Journal of Hydrology (2008) **360**, 252–264

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Groundwater discharge along a channelized Coastal Plain stream

Danita M. LaSage [a], Joshua L. Sexton [b], Abhijit Mukherjee [c], Alan E. Fryar [d,*], Stephen F. Greb [e]

[a] *Kentucky Department of Natural Resources, Division of Mine Permits, 2 Hudson Hollow Complex, Frankfort, KY 40601, USA*
[b] *J.L. Sexton and Son, P.O. Box 1267, North Tazewell, VA 24630, USA*
[c] *Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, University Station, Box X, Austin, TX 78713-8924, USA*
[d] *Department of Earth and Environmental Sciences, University of Kentucky, 101 Slone Building, Lexington, KY 40506-0053, USA*
[e] *Kentucky Geological Survey, University of Kentucky, 228 Mining and Mineral Resources Building, Lexington, KY 40506-0107, USA*

KEYWORDS
Channelization;
Coastal Plain;
Discharge;
Groundwater;
Kentucky

Summary In the Coastal Plain of the southeastern USA, streams have commonly been artificially channelized for flood control and agricultural drainage. However, groundwater discharge along such streams has received relatively little attention. Using a combination of stream- and spring-flow measurements, spring temperature measurements, temperature profiling along the stream-bed, and geologic mapping, we delineated zones of diffuse and focused discharge along Little Bayou Creek, a channelized, first-order perennial stream in western Kentucky. Seasonal variability in groundwater discharge mimics hydraulic-head fluctuations in a nearby monitoring well and spring-discharge fluctuations elsewhere in the region, and is likely to reflect seasonal variability in recharge. Diffuse discharge occurs where the stream is incised into the semi-confined regional gravel aquifer, which is comprised of the Mounds Gravel. Focused discharge occurs upstream where the channel appears to have intersected preferential pathways within the confining unit. Seasonal fluctuations in discharge from individual springs are repressed where piping results in bank collapse. Thereby, focused discharge can contribute to the morphological evolution of the stream channel.

Introduction

In its 2004 report *Groundwater Fluