (U.S. Environmental Protection Agency maximum contaminant level); hachured areas denote ^{99}Tc concentrations ≥ 25 pCi L^{-1}. Insets (not to scale) show relative positions of piezometers (A–G), wells (Y–Z and MW), USGS gauges (U), and streams at numbered locations.

flow measurements, hydrograph separation, and land use functions) (U.S. Environmental Protection Agency 1991). Thermal monitoring can also be useful for delineating gaining and losing reaches of streams because temporal variability in stream temperature along gaining reaches should be less than along losing reaches (Silliman and Booth 1993; Constantz 1998). Moreover, the difference between ground water and stream temperatures along gaining reaches can exceed 5°C in winter and 10°C in summer (White et al. 1987). The combination of physical, hydrochemical, and thermal techniques can yield more information than any single method (Hibbs 1993; Rice and Hornberger 1998; Constantz 1998).

In this paper, we examine interactions among ground water, the Ohio River, and tributary streams in adjoining watersheds. The U.S. Department of Energy (DOE) Paducah Gaseous Diffusion Plant (PGDP), a National Priorities List site, is bounded by Little Bayou and Bayou Creeks, which are first- and second-order streams in McCracken County, Kentucky. Since 1952, PGDP has produced enriched uranium for use in nuclear reactors. Releases of trichloroethene (TCE, which was used extensively as a degreasing solvent) and technetium-99 (^{99}Tc, a byproduct of uranium reprocessing) to ground water have resulted in plumes extending several kilometers offsite toward the Ohio River (Clausen et al. 1992). We hypothesized that infiltration from Bayou Creek could mobilize contaminants beneath PGDP and contaminated ground water could discharge to Little Bayou Creek. We discuss the use of physical, thermal, and hydrochemical techniques to delineate gaining and losing reaches of the creeks at various times and quantify mixing of waters from various sources during a two-year period. Finally, we compare our results with findings on ground water/stream interactions from other watersheds.

Site Description and Background

Physiography, Climate, and Hydrology

The study area is located in the Gulf Coastal Plain 16 km west of Paducah, Kentucky (Figure 1). The 2788 ha West Kentucky Wildlife Management Area surrounds PGDP (latitude 37° 06' N, longitude 88° 48' W) and extends to the Ohio River, 5 km northeast. Other land use in the study area includes the Tennessee Valley Authority (TVA) Shawnee Plant (a coal-fired generating station), farms, and rural residences. Land-surface elevations range from 107 to 116 m above mean sea level (amsl) around PGDP to 88 m amsl at the river (pool elevation). PGDP is situated on the drainage divide between Little Bayou Creek to the east and Bayou Creek to the west. Bayou Creek is a perennial, 14.5 km stream whose basin encompasses 4764 ha, extending from 4.0 km south of PGDP to the river. Little Bayou Creek, with a basin of approximately 2400 ha, originates south of PGDP and flows northward for 10.5 km. Prior to construction of the Shawnee Plant, Little Bayou Creek was a separate tributary of the Ohio River. Between 1953 and 1971, a 2.5 km reach was channelized around the Shawnee Plant and connected to Bayou Creek 340 m south of the river. Most of the flow in both creeks originates from water that is pumped from the river to PGDP, used in industrial processes, and then discharged via outfalls.

The climate of the lower Ohio Valley is humid-continental. The average annual air temperature (1961–1990) at Barkley Airfield, 6 km southeast of PGDP, is 14.0°C, with the lowest monthly average temperature in January (0.3°C) and the highest in July (26°C) (Illinois State Water Survey, unpublished data). Precipitation (annual average 1.25 m) is relatively evenly distributed throughout the year, with January being the driest month (83.1 mm) and April the wettest (127 mm). Using the method of Thornthwaite and Mather (1957) for 1969–1989 climatic data, CH2M Hill (1992) determined that actual evapotranspiration (ET) is less than potential ET (and both are greater than precipitation) from June through September.

Prior work provides limited information on ground water/stream interactions in the study area. Evaldi and McClain (1989) sought to identify losing and gaining reaches of Bayou and Little Bayou Creeks under baseflow conditions on August 15–16, 1989. Velocities were measured by wading with current meters at 150 to 180 m intervals along the creeks. Volumetric flow rates, which

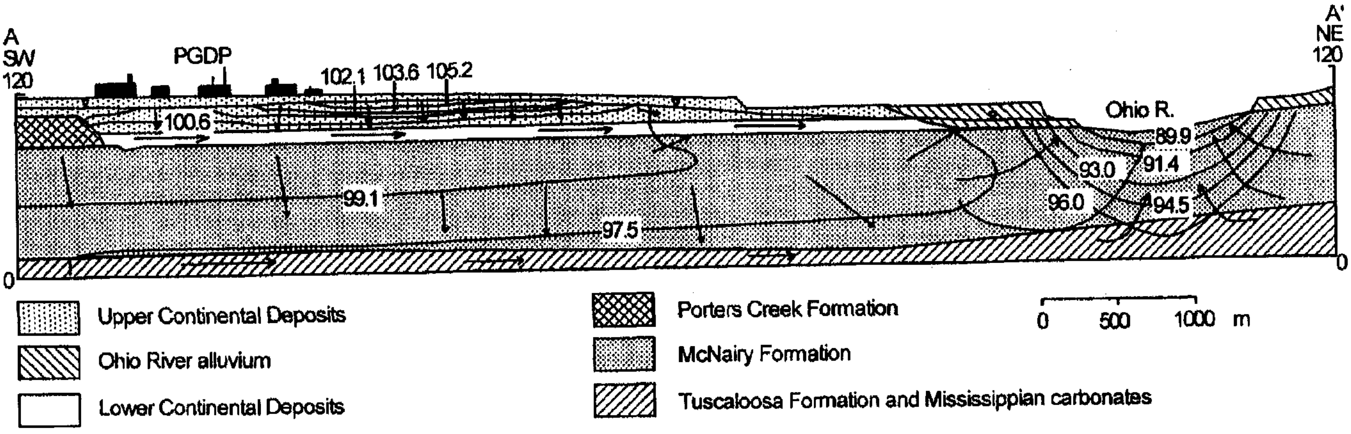

Figure 2. Hydrostratigraphic cross-section oriented approximately along line A-A′ shown in Figure 1 (from A.F. Diefendorf, Oak Ridge National Laboratory). Equipotential interval = 1.5 m (5 feet). Arrows indicate approximate directions of ground water flow when the Ohio River is at pool stage.

were calculated according to the cross-section method (Rantz 1982), were relatively constant along most of Little Bayou Creek, but increased within approximately 3.7 km of its mouth. Bayou Creek lost flow over the entire gauged reach (from 7.6 to 3.0 km upstream of the mouth). Final flow rates were 4.5×10^3 m^3 d^{-1} for Little Bayou Creek (1.7 km from the mouth) and 1.4×10^4 m^3 d^{-1} for Bayou Creek (3.1 km from the mouth) (Evaldi and McClain 1989). In comparison, outfall discharges averaged 2.7×10^3 m^3 d^{-1} for Little Bayou Creek and 1.5×10^4 m^3 d^{-1} for Bayou Creek from October 1987 through November 1988 (CH2M Hill 1992). Temperature measurements corroborated gauging data. Temperatures along Bayou Creek ranged from 22.3°C to 31.3°C, while temperatures along Little Bayou Creek ranged from 21.0°C to 24.9°C over the first 4.8 km before decreasing to 19.5°C along the last 600 m. Elevated temperatures 1 to 2 km downstream of outfalls probably resulted from effluent discharge (Roy et al. 1996).

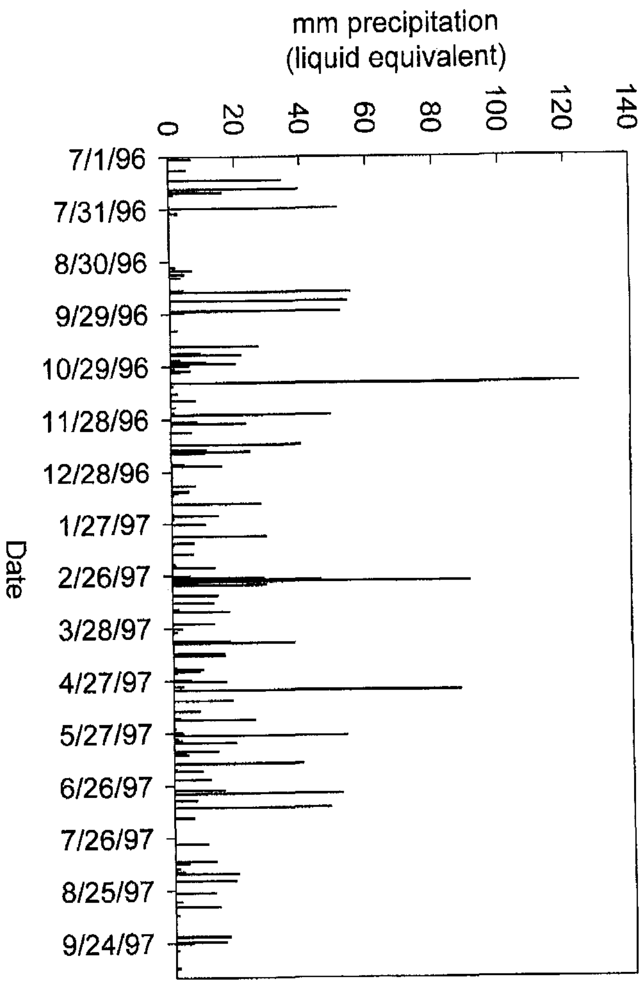

Figure 3. Daily precipitation at Barkley Airfield, Paducah, Kentucky, from July 1, 1996, through October 12, 1997 (from unpublished NWS data).

Hydrogeologic Setting

The Bayou and Little Bayou Creek watersheds are underlain by an approximately 90 to 120 m thick sequence of marginal marine to continental sediments, which unconformably overlie Mississippian carbonate bedrock (Clausen et al. 1992) (Figure 2). This clastic wedge dips south-southwest toward the axis of the Mississippi Embayment. The McNairy Formation (Cretaceous), which subcrops beneath PGDP at depths of approximately 21 to 30 m, consists of upper and lower clayey fine sands locally separated by silty clay (Davis 1996). Incision of the ancestral Tennessee River removed much of the Tertiary strata between the site of PGDP and the present Ohio River. Above this unconformity, the Continental Deposits (Pliocene-Pleistocene) form an upward-fining, valley-fill sequence. Chert gravel in a poorly sorted sand-silt matrix is overlain by sand and gravel lenses interbedded with lacustrine clays (Clausen et al. 1992). The Continental Deposits are mantled by loess and by alluvium adjacent to streams and the river. In the Bayou Creek watershed south of PGDP, the clayey Porters Creek Formation (Paleocene) is overlain by terrace gravels older and less extensive than those of the lower Continental Deposits.

Previous investigations in the vicinity of PGDP have provided a conceptual framework for ground water flow within the Continental Deposits, although flow within

Table 1
Well and Piezometer Construction Data

Well or Piezometer*	Lithology	Dates Installed	Ground or Bed Elevation** (m amsl)	Well or Piezometer Depth (m)	Elevation of Bottom of Screened or Perforated Interval (m amsl)	Elevation of Top of Screened or Perforated Interval (m amsl)
BB1A	Silt/sand (bed)	7/22/96	94.9	0.6	94.4	94.7
BB1B	Silt/sand (bed)	7/22/96	94.9	0.9	94.1	94.4
BB1Y	Sand (RGA/alluvium)	10/9-12/96	98.1	6.1	92.0	92.7
BB1Z	Sand (RGA/alluvium)	10/9-12/96	98.1	4.6	93.5	94.3
BB2A	Sand (bed)	8/31/96	100.9	1.2	99.9	100.2
BB2B	Sand (bed)	7/23/96	100.9	1.4	99.7	100.0
MW 142	Sand/gravel (RGA)	4/16-17/90	104.5	16.0	88.5	91.5
BB3A	Sand (bed)	8/31/96	105.8	1.2	104.7	105.0
BB3B	Sand (bed)	7/23/96	105.7	1.3	104.5	104.8
BB3Y	Sand/clay (UCRS/RGA)	12/18-23/96	108.6	12.0	96.6	97.3
BB4A	Gravel (bed)	7/23/96	108.8	0.7	108.2	108.5
BB5B	Hardpan (bed)	7/23/96	111.5	0.9	110.6	110.9
BB5C	Hardpan (bed)	7/23/96	111.5	0.8	110.7	111.0
BB5Y	Sand/gravel (terrace gravel)	12/17-23/96	114.9	6.1	108.8	109.6
BB5Z	Sand/gravel (terrace gravel)	12/17-23/96	114.9	4.6	110.4	111.1
LB1D	Sand/gravel (bed)	8/31/96	92.9	0.8	92.2	92.5
LB1E	Sand/gravel (bed)	8/31/96	92.9	1.0	92.0	92.3
LB1F	Sand/gravel (bar)	8/31/96	93.6	1.0	92.7	93.0
LB1G	Sand/gravel (bar)	8/31/96	93.7	1.3	92.5	92.8
LB1Y	Sand (RGA/alluvium)	10/8-12/96	98.3	8.4	89.9	90.7
LB1Z	Sand (RGA/alluvium)	10/8-12/96	98.4	7.0	91.3	92.1
LB2D	Silt/sand (bed)	8/31/96	95.6	0.9	94.8	95.1
LB2E	Silt/sand (bed)	8/31/96	95.6	0.5	95.2	95.5
LB6A	Silt/sand (bed)	10/8/96	95.6	1.0	94.7	95.0
LB6B	Silt/sand (bed)	10/8/96	95.7	0.8	95.0	95.3
LB6Y	Sand/gravel (RGA)	10/8-12/96	98.1	7.2	90.9	91.7
LB6Z	Sand/gravel (RGA)	10/9-12/96	98.1	5.8	92.3	93.0
LB3A	Silt/sand (bed)	7/23/96	99.0	0.5	98.6	98.9
LB3B	Silt/sand (bed)	7/23/96	99.0	0.8	98.3	98.6
MW 137	Gravel/silt/sand (RGA)	3/13-20/90	101.6	11.9	89.7	91.2
LB4A	Clay (bed)	7/23/96	105.9	0.5	105.5	105.8
LB4B	Clay (bed)	7/23/96	105.9	0.6	105.4	105.7
MW 191	Sand/gravel (RGA)	3/13-14/91	108.9	18.6	90.6	92.1
LB7Y	Sand (UCRS)	5/15-16/97	111.3	7.3	104.0	105.5

*Piezometers BB4B, BB5A, LB1A, LB1B, LB1C, LB2A, LB2B, LB2C, LB2D, and LB2E destroyed by floods.
**Bed elevation as of October 1997; bed elevation for LB2 piezometers (not surveyed) assumed = LB6A.

deeper units is less well understood. Flow is predominantly vertical (hydraulic gradient approximately 1) within the upper Continental Deposits (the Upper Continental Recharge System [UCRS] of Clausen et al. [1992]). Within the semiconfined lower Continental Deposits (known informally as the Regional Gravel Aquifer [RGA]), ground water tends to flow north-northeastward toward the Ohio River at an average hydraulic gradient of 0.0006 (Clausen et al. 1995). However, Ohio River flooding can cause gradient reversals. Flow within the RGA may also be affected by an east-west trending paleochannel beneath PGDP (Clausen et al. 1992) and by faults striking northeast-southwest (Langston et al. 1998). Some flow occurs downward from the RGA into the McNairy Formation beneath PGDP and upward from the McNairy Formation near the river (Davis 1996).

Three major contaminant plumes emanate from PGDP and extend within the RGA toward the Ohio River (Figure 1). The northwest plume, which appears to originate from multiple source areas, is aligned with the inferred paleochannel and faults mentioned previously. The far-field portion of the northwest plume may divide around an ash-settling pond at the Shawnee Plant, but the width of the plume probably also reflects flood-induced variability in flow directions in the RGA, consistent with seasonally fluctuating TCE and ^{99}Tc concentrations in monitoring wells (Clausen et al. 1992). Data of Evaldi and McClain (1989) suggest that the northwest plume and the offsite ^{99}Tc plume pass beneath a gaining reach of Little Bayou Creek, whereas the northeast plume passes beneath a reach having negligible changes in flow. These data are consistent with measurements of CH2M Hill (1991, 1992), who found that TCE and ^{99}Tc concentrations increased above background along Little Bayou Creek in the vicinity of the northwest and offsite ^{99}Tc plumes.

Methods

We conducted field investigations monthly from July 22, 1996, through October 12, 1997 (except for March 1997), with supplemental measurements on July 10, 1998, at multiple sites in the Bayou and Little Bayou Creek watersheds (Figure 1). Whenever possible, monitoring occurred when Bayou and Little Bayou Creeks were unaffected by runoff. However, rainfall was ≥ 15 mm during the two days preceding monitoring on July 22–23, September 21–23, November 25–26, and December 16–18, 1996, and August 19–21 and September 25, 1997 (Figure 3).

At five sites in each watershed, we installed clusters of two to four drive-point piezometers in the stream bed. Piezometers were fabricated from 1¼ inch nominal steel pipe (0.033 m inside diameter [I.D.], 1.22 to 1.83 m long) that was crimped by a hydraulic press along the bottom 0.1 m and perforated with approximately 80 0.4 mm diameter holes along the next 0.3 m. Piezometers were bailed occasionally to remove silt. One or two streambank monitoring wells consisting of 2-inch nominal (0.053 m I.D.) PVC pipe were later installed in augered holes at three sites in each watershed. Screened intervals were sand-packed and, for paired wells, were vertically offset by 1.5 m. Piezometer and well locations are prefixed by BB for (Big) Bayou and LB for Little Bayou; piezometers at each location were given the suffixes A through G and wells the suffixes Y and Z. Depths, perforated or screened intervals, and drilling dates for piezometers and wells are listed in Table 1. Hydraulic heads, stream stages, and bed elevations were referenced to surveyed top-of-casing elevations, with combined surveying and measurement errors ≤ 0.04 m. We calculated the vertical hydraulic gradient ($\Delta h/\Delta z$) by defining Δz as the difference between the midpoint elevation of the screened or perforated interval and the bed elevation at the nearest piezometer(s).

We measured stream and air temperatures and downhole temperatures in piezometers and wells. Following White et al. (1987), we also used a 1.0 or 1.3 m long, stainless-steel thermistor probe and a digital thermometer (Yellow Springs Instrument Co., Yellow Springs, Ohio). We measured temperatures at the bed or bank surface and at the maximum depth to which the probe could be pushed, which was limited by refusal in clayey and cobbly sediments and by the length of the probe in sandy and gravelly sediments.

We installed portable seepage meters (modified from the design of Lee [1977]) in the stream bed at various locations. Seepage meters were fabricated from a 0.15 m length of 4 inch nominal (0.10 m I.D.) PVC pipe, which was capped with a polycarbonate sheet and connected via Tygon™ tubing to a condom. We calculated specific discharge (in m d^{-1}) as

$$q = Q/A$$

where Q is the volumetric discharge rate (m^3 d^{-1}) and A is the cross-sectional area of the seepage meter (0.0079 m^2). We also gauged stream flow at selected sites, according to the cross-section method of Rantz (1982), by wading with a Flo-Mate Model 2000 portable flowmeter (Marsh-McBirney, Frederick, Maryland). For comparison with seepage-meter data, we estimated the net specific discharge q_n along a reach as

$$q_n = \frac{(Q_d/w_d - Q_u/W_u)}{L}$$

where the subscripts d and u refer to downstream and upstream gauging transects, respectively; w is the width of a transect; and L is the length of the reach. Positive values of q_n indicate gaining conditions, whereas negative values indicate losing conditions. Wallin (1998) provides additional details of flow measurements and well and piezometer installation techniques.

In January, May, August, and October 1997, we sampled Y-series wells and adjoining reaches of the creeks for metals and metalloids, anions, oxygen-18, and (at some sites) volatile organic compounds (VOCs) and ^{99}Tc. In January 1997, we collected stream and ground water samples only at locations BB5, BB1, LB6, and LB1 because well LB7Y had not yet been drilled and because of difficulties in pumping well BB3Y. We also collected stream and spring water samples for VOCs along Little Bayou Creek in July 1998. We report the results of analyses for B, Cl$^-$, ^{18}O, TCE, and ^{99}Tc. Boron is a solute associated with fly-ash leachate (Simsiman et al. 1987; Davidson and Bassett 1993), while Cl$^-$ is a relatively conservative tracer of solute movement in dilute surface and ground waters (Hem 1992). At temperatures less than 50°C, ^{18}O is a conservative tracer of water movement beneath the upper soil zone. Concentrations depend upon the isotopic composition of precipitation and the extent of evaporation, which differentially enriches liquid water in ^{18}O (Freeze and Cherry 1979).

We sampled ground water with a submersible pump in January and with a peristaltic pump subsequently. Each well was pumped at an approximate rate of 500 mL min^{-1} and sampled when temperature, pH, and Eh had stabilized. Both ground water samples and stream water grab samples were passed through disposable in-line filters (0.45 µm pore size). We collected anion samples in 500 mL polyethylene bottles and ^{18}O samples in 500 mL glass bottles without preservatives. Metals, metalloids, and ^{99}Tc were collected in polyethylene bottles and preserved with 6N HNO_3 (5 mL acid per 500 mL bottle for metals and metalloids; 10 mL acid per 1000 mL for ^{99}Tc). VOCs were collected in 40 mL amber glass vials, acidified with two drops of 6N HCl, and sealed with Teflon™-backed silicone septa without headspace. Samples were stored at approximately 4°C prior to analyses and, except for ^{18}O, were analyzed within holding times specified by the U.S. Environmental Protection Agency. Metals and metalloids were analyzed by inductively coupled plasma spectrometry and anions by ion chromatography at the Kentucky Geological Survey and at Quanterra

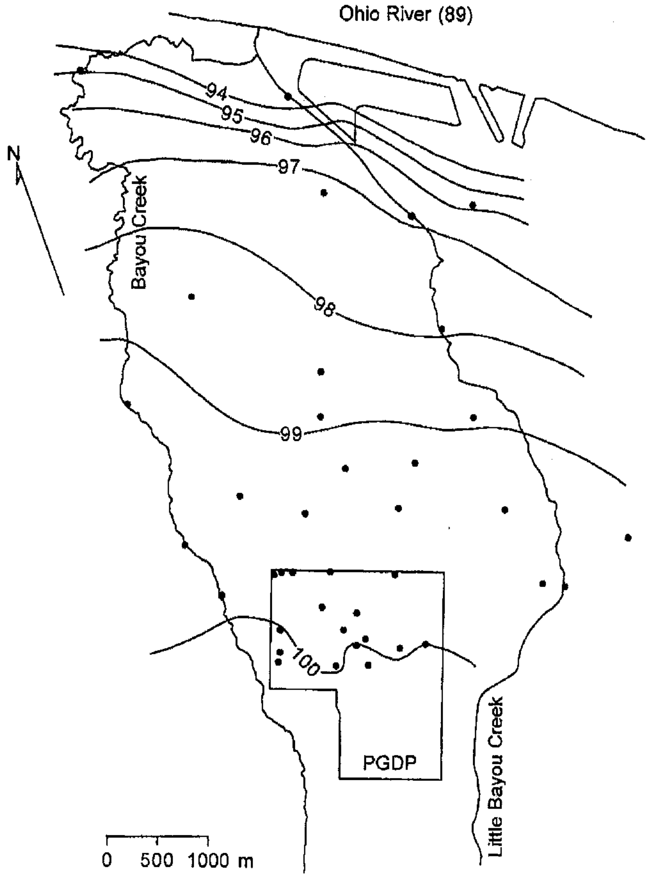

Figure 4. Hydraulic heads in the RGA on September 24–25, 1997 (contour interval = 1 m) (Lockheed Martin Energy Systems, unpublished data).

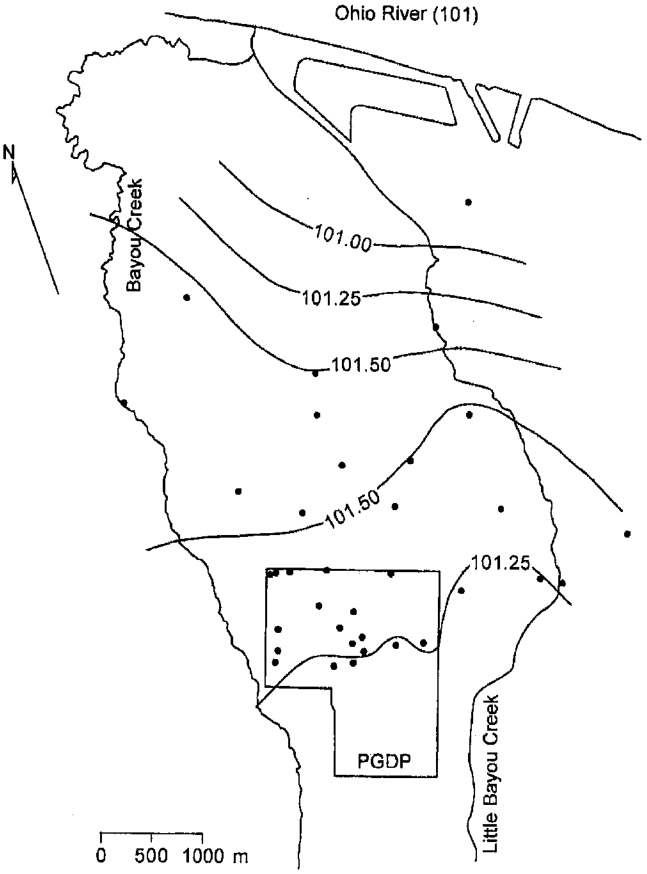

Figure 5. Hydraulic heads in the RGA on March 24–25, 1997 (contour interval = 0.25 m) (Lockheed Martin Energy Systems, unpublished data).

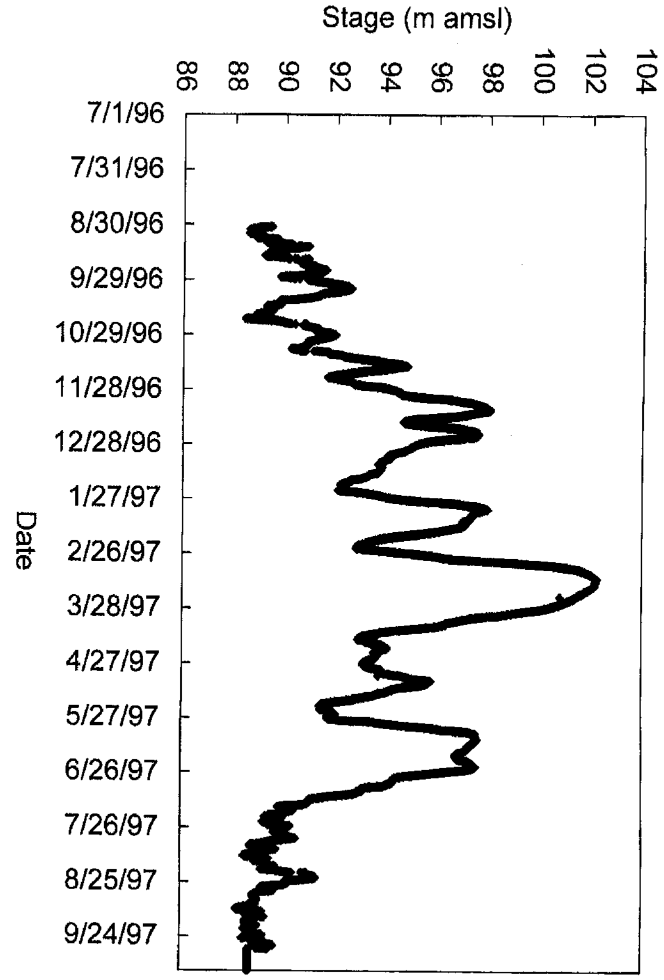

Figure 6. Hourly Ohio River stage at Metropolis, Illinois, from August 31, 1996, through October 12, 1997 (from provisional USGS data).

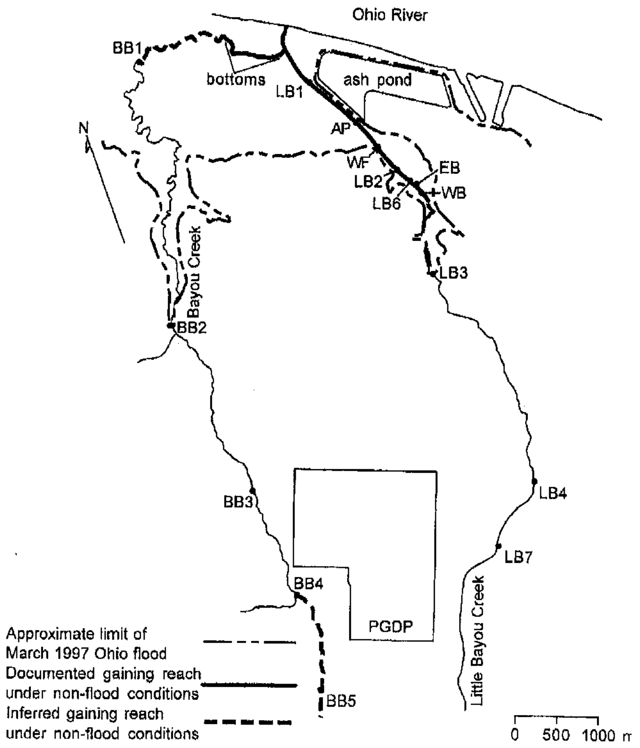

Figure 7. Approximate limit of Ohio River flooding during March 1997 and extent of gaining reaches of creeks during non-flood periods. Other reaches (between BB1 and BB4 and upstream of LB3) tend to lose flow during non-flood periods.

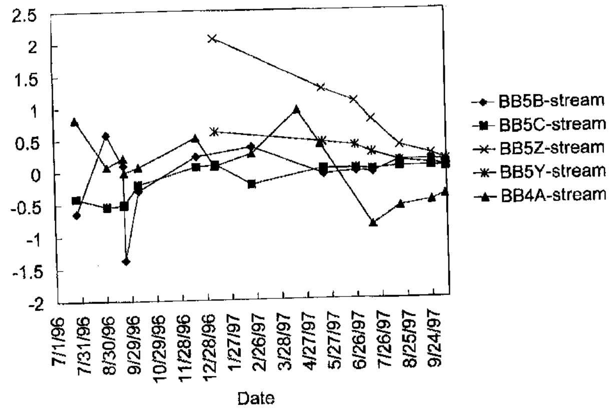

Figure 8. Vertical hydraulic gradients between piezometers or wells and Bayou Creek at BB5 and BB4 (see Figure 1 for locations and Table 1 for piezometer and well completion data). Values > 0 indicate upward flow and values < 0 indicate downward flow.

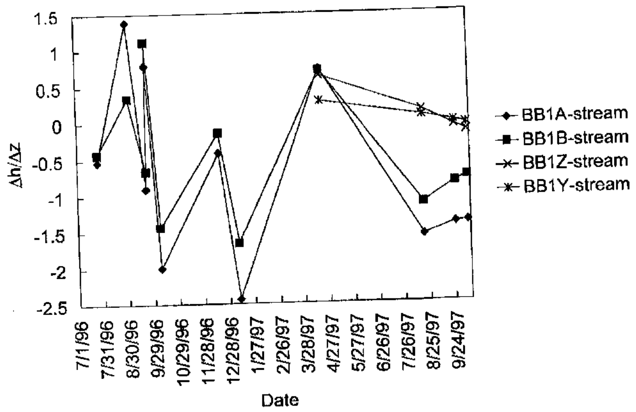

Figure 9. Vertical hydraulic gradients between piezometers or wells and Bayou Creek at BB1.

Inc. (Earth City, Missouri). VOCs were analyzed by gas chromatography and ^{99}Tc by liquid scintillation counting at Quanterra. ^{18}O was analyzed by mass spectrometry at the University of Georgia with a precision of 0.15 ‰. We report ^{18}O in ‰ deviation from a value of 0 for standard mean ocean water (SMOW) by means of the δ notation, where R refers to the isotopic ratio ($^{18}O/^{16}O$):

$$\delta = ((R_{sample}/R_{standard}) - 1) \times 1000$$

Results

Ground Water Flow and Hydraulic Gradients

The direction of ground water flow varied with location in the watersheds and with time during our study. Flow in the RGA was toward the Ohio River when it was near pool elevation, as shown for September 24-25, 1997 (Figure 4), when river stage was 88.5 to 89.3 m amsl at Metropolis, Illinois, 5.6 km upriver of the mouth of Bayou Creek (Lockheed Martin Energy Systems and U.S. Geological Survey [USGS], unpublished data). In contrast, on March 24–25, 1997, when the river was 101 m amsl at Metropolis, the RGA was virtually stagnant as far as PGDP, with hydraulic heads generally decreasing to the south-southeast (Figure 5). From February 26 through March 3, Barkley Airfield recorded 0.20 m of rainfall, while other parts of the lower Ohio and Tennessee valleys received 0.076 to 0.30 m (National Weather Service [NWS], unpublished data) (Figure 3). Consequently, the Ohio River was in flood (above 97 m amsl) at Metropolis from March 1 through April 6, with a crest of 102.2 m amsl on March 11 (USGS and U.S. Army Corps of Engineers, unpublished data) (Figure 6). The crest at Paducah, 15 km upriver, was the highest since February 13, 1950. We inferred the approximate limit of Ohio River flooding in the Bayou Creek and Little Bayou Creek watersheds (Figure 7) by tracing the crest elevation on the topographic quadrangle map (U.S. Geological Survey 1982).

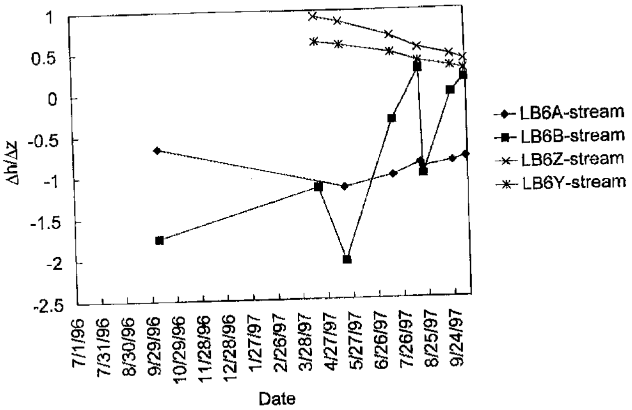

Figure 10. Vertical hydraulic gradients between piezometers or wells and Little Bayou Creek at LB6.

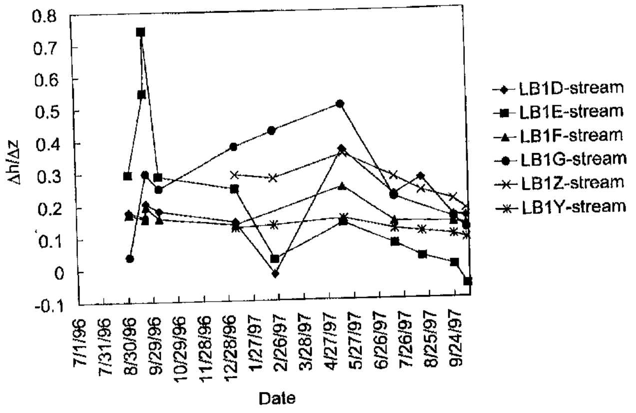

Figure 11. Vertical hydraulic gradients between piezometers or wells and Little Bayou Creek at LB1.

Vertical hydraulic gradients between the creeks and wells ($\Delta h/\Delta z_w$) varied seasonally and episodically (e.g., with Ohio River flooding). Values of $\Delta h/\Delta z_w$ tended to be positive (upward) near the creeks' headwaters and the mouths and negative (downward) along intervening reaches, and were greater for shallower (Z) wells than for deeper (Y) wells where paired wells occur. $\Delta h/\Delta z_w$ was greatest for well BB5Z, upstream of PGDP (maximum 2.1 on January 9). Absolute values of $\Delta h/\Delta z_w$ at sites other than BB5 were less than one. In general, $\Delta h/\Delta z_w$ decreased from April to October 1997 at sites BB5, BB1, LB6, and LB1 (Figures 8 through 11) and from May to October at LB7 (where hydraulic head in well LB7Y was

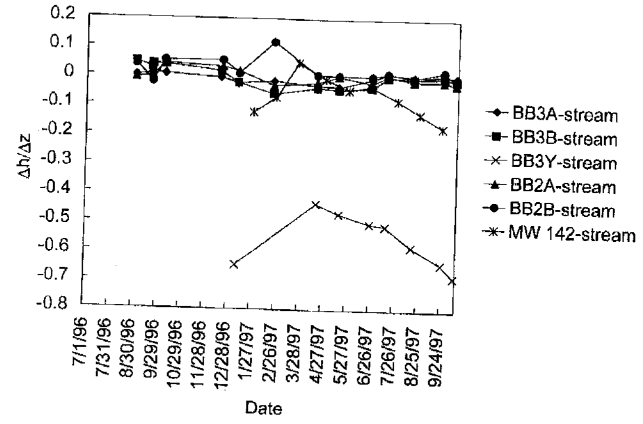

Figure 12. Vertical hydraulic gradients between piezometers or wells and Bayou Creek at BB3 and BB2. Note that $\Delta h/\Delta z_w$ values were determined for MW 142 from USGS stream-stage data.

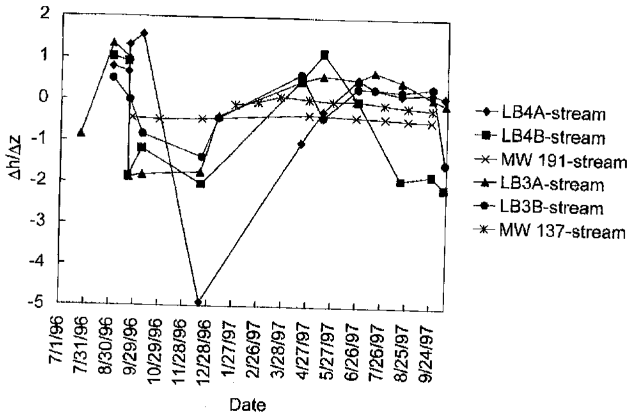

Figure 13. Vertical hydraulic gradients between piezometers or wells and Little Bayou Creek at LB4 and LB3. Note that $\Delta h/\Delta z_w$ values were determined for MW 191 by extrapolating manual stream-stage measurements and for MW 137 from USGS stream-stage data.

always above the stream, but stage was not measured). Decreases in $\Delta h/\Delta z_w$ coincided with falling hydraulic heads in these wells. At BB1, $\Delta h/\Delta z_w$ for both wells became downward between August 18 and September 25 (Figure 9). Conversely, hydraulic heads rose in wells at BB1 and LB1 (although stage was not measured) when Ohio River flooding backed up the creeks in December 1996 and June 1997. For well BB3Y and PGDP wells MW 142 (adjoining BB2), MW 137 (at LB3), and MW 191 (at LB4), $\Delta h/\Delta z_w$ values became less negative (Figures 12 through 13) as hydraulic heads rose following the March 1997 flood. $\Delta h/\Delta z_w$ for MW 137 became upward from March 24 through June 24, while $\Delta h/\Delta z_w$ for MW 142 was upward on March 25.

Vertical hydraulic gradients between the creeks and piezometers ($\Delta h/\Delta z_p$) fluctuated more in response to individual storms, but also varied seasonally and, possibly, in response to Ohio River flooding (Figures 8 through 13). $\Delta h/\Delta z_p$ reversals were evident at all sites; $\Delta h/\Delta z_p$ ranges were broadest for piezometer LB4A (1.6 to –4.9 [Figure 13]) and narrowest for piezometer BB3A (0.013 to –0.034 [Figure 12]). $\Delta h/\Delta z_p$ was consistently upward at site LB1, except for LB1D on February 22, 1997 (–0.019) and LB1E on October 10, 1997 (–0.059). However, $\Delta h/\Delta z_p$ values, like $\Delta h/\Delta z_w$ values, decreased from May to October 1997 at LB1 (Figure 11). Piezometer BB4A showed a long-term $\Delta h/\Delta z_p$ reversal (upward from July 1996 through May 1997 [except on September 22, 1996], then downward in July–October 1997) (Figure 8). Hydraulic gradients became upward for piezometers at LB3, as for well MW 137, in spring and summer 1997 following Ohio River flooding (Figure 13). Short-term $\Delta h/\Delta z_p$ fluctuations in part may have resulted from slow reequilibration with stage changes where the bed is indurated (at BB5) or silty to clayey (at BB1, LB4, LB3, LB6, and LB2). Fluctuations were less pronounced and $\Delta h/\Delta z_p$ ranges were narrower where the bed is sandy (at BB3 and BB2) or gravelly to cobbly (at BB4 and LB1). We typically bailed piezometers where water levels appeared stagnant (i.e., where piezometers may have been inundated). If at least a day elapsed after bailing and water levels did not appear to have recovered, or if piezometers were submerged, we did not record data. (We do not show hydraulic data for piezometers that washed out prior to October 1997.)

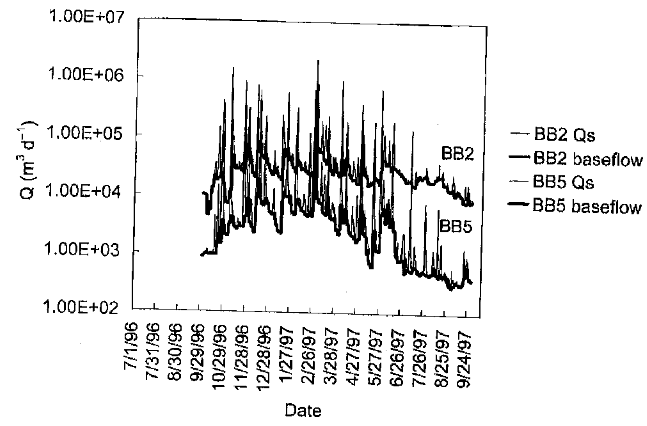

Figure 14. Daily stream flow (Q_s) and base flow (determined by HYSEP) during water year 1997 at USGS gauges on Bayou Creek.

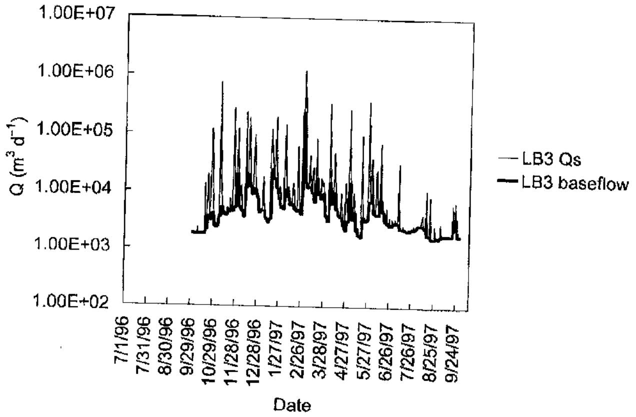

Figure 15. Daily stream flow (Q_s) and base flow (determined by HYSEP) during water year 1997 at USGS gauge on Little Bayou Creek.

Discharge Measurements and Observations

Stream-flow rates (Q_s) were determined by USGS from stage-discharge rating curves for recording gauges

Table 2

Stream-Flow and Base-Flow Rates (Water Year 1997 and Historical Averages) at USGS Gauges

(Maximum specific discharge [q] measured with seepage meters, net specific discharge [q_n] estimated between gauging locations, and ranges of specific discharge [q_z] from modeling of annual temperature ranges in piezometers[Table 3])

USGS Gauge	Q (m^3 d^{-1})	Meter site	q max. (m d^{-1})	Date	K010-LB3 q_n* (m d^{-1})	Date	LB3-LB2 q_n* (m d^{-1})	LB2-AP q_n* (m d^{-1})	Site	q_z min. (m d^{-1})	q_z max. (m d^{-1})
BB2 avg. flow WY91-97	5.31E+04	Bottoms	1.1	10/1/96	–0.040	9/22/96†		–0.24	BB1B	–0.0012	0.025
BB2 avg. flow WY97	7.56E+04	BB1	0.0098	10/15/96**	0.020	10/9/96**	–0.24	0.23	BB2B	–0.0042	–0.016
BB2 avg. base flow WY97	3.29E+04	BB2	0.014	10/30/96	0.16	11/23/96	–0.74	0.36	BB5C	–0.0055	0.016
BB5 avg. flow WY91–97	1.65E+04	BB3	0.0019	11/6/96	0.10	1/8/97†	–0.17	0.10	LB3B	0.0031	0.034
BB5 avg. flow WY97	2.45E+04	BB4	0.022	11/11/96	0.19	2/23/97†	–0.40	0.17	LB4B	0.0083	0.043
BB5 avg. base flow WY97	4.80E+03	LB1	0.91	11/20/96	0.20	4/18/97**†	–0.27	0.30			
LB3 avg. flow WY91–97	1.73E+04	LB1 boil	0.92	12/4/96	0.27	5/16/97**	0.079	0.31			
LB3 avg. flow WY97	2.48E+04	Ash pond	0.38	12/10/96	0.17	8/19/97†	–0.095	0.092			
LB3 avg. base flow WY97	7.14E+03	LB2	0.012	1/7/97	0.20						
		LB6	0.027	1/14/97**	0.13						
		LB6 boil	0.24	2/7/97	0.46						
		LB3	0.0020	2/18/97	0.24						
		LB4	0.0072	2/25/97	0.18						
				3/6/97**	0.69						
				3/11/97**	0.70						
				3/20/97**	1.1						
				3/24/97**	0.46						
				4/1/97	0.15						
				5/13/97**	0.011						
				5/22/97**	0.10						
				5/27/97	0.099						
				6/3/97	0.48						
				6/17/97	0.28						
				6/24/97	0.14						
				8/7/97	0.079						
				8/12/97	0.034						
				9/2/97	-0.030						
				9/9/97**	-0.030						
				9/30/97**	-0.034						

*q_n calculated using measured channel widths at LB2 (6.10–6.55 m) and ash pond (6.28–7.47 m) and an estimated channel width of 3.5 m between K010 and LB3

**Q_s at LB3 estimated by USGS

†runoff indicated by HYSEP at LB3 or (on September 22, 1996) observation of the stream at LB2.

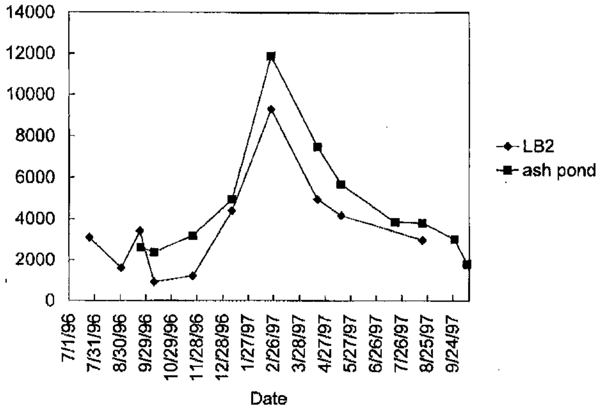

Figure 16. Stream flow gauged by wading at locations along Little Bayou Creek.

at sites BB5, BB1, and LB3. For water year (WY) 1997 (October 1, 1996–September 30, 1997), daily Qs values were least in late summer and early autumn and greatest on March 1 (Figures 14 and 15). Stream-flow rates were estimated by USGS for 69 days at BB5, 162 days at BB2, and 130 days at LB3 because stage records were affected by siltation, ice, or flood damage. Because precipitation during WY 1997 (1.52 m) was above average (1.25 m), annual average Q_s values exceeded historical averages (WY 1991–1997; Table 2). We used the fixed-interval method (with an interval of three days) in the program HYSEP (Sloto and Crouse 1996) to separate hydrographs into base-flow and runoff components. At BB2 and LB3, which are downstream of the PGDP outfalls, base flow is largely sustained by effluent. Base flow constituted a larger percentage of WY 1997 stream flow at BB2 (43.5%) and at LB3 (28.8%) than at BB5 (19.6%), which is upstream of the outfalls (Table 2). Outfall discharges, which were typically monitored by PGDP staff several times per month, averaged 1.9×10^4 m^3 d^{-1} to Bayou Creek and 1.7×10^3 m^3 d^{-1} to Little Bayou Creek during WY 1997 (Bechtel Jacobs, unpublished data). For Little Bayou Creek, which has no perennial tributaries, we estimated q_n between the only continuous outfall (K010) and LB3 (approximately 4.27 km downstream) for dates when HYSEP indicated no surface runoff at LB3. Estimated q_n values were greater than zero except for the beginning (October 1, 1996) and end (September 2, 9, and 30, 1997) of the water

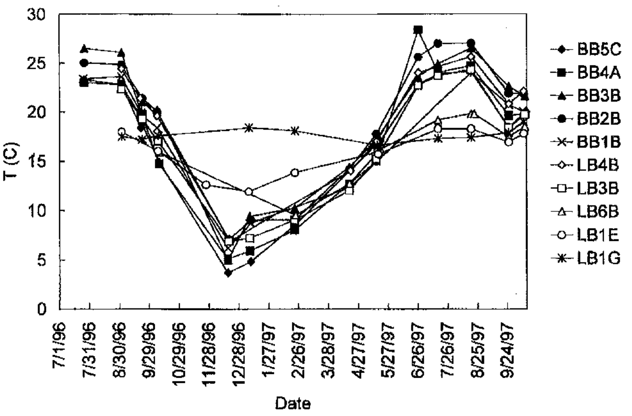

Figure 17. Temperatures for one piezometer at each cluster except LB1 (for which both east- and west-bank piezometers are shown) and LB2 (for which no piezometers are shown, because they washed out prior to the end of the study).

Table 3
Maximum and Minimum Temperatures and Temperature Ranges for Piezometers, Wells, Sites of Bed Probing, and Adjoining Stream Reaches

Location	Min. T (°C)	Max. T (°C)	T range (°C)
BB1A	5.7	25.1	19.4
BB1B	6.2	24.0	17.8
BB1Y	10.5	16.0	5.5
BB1Z	10.1	16.4	6.3
BB1 stream	2.9	26.7	23.8
BB2A	6.9	27.7	20.8
BB2B	7.1	27.0	19.9
BB2 stream	3.5	31.8	28.3
BB3A	4.4	27.1	22.7
BB3B	4.4	26.5	22.1
BB3Y	14.1	15.5	1.4
BB3 stream	3.5	31.5	28.0
BB4A	5.1	28.4	23.3
BB4 stream	2.8	29.7	26.9
BB5B	1.0	24.1	23.1
BB5C	3.7	24.1	20.4
BB5Y	12.0	15.8	3.8
BB5Z	11.7	16.2	4.5
BB5 stream	1.4	28.9	27.5
LB1D	11.3	18.7	7.4
LB1E	11.9	18.3	6.4
LB1F	15.9	19.5	3.6
LB1G	16.6	19.0	2.4
LB1Y	14.0	15.8	1.8
LB1Z	13.8	16.8	3.0
LB1 bed (midstream)	16.2	19.5	3.3
LB1 stream	8.0	21.0	13.0
Ash-pond bed (midstream)	9.4	21.1	11.7
Ash-pond stream	5.8	23.1	17.3
LB2D	6.2	20.8	14.6
LB2E	5.8	21.7	15.9
LB2 bed (midstream)	9.7	21.2	11.5
LB2 stream	3.2	23.8	20.6
LB6A	9.3	19.6	10.3
LB6B	9.5	19.8	10.3
LB6Y	8.7	17.2	8.5
LB6Z	8.4	17.2	8.8
LB6 bed (west bank)	10.4	19.8	9.4
LB6 stream	0.9	23.7	22.8
LB3A	4.2	25.4	21.2
LB3B	6.9	24.3	17.4
LB3 stream	1.0	28.0	27.0
LB4A	4.7	26.8	22.1
LB4B	6.9	25.6	18.7
LB4 stream	3.3	29.1	25.8
LB7Y	14.3	16.1	1.8

year and peaked at 1.1 m d^{-1} on March 20 (Table 2). We did not attempt to estimate q_n between BB5 and BB2 because two perennial tributaries that enter Bayou Creek along that reach were not gauged.

We gauged reaches of both creeks by wading where the bed was relatively uniform. Because of morphologic changes (pooling behind beaver dams and logjams and the migration of shoals and bars) at some sites and our interest in delineating areas of ground water discharge, we focused partway through the study on gauging along the channelized portion of Little Bayou Creek. Between LB2 and a location along the ash pond approximately 760 m downstream, the only surface water inflows are two ephemeral tributaries. At each end of this reach, Q_s decreased to a minimum in October 1996, peaked in February 1997, then decreased to another minimum in August–October 1997 (Figure 16). Values of q_n did not show seasonal trends along the reach, but were greater than zero (indicating upward flow) except on September 22, 1996 (following 54 mm of rainfall on September 21) (Table 2). The maximum q_n value along the reach was 0.36 m d^{-1} on November 23, 1996. We also estimated q_n between LB3 and LB2 (an approximate distance of 1.53 km) using daily Q_s values recorded by USGS at LB3 for dates when we gauged at LB2. In contrast to the reach between LB2 and the ash pond, estimated q_n values between LB3 and LB2 were less than zero except on May 16, 1997 (0.079 m d^{-1}) (Table 2).

We emplaced a seepage meter at least once at each piezometer cluster (except BB5, because of the hardpan in the stream bed) as well as in the Bayou Creek bottoms downstream of BB1 and along the ash pond between sites AP and LB1 (Figure 1). After November 1996, seepage meters were placed only in areas of suspected ground water discharge, where meters were usually left in the bed for less than an hour. Elsewhere, meters were left up to 31 hours. If left too long, the condom would fill to capacity, precluding a reliable measurement. Maximum values of q measured along reaches incised into the RGA (along the ash pond, at LB1, and in the Bayou Creek bottoms) ranged from 0.38 to 1.1 m d^{-1} (Table 2). Along other reaches, q was ≤ 0.028 m d^{-1} (the value measured approximately 50 m upstream of the RGA contact in the Bayou Creek bottoms) except at LB6, where a value of 0.24 m d^{-1} was measured atop a sand boil in the bed on April 18, 1997. In comparison, q was 0.92 m d^{-1} for a sand boil at LB1 on May 16.

In addition to sand boils, we observed seeps and springs along segments of both creeks. Seeps were particularly notable on the south bank of Bayou Creek in the bottoms and on the east bank of Little Bayou Creek along the ash pond. Springs flowed on both banks along a reach of Little Bayou Creek extending from approximately 200 m to 40 m upstream of LB6. Although we did not gauge these springs, Evaldi and McClain (1989) recorded a Q value of 390 m^3 d^{-1} for one of them. At BB4, where an unnamed perennial stream enters Bayou Creek along a closed landfill, ground water discharge was evident from iron oxyhydroxide flocs in the bed. Phillips and Douthitt (1993) suggested that a leaky clay cap on the landfill allowed infiltration of precipitation, leading to leachate generation and water-table mounding.

Temperature Measurements and Modeling

Stream and bed temperatures tended to track air temperatures, fluctuating seasonally from minima in winter to maxima in summer (as shown for representative piezometers in Figure 17). During our study, air temperatures at Barkley Airfield ranged from –19°C on January 11, 1997, to 37°C on July 27, 1997 (NWS, unpublished data). Fluctuations generally decreased with increasing depth: for example, piezometer temperatures tended to be less than stream temperatures in summer and greater in winter. The temporal temperature range (Table 3) was narrower for the deeper piezometer in all pairs except at BB5 and LB6 (excluding BB4, where one piezometer was washed away) and was narrower in the deeper well at locations with paired wells. Stream-temperature ranges varied from 23.8°C (at BB1) to 28.3°C (at BB2) along Bayou Creek and decreased downstream from LB3 (27.0°C) to LB1 (13.0°C) along Little Bayou Creek. Piezometer-temperature ranges were narrowest along Bayou Creek at BB1B (17.8°C) and along Little Bayou Creek at LB1G (2.4°C). The range for each piezometer at LB1 was ≤ 7.4°C, with those on the east bank along the ash pond (F and G) having narrower ranges and greater maximum values than those on the west bank (D and E). Well-temperature ranges varied from 1.4°C for BB3Y (minimum 14.1°C, maximum 15.5°C) to 8.8°C for LB6Z (minimum 8.4°C, maximum 17.2°C). (Relatively broad temperature ranges for wells at LB6 may have resulted from the proximity of the water column to land surface [wells flowed in April and June 1997] and a lack of shade.)

We estimated q values from temperature ranges for piezometers at BB1, BB2, BB5, LB3, and LB4 using the program FOURIER.PE (Lapham 1999). Vertical flow of heat and ground water between homogeneous sediment and an overlying stream can be described by the equation

$$k\frac{\partial^2 T}{\partial z^2} - q_z c_w \rho_w \frac{\partial T}{\partial z} = c\rho \frac{\partial T}{\partial t}$$

where k is thermal conductivity, T is temperature, z is the depth coordinate, c_w is the volumetric heat capacity of water (1.0 cal cm^{-3}°C^{-1}), ρ_w is the density of water (1.0 g cm^{-3}), c is the volumetric heat capacity of the sediment, and ρ is the wet bulk density of the sediment (after Lapham 1989). FOURIER.PE assumes that surface temperature above a semi-infinite porous medium varies sinusoidally for part of the year and is 0°C for the remainder of the year. We assumed that stream temperatures at modeled sites varied sinusoidally during WY 1997 except for January 8–14 (air temperatures were ≤ 0 °C throughout that week [NWS, unpublished data]). Because outfall discharges at BB3 and ash-pond seepage at LB1 probably kept stream temperatures above 0°C, and because of gaps in the piezometer temperature records for BB4, LB2, and LB6, we did not model seepage at those sites. We assumed that the average annual stream temperature and the semiamplitude of annual stream-temperature fluctuation both were 14°C (average annual air temperature) and that ground water temperature was 15°C. We varied the thermal diffusivity (k/c) over a realistic range for sediments (0.0024 to 0.0099 cm^2 s^{-1}) (Lapham 1989) and simultaneously varied q_z to match the observed temperature range at the midpoint of the perforated interval. Resulting values of q_z were less than zero

Table 4
Solute and Oxygen-18 Concentrations in Stream (S suffix except as noted), Spring, and Well (Y suffix) Water

Sample Location	Date	B (mg L^{-1})	Cl$^-$ (mg L^{-1})	δ^{18}O (‰ SMOW)	TCE (μg L^{-1})	^{99}Tc (pCi L^{-1})
BB1S	1/6/97	<0.023	36.2	–4.7		
BB1S	5/16/97	<0.023	33.6	–4.1		
BB1S	8/22/97	0.055	50.7	–3.5		
BB1S	10/10/97	0.085	36.9	–3.5		
BB1Y	1/6/97	<0.023	6.8	–6.1		
BB1Y	5/16/97	<0.023	7.3	–6.4		
BB1Y	8/22/97	<0.023	8.0	–6.1		
BB1Y	10/10/97	<0.023	7.6	–6.4		
BB3S	5/17/97	0.091	60.6	–3.3		
BB3S	8/21/97	<0.023	22.8	–4.6		
BB3S	10/11/97	0.169	79.0	–3.3		
BB3Y	5/18/97	<0.023	3.8	–6.2		
BB3Y	8/21/97	<0.023	3.9	–6.2		
BB3Y	10/11/97	<0.023	3.8	–6.5		
BB5S	1/9/97	<0.023	11.6	–6.3		
BB5S	5/18/97	<0.023	16.1	–4.8		
BB5S	8/20/97	<0.023	16.1	–5.0		
BB5S	10/12/97	<0.023	18.5	–5.4		
BB5Y	1/9/97	<0.023	3.2	–6.1		
BB5Y	5/18/97	<0.023	3.2	–6.3		
BB5Y	8/20/97	<0.023	3.4	–6.2		
BB5Y	10/12/97	<0.023	3.3	–6.2		
LB1S	1/7/97	0.623	16.7	–6.0		
LB1S	5/16/97	0.862	22.8	–5.6	3	8.20 ± 2.11
LB1S	8/21/97	0.736	18.9	–5.2	2	23.8 ± 6.0
LB1S	10/10/97	0.915	21.5	–5.4	2	15.7 ± 3.9
LB1Y	1/7/97	<0.023	12.7	–5.9		
LB1Y	5/17/97	0.091	11.8	–5.9	<1	7.92 ± 3.2
LB1Y	8/21/97	<0.023	12.1	–5.8	<1	<8.02
LB1Y	10/10/97	0.042	12.3	–6.0	<1	<10.7
AP	7/10/98				4	
WF	7/10/98				12	
LB2S	7/10/98				17	
LB6S	1/7/97	0.036	16.0	–6.0	11	6.98 ± 1.50
LB6S	5/17/97	<0.023	30.0	–5.7	36	5.60 ± 1.85
LB6S	8/19/97	<0.023	36.0	–4.4	24	51.1 ± 8.0
LB6S	10/11/97	<0.023	30.2	–4.9	26	36.5 ± 5.3
LB6S	7/10/98				16	
LB6Y	1/7/97	<0.025	32.5	–6.1	10	24.1 ± 2.9
LB6Y	5/17/97	<0.023	34.6	–6.2	12	53.4 ± 5.8
LB6Y	8/19/97	<0.023	32.4	–6.3	17	19.8 ± 10.4
LB6Y	10/11/97	<0.023	34.3	–6.2	16	31.1 ± 4.9
EB	7/10/98				46*	
WB	7/10/98				220*	
LB7S	5/19/97	<0.023	27.9	–5.7		
LB7S	8/20/97	<0.023	23.0	–3.9	<1	<8.26
LB7S	10/12/97	<0.023	27.7	–4.8	<1	5.42 ± 3.11
LB7Y	5/19/97	<0.023	62.1	–6.2		
LB7Y	8/20/97	<0.023	59.9	–6.2	<1	
LB7Y	10/12/97	<0.023	60.0	–6.2	<1	<5.08

* = estimated (beyond calibration range of GC). S = stream; AP (ash pond) and WF (waterfall) were stream-water sampling sites along Little Bayou Creek; EB = east-bank spring and WB = west-bank spring.

(downward) for BB2B, greater than zero (upward) for LB4B and LB3B, and ranged from negative to positive for BB5C and BB1B. Absolute values of q_z ranged from 0.0012 m d^{-1} for BB1B to 0.043 m d^{-1} for LB4B (Table 2).

Like seepage-meter placement and stream gauging, temperature probing was initially conducted at multiple locations in each watershed (although bed lithology and morphology limited the use of these techniques at BB5 and LB7). After October 1996, we focused on possible sites of ground water discharge, including the Bayou Creek bottoms and Little Bayou Creek downstream of LB3. When the bottoms were accessible (September–November 1996 and July–October 1997), we probed at various points along a reach approximately 500 m long. Within 20 m downstream of the RGA contact, temperatures at depth decreased by 4.7°C to 4.8°C (to 14.7°C in August 1997 and 14.4°C in October 1997). Where we observed seeps in the bottoms, bed and bank temperatures ranged from 14.3°C to 16.5°C, while temperatures at the base of the water column were as much as 24.4°C. In July 1998, we probed two sand boils along Little Bayou Creek approximately 40 to 200 m upstream of LB6. As in the bottoms, temperatures at depth (14.2°C to 14.3°C) were distinctly lower than the stream temperature (23.1°C at the downstream end of the reach). Downstream, the temporal range in bed temperature (Table 3) increased slightly from LB6 (9.4°C along the west bank) to the reach between LB2 and the ash pond (11.5°C to 11.7°C at midstream), then decreased to LB1 (3.3°C at midstream). From September 1996 through May 1997, we also probed at both piezometer nests at LB1. Except in September, temperatures at depth increased from the west bank through midstream to the east bank. The maximum temperature (21.2°C) was recorded beneath the east bank in January 1997, which suggests a thermal anomaly associated with ash-pond seepage.

Hydrochemical Parameters and Modeling

Chloride and $\delta^{18}O$ concentrations in stream water varied with both location and time (Table 4). In stream water, Cl^- concentrations were lowest at BB5 (11.6 to 18.5 mg L^{-1}), greatest at BB3 in May and October 1997 (60.6 to 79.0 mg L^{-1}), and greatest at BB1 in August 1997 (50.7 mg L^{-1}). Along Little Bayou Creek, Cl^- was lowest at LB1 (except in January) and increased from LB7 to LB6. Trends in $\delta^{18}O$ were similar to those of Cl^- along Bayou Creek: $\delta^{18}O$ was always lowest at BB5 (-6.3 to -4.8 ‰), highest in May and October at BB3 (–3.3 ‰), and highest in August at BB1 (–3.5 ‰). Along Little Bayou Creek, $\delta^{18}O$ was relatively invariant in January and May, but $\delta^{18}O$ decreased downstream in August and October. Increased Cl^- and $\delta^{18}O$ concentrations in stream water at BB3 relative to BB5 are associated with outfall discharges. In May and October, Cl^- and $\delta^{18}O$ in stream water at LB7 were less than at BB3, which suggests that the composition of outfall discharges to the two creeks differed. Decreases in stream water Cl^- between BB3 and BB1 in May and October 1997 may reflect dilution by tributaries to Bayou Creek, but the reason for the increase in Cl^- along this reach in August is unclear.

Table 5

Geochemical Models of Ground Water/Stream Water Mixing Along Bayou and Little Bayou Creeks and Concentration Factors for Evaporation of BB5Y Ground Water to Yield BB5 Stream Water

Date	Model	Parameter	End Member 1%	End Member 2%
5/97	BB5Y + BB5S = BB3Y	Cl^-	95	5
		$\delta^{18}O$	93	7
	BB5Y + BB3S = BB3Y	Cl^-	99	1
		$\delta^{18}O$	97	3
	BB3Y + BB3S = BB1Y	Cl^-	94	6
		$\delta^{18}O$	N/A	N/A
	BB3Y + BB1S = BB1Y	Cl^-	88	12
		$\delta^{18}O$	N/A	N/A
	LB7S + LB6Y = LB6S	Cl^-	69	31
		$\delta^{18}O$	100	0
8/97	BB5Y + BB5S = BB3Y	Cl^-	96	4
		$\delta^{18}O$	100	0
	BB5Y + BB3S = BB3Y	Cl^-	97	3
		$\delta^{18}O$	100	0
	BB3Y + BB3S = BB1Y	Cl^-	78	22
		$\delta^{18}O$	94	6
	BB3Y + BB1S = BB1Y	Cl^-	91	9
		$\delta^{18}O$	96	4
	LB7S + LB6Y = LB6S	Cl^-	N/A	N/A
		$\delta^{18}O$	79	21
10/97	BB5Y + BB5S = BB3Y	Cl^-	97	3
		$\delta^{18}O$	N/A	N/A
	BB5Y + BB3S = BB3Y	Cl^-	99	1
		$\delta^{18}O$	N/A	N/A
	BB3Y + BB3S = BB1Y	Cl^-	95	5
		$\delta^{18}O$	97	3
	BB3Y + BB1S = BB1Y	Cl^-	89	11
		$\delta^{18}O$	97	3
	LB7S + LB6Y = LB6S	Cl^-	62	38
		$\delta^{18}O$	93	7

Date	Model	Parameter	Evaporation Factor
1/97	BB5Y → BB5S	Cl^-	3.6
		$\delta^{18}O$	1.0
5/97	BB5Y → BB5S	Cl^-	5.0
		$\delta^{18}O$	1.3
8/97	BB5Y → BB5S	Cl^-	4.7
		$\delta^{18}O$	1.2
10/97	BB5Y → BB5S	Cl^-	5.6
		$\delta^{18}O$	1.2

Chloride and $\delta^{18}O$ values in ground water varied with location but were relatively invariant with time (Table 4). Chloride concentrations varied by ≤ 2.2 mg L^{-1} in each well. Average Cl^- concentrations in ground water along Bayou Creek increased downstream (from 3.3 mg L^{-1} in BB5Y to 7.4 mg L^{-1} in BB1Y), while average concentrations in ground water along Little Bayou Creek decreased downstream (from 60.7 mg L^{-1} in LB7Y to 12.2 mg L^{-1} in LB1Y). Along Bayou Creek, Cl^- was always lower in ground water than in stream water; along Little Bayou Creek, Cl^- was lower in stream water than in ground water at LB7 and (except for August 1997) at LB6. Except at BB5 and LB1 in January, ground water was always depleted in ^{18}O relative to stream water. Values of $\delta^{18}O$ in ground water varied from –5.8 to –6.5 ‰, but the temporal range for any well was ≤ 0.3 ‰ and the range among wells at any time was ≤ 0.5 ‰. Sturchio et al. (1998) reported $\delta^{18}O$ values of –4.9 to –5.8 ‰ for other RGA and UCRS wells.

Among trace solutes, B was monitored at all sampling locations in both watersheds, while TCE and ^{99}Tc were monitored in stream and ground water beginning in January 1997 at LB6, in May 1997 at LB1, and in August 1997 at LB7. Boron was detected consistently in stream water at LB1 (at concentrations of 0.623 to 0.915 mg L^{-1}) and sporadically in well LB1Y and in stream water at BB3 and BB1 (at concentrations ≤ 0.169 mg L^{-1}). At other times and locations, B concentrations were below detection limit (0.023 to 0.025 mg L^{-1}) or measured both in the sample and a blank (for stream water at LB6 in January 1997). Sampling for TCE and ^{99}Tc focused initially on LB6 because of its proximity to the northwest plume. In stream water, TCE concentrations were below detection limit (< 1 μg L^{-1}) at LB7, 11 to 36 μg L^{-1} at LB6, and 2 to 3 μg L^{-1} at LB1 (Table 4). ^{99}Tc activities in stream water were < 8.26 pCi L^{-1} at LB7, 5.60 to 51.1 pCi L^{-1} at LB6, and 8.20 to 23.8 pCi L^{-1} at LB1. Among the wells sampled, only LB6Y had detectable TCE (10 to 17 μg L^{-1}) and consistently detectable ^{99}Tc (19.8 to 53.4 pCi L^{-1}). TCE was always higher in stream water than in ground water at LB6 and LB1. However, TCE concentrations were highest in the two springs sampled upstream of LB6 in July 1998 (estimated concentrations 46 to 220 μg L^{-1} in undiluted samples).

We used Cl^- and $\delta^{18}O$ as mixing parameters in the program NETPATH (Plummer et al. 1994) to assess infiltration from Bayou Creek between BB5 and BB1 and ground water discharge to Little Bayou Creek between LB7 and LB6. We did not quantify mixing downstream of LB6 because of a lack of hydrochemical data for the TVA ash pond. Following Evaldi and McClain (1989), models included (1) BB5Y ground water + BB5 or BB3 stream water → BB3Y ground water, (2) BB3Y ground water + BB3 or BB1 stream water → BB1Y ground water, and (3) LB7 stream water + LB6Y ground water → LB6 stream water. Because neither BB3 nor LB7 was sampled in January 1997, we calculated mixing percentages for May, August, and October 1997 (Table 5). Agreement between Cl^--derived and $\delta^{18}O$-derived percentages was better for Bayou Creek than for Little Bayou Creek. Model 1 suggests that 0% to 7% of ground water in BB3Y originated as stream water between BB5 and BB3. Model 2 suggests that 3% to 6% (for $\delta^{18}O$) or 5% to 22% (for Cl^-) of ground water in BB1Y originated as stream water between BB3 and BB1. Model 3 indicates that 0% to 21% (for $\delta^{18}O$) or 31% to 38% (for Cl^-) of stream water at LB6 was contributed by ground water resembling LB6Y in composition. Although mixing percentages varied with time in each case, a trend is apparent only for the mixture BB5Y ground water + BB5 stream water → BB3Y ground water, in which the percentage of infiltrating stream water decreased from May through October. No solution could be obtained for $\delta^{18}O$ for model 1 in October, for $\delta^{18}O$ for model 2 in May, or for Cl^- for model 3 in August.

Because Bayou Creek base flow is sustained by ground water discharge upstream of the outfalls, we used Cl^- and $\delta^{18}O$ in NETPATH to calculate evaporation factors at BB5 (assuming that BB5Y data represent the composition of base flow). Results indicate that BB5 stream water represents ground water that has been concentrated by a factor of 3.6 to 5.6 (for Cl^-) or 1.0 (i.e., no evaporation) to 1.3 (for $\delta^{18}O$) (Table 5). Evaporation factors were lowest for January 1997, when temperatures were lowest, and highest for May, although temperatures peaked in July.

Discussion

Losing and Gaining Reaches

Losing conditions tended to occur between BB4 and BB1 along Bayou Creek and upstream of LB3 along Little Bayou Creek, while gaining conditions tended to occur upstream of BB4 and downstream of BB1 along Bayou Creek and downstream of LB3 along Little Bayou Creek (Figure 7). Mixing calculations along Bayou Creek and $\Delta h/\Delta z_w$ values less than zero indicate losing conditions, which coincided with stream-temperature ranges greater than or equal to 23.8°C and piezometer-temperature ranges greater than or equal to 17.8°C. Gaining conditions are indicated by observations of seeps, springs, and sand boils, typical $\Delta h/\Delta z$ values greater than zero (except at LB7, where the UCRS appears to be confined), mixing calculations between LB7 and LB6, and evaporation calculations for BB5. Along gaining reaches downstream of PGDP, bed and bank temperatures were as much as 9.8°C cooler than stream temperatures in summer and early autumn. Along gaining reaches of Little Bayou Creek, temperature ranges were less than or equal to 22.8°C for the stream, less than or equal to 15.9°C for piezometers, and less than or equal to 11.7°C for the bed. Maximum q values measured by seepage meters were less than or equal to 0.014 m d^{-1} along losing reaches and greater than or equal to 0.022 m d^{-1} along gaining reaches. Gaining and losing reaches may be interspersed between BB5 and BB3 (relatively broad temperature ranges and low q values suggest that discharge at BB5 and BB4 is local) and between LB4 and LB2 (as indicated by typical q_n values greater than zero between outfall K010 and LB3 and less than zero between LB3 and LB2). Although Evaldi and McClain (1989) concluded there was no net discharge between the outfalls and LB3, our results are otherwise consistent with their data and with a pre-PGDP topographic map (U.S. Geological Survey 1932) showing Little Bayou Creek downstream of LB3 as perennial. Our results also support the hypothesis of Clausen et al. (1992) that infiltration occurs where stream-bed deposits connect the terrace gravels with the RGA between BB5 and BB3.

Fluctuations in the magnitude and direction of hydraulic gradients, in values of Q_s and q_n, and in mixing percentages indicate temporal variability in seepage along the creeks. Submonthly $\Delta h/\Delta z_p$ fluctuations are consistent with stage changes following storms within the

Bayou Creek and Little Bayou Creek watersheds. Longer-term variability in seepage is associated with Ohio River flooding and seasonal dry periods. Spring 1997 floods caused hydraulic-gradient reversals and lateral flow away from the river (and, possibly, upward flow at LB3 and BB2). Ephemeral sand boils and seeps (e.g., at LB6 and LB1 in April and May) suggest temporary increases in discharge to Little Bayou Creek following flooding. During summer and early autumn, $\Delta h/\Delta z_w$ decreased or became downward (as did $\Delta h/\Delta z_p$ at BB4 and LB1), Q_s decreased, and, according to mixing calculations, the volume of infiltration from Bayou Creek upstream of BB3 decreased. Below-average rainfall (363 mm versus a normal total of 417 mm [NWS, unpublished data]) from June 1 through October 12, 1997, may have accentuated these declines. Similarly, Clausen et al. (1992) observed $\Delta h/\Delta z$ reversals (upward in January–August 1991, then downward until December 1991) in paired RGA and UCRS wells 1.2 km from the river.

Limitations of Results

In some instances, specific discharge or $\Delta h/\Delta z$ data seem to give inconsistent results, which can be explained by differences in measurement scales or inaccuracy in calculations. For example, q_n values between outfall K010 and LB3 ranged from –0.030 to 1.1 m d^{-1}, modeled q_z values are 0.0083 to 0.043 m d^{-1} for piezometer LB4B, the maximum q value measured at LB4 was 0.0072 m d^{-1}, and $\Delta h/\Delta z_w$ between MW 191 and Little Bayou Creek ranged from –0.33 to –0.47. Relative to seepage-meter data, q_n values are averaged over much larger spatial scales (> 10^3 m^2 versus < 10^{-2} m^2) and q_z values are averaged over much larger time scales (annual versus hourly to daily). Both q_n values and q_z values can account for inflows or outflows, whereas seepage meters only measured inflows (i.e., q values greater than zero). However, q_n values include evapotranspirative losses (and, in some instances, runoff and transient storage) and are affected by uncertainties in Q_s measurements and stage-discharge correlations. Temperature ranges used in q_z modeling are affected by lack of continuous measurements and by radiant heating and cooling of piezometers (Lapham 1989). Nonetheless, the magnitudes of q_n values and q_z values (except the minimum of 0.0012 m d^{-1} for BB1B) fall within the range of maximum q values measured by seepage meters (0.0019 to 1.1 m d^{-1}). Small, positive q values along losing reaches and $\Delta h/\Delta z_p$ values that are near-zero or oppositely directed to $\Delta h/\Delta z_w$ suggest downstream flow within the bed, which gauging does not measure (Zellweger et al. 1989). In general, the assumption of unidirectional vertical seepage to and from the creeks is convenient for calculations and modeling but is simplistic.

Mixing models require the simplifying assumptions that initial and final waters fall along a flowpath and that all endmembers are represented (Plummer et al. 1994). Ground water flow from BB5 to BB3 is reasonable (Figure 4), but we assume that BB3 is a surrogate for ground water upgradient of BB1 (in the RGA west of Bayou Creek). Differences in mixing percentages and evaporation factors determined from Cl^- and $\delta^{18}O$ are consistent with our observation that ranges of Cl^- concentrations are broader than ranges of $\delta^{18}O$ in ground water (i.e., sources of Cl^- may be more diverse than sources of $\delta^{18}O$). Mixing percentages for Little Bayou Creek underestimate the results of mass-balance calculations using stream-flow data. We obtained Q_s values of 3.6×10^3 m^3 d^{-1} on May 16 and 3.0×10^3 m^3 d^{-1} on August 19 by gauging at LB6. Q_s values determined by USGS at LB3 were 1.8×10^3 m^3 d^{-1} on May 16 and 2.1×10^3 m^3 d^{-1} on August 19 (including 2.1×10^2 m^3 d^{-1} runoff indicated by HYSEP, which we subtract because rain began after we finished gauging at LB6). These data suggest that ground water discharge between LB3 and LB6 contributed 50% of stream flow during May sampling (versus 31% indicated by Cl^- and 0% indicated by $\delta^{18}O$) and 41% of stream flow during August sampling (versus 21% indicated by $\delta^{18}O$). Mixing percentages for both creeks in August and evaporation factors for BB5 in January and August are inexact because precipitation and runoff occurred during sampling periods. We did not account for the composition of soil water (which contributes to runoff) or throughfall (Rice and Hornberger 1998). HYSEP indicates that the contribution of runoff to stream flow was 20% at BB5 on January 9, 69% at BB5 and 79% at LB3 on August 20, and 15% at BB2 on August 21.

Comparisons with Studies of Other Watersheds

Our conceptual model of ground water/stream interactions in the Bayou and Little Bayou Creek watersheds is consistent with observations in other watersheds. At the scale of ground water interactions with the Ohio River, our system can be categorized as base-flow rather than under-flow dominated (flow is toward [or during floods, away from] the river rather than parallel to it) (Figures 4 and 5). In studying 24 alluvial systems (not including the Ohio River), Larkin and Sharp (1992) found that the under-flow component dominates when the channel gradient is greater than 0.0008, the sinuosity of the river is less than 1.3, the river penetrates less than 20% of the alluvial aquifer thickness, the river's width/depth ratio is greater than 60, and the fluvial depositional system is valley-fill or mixed-load to bed-load. The sinuosity between locks and dams 52 and 53 (Ohio River milepoints 938.9 to 962.6) is 1.1 (U.S. Geological Survey 1987), and the width/depth ratio in the vicinity of PGDP (river milepoints 945 to 950) is approximately 280 to 340 (U.S. Geological Survey 1982; U.S. Army Corps of Engineers, unpublished data, 1997). However, the channel gradient between locks and dams 52 and 53 at pool stage is 0.000096, and the river penetrates the entire thickness of the RGA and modern alluvium (Figure 2). Our conceptual model agrees with that of Freeze and Cherry (1979, p. 205): in a tributary watershed, both ground water and the tributary flow toward the river, and the tributary loses water as it traverses the recharge zone (downstream of its headwaters) and gains water again in the discharge zone near the river. Silliman and Booth (1993) observed a similar sequence of losing and gaining reaches along Juday Creek, a tributary to the St. Joseph River in northwestern Indiana.

At the scale of ground water interactions with the creeks, our inference of downstream flow within the bed as well as seepage to and from the aquifer falls within the framework of the hyporheic zone. Triska et al. (1989) defined two separate hyporheic zones adjoining a third-order stream: a shallow zone, beneath the channel, containing greater than 98% advected stream water and a deeper zone, extending at least 10 m laterally from the channel, containing 10% to 98% stream water. White (1993, p. 62) defined the hyporheic zone more generally as "the saturated interstitial areas beneath the stream bed and into the stream banks that contain some proportion of channel water or that have been altered by channel water infiltration." Consequently, the limits of the hyporheic zone vary in time and space (e.g., with flooding and bank storage) (Boulton et al. 1998). Recent studies of streams like Bayou and Little Bayou Creeks (first- to third-order, with sandy to cobbly channel deposits) have identified multiple hyporheic zones, each on the order of 10 m long, arrayed sequentially downstream (Harvey and Bencala 1993; Hendricks and White 1995; Wroblicky et al. 1998). Spacings between these zones depend upon the placement of bed forms (e.g., in pool-riffle-pool sequences) and bars through which stream water flows. Like Larkin and Sharp (1992) at the river scale, such studies demonstrate that ground water/stream interactions are coupled to channel geomorphology and permeability of alluvium. We did not attempt to delineate hyporheic zones, but $\Delta h/\Delta z_w$ data and reach-scale parameters (mixing ratios and q_n values) helped to differentiate ground water recharge and discharge from stream water advection along Bayou and Little Bayou Creeks. Seepage-meter measurements, bed/bank temperature data, and (to a lesser extent) $\Delta h/\Delta z_p$ data, while probably influenced by stream water advection, tended to be distinctive along gaining reaches.

Implications for Contaminant Transport and Fate

Although other recent studies have noted that discharge to streams can limit VOC plume migration (e.g., Imbrigiotta et al. 1996; Vroblesky et al. 1996; Kim and Hemond 1998), we are not aware of studies that have focused on hydraulic interactions among plumes, rivers, and tributaries. Infiltration along Bayou Creek, augmented by outfall discharges, may help to mobilize contaminants in source areas of the northwest plume, although infiltration from lagoons and leaky water mains at PGDP is probably more significant (Jacobs EM Team 1998). Along Little Bayou Creek, increases in TCE and ^{99}Tc in stream water between LB7 and LB6, like data of CH2M Hill (1991, 1992), suggest seepage from the northwest plume and, possibly, the offsite ^{99}Tc plume. In particular, TCE concentrations for springs EB and WB indicate discharge from the northwest plume. Between LB6 and LB1, decreases in TCE, ^{99}Tc, and Cl^- and the increase in B indicate dilution of contaminants in stream water by seepage from both the RGA (cross-gradient from the plumes) and the ash pond. Decreases in $\delta^{18}O$ of stream water between LB7 and LB1 in August and October 1997 and the relatively narrow and depleted range of $\delta^{18}O$ in stream water at LB1 (–5.2 ‰ to –6.0 ‰) are also consistent with ground water discharge. Because ^{99}Tc occurs as the relatively conservative anion TcO_4^- within Eh and pH ranges characteristic of oxic surface and ground waters (Wildung et al. 1979), ^{99}Tc concentrations offer a baseline against which to compare TCE concentrations. The decrease in the TCE/^{99}Tc ratio from LB6 to LB1 suggests that TCE in stream water was not only diluted, but also removed by processes that do not affect TcO_4^-, such as volatilization, sorption, or biodegradation.

Contaminant concentrations in both stream water and ground water fluctuated with time. Increased TCE concentrations in Little Bayou Creek in May 1997 suggest that flooding shifted the position of the northwest plume (as inferred by Clausen et al. [1992]) and thus altered the discharge of contaminated ground water to the stream. TCE and ^{99}Tc concentrations in stream water at LB6 were greater in August and October than in January, which suggests that base flow from the plumes provided an increased proportion of stream flow in summer and early autumn. However, we do not know why TCE and ^{99}Tc concentrations in stream water increased at different times (May versus August), nor why fluctuations in ^{99}Tc and TCE concentrations in well LB6Y did not track fluctuations in stream water concentrations. Runoff probably did not affect contaminant concentrations in stream water samples from LB6: we finished sampling within an hour after light rain began on August 19, and HYSEP did not indicate runoff along Little Bayou Creek during other sampling times at LB6.

Conclusions

Using hydraulic, thermal, and hydrochemical techniques, we delineated spatial and temporal variability in seepage along first- and second-order tributaries of the Ohio River between July 1996 and July 1998. Losing conditions tended to occur along Bayou Creek from approximately 7.8 km to 2.7 km upstream of its mouth and along Little Bayou Creek from its headwaters to a point approximately 3.6 km upstream of its confluence with Bayou Creek. Gaining conditions, which occurred above and below the losing reach of Bayou Creek and below the losing reach of Little Bayou Creek, tended to be associated with gravelly to cobbly sediments, although springs along Little Bayou Creek may flow along joints and fractures in clay overlying the RGA. Downward hydraulic gradients from the stream to stream-bank wells indicated losing conditions, while gaining conditions were indicated by visual observations of discharge and upward hydraulic gradients from wells and stream-bed piezometers to the stream. Mixing models using Cl^- and $\delta^{18}O$ supported inferences of losing and gaining conditions. Along gaining reaches, annual ranges of stream, bed, and bank temperatures tended to be narrower, bed/bank temperatures in summer and early autumn tended to be cooler, and maximum values of specific discharge measured by seepage meters were greater than along losing reaches. Specific-discharge values estimated from stream gauging and from modeling of vertical heat and fluid flow did not conclusively identify losing and gaining reaches, although the magnitude of estimated values fell within the range of seepage-meter measurements. Temporary reversals in hydraulic gradients and changes in seepage rates were associated with local storms, Ohio River flooding in spring, and dry periods in summer and early autumn.

Our findings confirm that seepage along tributaries can affect contaminant transport in riverine watersheds. Infiltration along Bayou Creek may help to mobilize contaminants beneath the northwest corner of PGDP, and migration of the northwest plume toward the Ohio River is limited by discharge to Little Bayou Creek. Downstream dilution by uncontaminated ground water lowers concentrations of TCE and ^{99}Tc in Little Bayou Creek. Although ^{99}Tc data are ambiguous, increased TCE concentrations in Little Bayou Creek in May 1997 suggest that flooding temporarily altered the discharge of contaminated ground water to the stream. We are currently examining seasonal variability in contaminant concentrations, stream flow and seepage, and TCE mass removal along the gaining reach of Little Bayou Creek. Mass-removal processes could include volatilization from the stream surface and sorption and biodegradation in the riparian and hyporheic zones. We anticipate that our findings will be particularly relevant to other sites where plumes migrate toward rivers in the Gulf and Atlantic Coastal Plains.

Acknowledgments

The research described herein was supported by USGS grant 1434-HQ-96-6R-02672 and by the Agreement-in-Principle between DOE and the Commonwealth of Kentucky through the Kentucky Water Resources Research Institute. The contents of this paper do not necessarily reflect the views and policies of the Departments of the Interior and Energy, nor does mention of trade names or commercial products constitute endorsement by the United States Government. We thank DOE, TVA, the Kentucky Department of Fish and Wildlife Resources, and Ronald Lamb for access to their properties. David Butler, Mark Kulp, Danita LaSage, Jonathan McIntyre, Todd Mullins, Christofer Sweat, Matt Vick, and Jessica Wichtowski helped with field work. Stan Knaus and Jana White (Bechtel Jacobs) provided logistical support. We appreciate the assistance of Bart Davidson and Richard Smath (Kentucky Geological Survey) and David Reynolds with surveying; Bill McClain (University of Georgia) with ^{18}O analyses; Alan Brown and Dennis McClain (USGS) and Tom Priddy (University of Kentucky) in furnishing hydrologic and climatic data; and Wayne Lapham (USGS) with modeling. Susan Hendricks, Lyle Sendlein, and David Wenner offered helpful advice. Critiques by Jim Constantz and two anonymous reviewers improved the manuscript considerably.

References

Böhlke, J.K., and J.M. Denver. 1995. Combined use of groundwater dating, chemical, and isotopic analyses to resolve the history and fate of nitrate contamination in two agricultural watersheds, Atlantic coastal plain, Maryland. *Water Resources Research* 31, no. 9: 2319–2339.

Boulton, A.J., S. Findlay, P. Marmonier, E.H. Stanley, and H.M. Valett. 1998. The functional significance of the hyporheic zone in streams and rivers. *Annual Review of Ecology and Systematics* 29: 59–81.

CH2M Hill. 1991. Results of the site investigation, Phase I, at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky. Report KY/ER-4, prepared for the U.S. Department of Energy under subcontract to DOE contract DE-AC05-76OR00001. Oak Ridge, Tennessee: CH2M Hill.

CH2M Hill. 1992. Results of the site investigation, Phase II, at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky. Report KY/SUB/13B-97777C P-03/1991/1, prepared for the U.S. Department of Energy under subcontract to DOE contract DE-AC05-76OR00001. Oak Ridge, Tennessee: CH2M Hill.

Clausen, J.L., J.W. Douthitt, K.R. Davis, and B.E. Phillips. 1992. Report of the Paducah Gaseous Diffusion Plant groundwater investigation phase III. Report KY/E-150, prepared for the U.S. Department of Energy under subcontract to DOE contract DE-AC05-76OR00001. Kevil, Kentucky: Martin Marietta Energy Systems.

Clausen, J.L., J. Zutman, D.A. Pickering, and N. Farrow. 1995. Final report on drive-point profiling of the Northwest Plume and analysis of related data. Report KY/ER-66, prepared for the U.S. Department of Energy under subcontract to DOE contract DE-AC05-76OR00001. Kevil, Kentucky: Martin Marietta Energy Systems.

Constantz, J. 1998. Interaction between stream temperature, streamflow, and groundwater exchanges in alpine streams. *Water Resources Research* 34, no. 7: 1609–1615.

Davidson, G.R., and R.L. Bassett. 1993. Application of boron isotopes for identifying contaminants such as fly ash leachate in groundwater. *Environmental Science & Technology* 27, no. 1: 172–176.

Davis, K.R. 1996. The McNairy Formation in the area of the Paducah Gaseous Diffusion Plant. Report KY/EM-148, prepared for the U.S. Department of Energy under subcontract to DOE contract DE-AC05-76OR00001. Kevil, Kentucky: Martin Marietta Energy Systems.

Evaldi, R.D., and D.L. McClain. 1989. Streamflow, specific-conductance, and temperature data for Bayou and Little Bayou Creeks near Paducah, Kentucky, August 15 and 16, 1989. U.S. Geological Survey Open-File Report 89–582. Louisville, Kentucky: USGS.

Freeze, R.A., and J.A. Cherry. 1979. *Groundwater.* Englewood Cliffs, New Jersey: Prentice-Hall.

Harvey, J.W., and K.E. Bencala. 1993. The effect of streambed topography on surface-subsurface water exchange in mountain catchments. *Water Resources Research* 29, no. 1: 89–98.

Hem, J.D. 1992. Study and interpretation of the chemical characteristics of natural water. U.S. Geological Survey Water-Supply Paper 2254, 3rd ed. Washington, D.C.: U.S. Government Printing Office.

Hendricks, S.P., and D.S. White. 1995. Seasonal biogeochemical patterns in surface water, subsurface hyporheic, and riparian ground water in a temperate stream ecosystem. *Archiv für Hydrobiologie* 134: 459–490.

Hibbs, B.J. 1993. Numerical modeling and hydrologic analysis of floodplain hydrogeology, bank storage interactions, and underflow in the Colorado River alluvial aquifer. Ph.D. thesis, Department of Geological Sciences, The University of Texas at Austin.

Imbrigiotta, T.E., T.A. Ehlke, B.H. Wilson, and J.T. Wilson. 1996. Case study: Natural attenuation of a trichloroethene plume at Picatinny Arsenal, New Jersey. In *Symposium on Natural Attenuation of Chlorinated Organics in Ground Water,* U.S. Environmental Protection Agency report EPA/540/R-96/509, 83-89. Washington, D.C.: U.S. EPA.

Jacobs EM Team. 1998. Ground water flow model recalibration and transport model construction at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky. Report DOE/OR/07-1742&D0, prepared for the U.S. Department of Energy under subcontract to DOE contract DE-AC05-98OR22700. Kevil, Kentucky: Jacobs EM Team.

Job, C.A., and J.J. Simons. 1996. EPA update: Ground and surface water interaction, watershed management, and monitoring. *Ground Water Monitoring & Remediation* 16, no. 3: 68–69.

Kim, H., and H.F. Hemond. 1998. Natural discharge of volatile organic compounds from contaminated aquifer to surface waters. *Journal of Environmental Engineering* 124, no. 8: 744–751.

Langston, C., J. McIntyre, and R. Street. 1998. Investigation of the shallow subsurface near the Paducah Gaseous Diffusion Plant using SH-wave seismic methods. Society of Exploration Geophysicists, 1998 Technical Program, Expanded Abstracts, vol. 1, 878–880. Tulsa, Oklahoma: Society of Exploration Geophysicists.

Lapham, W.W. 1989. Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity. U.S. Geological Survey Water-Supply Paper 2337. Washington, D.C.: U.S. Government Printing Office.

Lapham, W.W. 1999. Personal communication, USGS. Reston, Virginia, May.

Larkin, R.G., and J.M. Sharp, Jr. 1992. On the relationship between river-basin geomorphology, aquifer hydraulics, and ground-water flow direction in alluvial aquifers. *Geological Society of America Bulletin* 104, no. 12: 1608-1620.

Lee, D.R. 1977. A device for measuring seepage flux in lakes and estuaries. *Limnology and Oceanography* 22, no. 1: 140–147.

Lorah, M.M., L.D. Olsen, B.L. Smith, M.A. Johnson, and W.B. Fleck. 1997. Natural attenuation of chlorinated volatile organic compounds in a freshwater tidal wetland, Aberdeen Proving Ground, Maryland. U.S. Geological Survey Water-Resources Investigations Report 97–4171. Baltimore, Maryland: USGS.

Lowrance, R. 1992. Groundwater nitrate and denitrification in a Coastal Plain riparian forest. *Journal of Environmental Quality* 21: 401–405.

Phillips, B.E., and J.W. Douthitt. 1993. Hydrogeologic assessment of the C-746-K landfill and vicinity. Report KY/ER-24, prepared for the U.S. Department of Energy under subcontract to DOE contract DE-AC05-76OR00001. Kevil, Kentucky: Martin Marietta Energy Systems.

Plummer, L.N., E.C. Prestemon, and D.L. Parkhurst. 1994. An interactive code (NETPATH) for modeling *net* geochemical reactions along a flow *path*, version 2.0. U.S. Geological Survey Water-Resources Investigations Report 94–4169. Reston, Virginia: USGS.

Rantz, S.E. 1982. Measurement and computation of streamflow, volume 1, Measurement of stage and discharge. U.S. Geological Survey Water-Supply Paper 2175. Washington, D.C.: U.S. Government Printing Office.

Rice, K.C., and G.M. Hornberger. 1998. Comparison of hydrochemical tracers to estimate source contributions to peak flow in a small, forested, headwater catchment. *Water Resources Research* 34, no. 7: 1755–1766.

Roy, W.K., M.G. Ryon, R.L. Hinzman, J.G. Smith, J.J. Beauchamp, M.R. Smith, B.A. Carrico, R.P. Hoffmeister, M.K. McCracken, and R.A. Norman. 1996. Thermal discharges from Paducah Gaseous Diffusion Plant outfalls: Impacts on stream temperatures and fauna of Little Bayou and Big Bayou Creeks. Oak Ridge National Laboratory Environmental Sciences Division report ORNL/TM-13183. Oak Ridge, Tennessee: Oak Ridge National Laboratory.

Silliman, S.E., and D.F. Booth. 1993. Analysis of time-series measurements of sediment temperature for identification of gaining vs. losing portions of Juday Creek, Indiana. *Journal of Hydrology* 146: 131–148.

Simsiman, G.V., G. Chesters, and A.W. Andren. 1987. Effect of ash disposal ponds on groundwater quality at a coal-fired plant. *Water Research* 21, no. 4: 417–426.

Sloto, R.A., and M.Y. Crouse. 1996. HYSEP: A computer program for streamflow hydrograph separation and analysis. U.S. Geological Survey Water-Resources Investigations Report 96–4040. Lemoyne, Pennsylvania: USGS.

Squillace, P.J., E.M. Thurman, and E.T. Furlong. 1993. Groundwater as a nonpoint source of atrazine and deethylatrazine in a river during base flow conditions. *Water Resources Research* 29, no. 6: 1719–1729.

Sturchio, N.C., J.L. Clausen, L.J. Heraty, L. Huang, B.D. Holt, and T.A. Abrajano, Jr. 1998. Chlorine isotope investigation of natural attenuation of trichloroethene in an aerobic aquifer. *Environmental Science & Technology* 32, no. 20: 3037–3042.

Thornthwaite, C.W., and J.R. Mather. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. *Publications in Climatology* 10: 183–311.

Triska, F.J., V.C. Kennedy, R.J. Avanzino, G.W. Zellweger, and K.E. Bencala. 1989. Retention and transport of nutrients in a third-order stream in northwestern California: Hyporheic processes. *Ecology* 70, no. 6: 1893–1905.

U.S. Environmental Protection Agency. 1991. A review of methods for assessing nonpoint source contaminated ground-water discharge to surface water. Report EPA/570/9-91-010. Washington, D.C.: U.S. EPA.

U.S. Geological Survey. 1932. LaCenter Quadrangle, Kentucky-Illinois, 1:62,500-scale topographic map. Washington, D.C.: USGS.

U.S. Geological Survey. 1982. Joppa Quadrangle, Kentucky-Illinois, 1:24,000-scale topographic map. Washington, D.C.: USGS.

U.S. Geological Survey. 1987. Paducah, Kentucky-Illinois-Missouri-Indiana, 1:250,000-scale topographic map. Washington, D.C.: USGS.

Vroblesky, D.A., L.C. Rhodes, J.F. Robertson, and J.A. Harrigan. 1996. Locating VOC contamination in a fractured-rock aquifer at the ground-water/surface-water interface using passive vapor collectors. *Ground Water* 34, no. 2: 223–230.

Wallin, E.J. 1998. Ground-water/stream-water interactions in the vicinity of the Paducah Gaseous Diffusion Plant, McCracken County, Kentucky. M.S. thesis, Department of Geological Sciences, University of Kentucky.

Ward, C.H. 1996. Introductory talk: Where are we now? Moving to a risk-based approach. In *Symposium on Natural Attenuation of Chlorinated Organics in Ground Water*, U.S. Environmental Protection Agency report EPA/540/R-96/509, 1–3. Washington, D.C.: U.S. EPA.

White, D.S. 1993. Perspectives on defining and delineating hyporheic zones. *Journal of the North American Benthological Society* 12, no. 1: 61–69.

White, D.S., C.H. Elzinga, and S.P. Hendricks. 1987. Temperature patterns within the hyporheic zone of a northern Michigan river. *Journal of the North American Benthological Society* 6, no. 2: 85–91.

Wildung, R.E., K.M. McFadden, and T.R. Garland. 1979. Technetium sources and behavior in the environment. *Journal of Environmental Quality* 8, no. 2: 156–161.

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. Ground water and surface water, a single resource. U.S. Geological Survey Circular 1139. Denver, Colorado: USGS.

Wroblicky, G.J., M.E. Campana, H.M. Valett, and C.N. Dahm. 1998. Seasonal variation in surface-subsurface water exchange and lateral hyporheic area of two stream-aquifer systems. *Water Resources Research* 34, no. 3: 317–328.

Zellweger, G.W., R.J. Avanzino, and K.E. Bencala. 1989. Comparison of tracer-dilution and current-meter discharge measurements in a small gravel-bed stream, Little Lost Man Creek, California. U.S. Geological Survey Water-Resources Investigations Report 89-4150. Menlo Park, California: USGS.

Biographical Sketches

Alan E. Fryar *is an assistant professor in the Department of Geological Sciences at the University of Kentucky (101 Slone Bldg., Lexington, KY 40506-0053; phone (606) 257-4392; fax (606) 323-1938). He received a B.S. from Duke University, an M.S. from Texas A&M University, and his Ph.D. from the University of Alberta, all in geology. He teaches courses in hydrogeology and environmental geology and conducts research in ground water-surface water interactions, natural attenuation of contaminants, hydrochemical delineation of recharge, and chemical evolution of ground water.*

Eric J. Wallin *is a hydrogeologist with GME Consultants (P.O. Box 250, Crosby, MN 56441), where he conducts environmental site assessments, remedial investigations, and ground water monitoring programs. He received a B.S. from Georgia Southern University and an M.S. from the University of Kentucky, both in geology, and served in the U.S. Army.*

David L. Brown *is an assistant professor in watershed hydrology at the California State University, Chico (Department of Geosciences, Chico, CA 95929). He received an M.S. in hydrology and hydrogeology at the University of Nevada, Reno, and his Ph.D. in soil science from the University of California, Berkeley. He teaches hydrology and environmental science courses and conducts research in ground water-surface water interactions, hillslope hydrology, and nonpoint source pollution.*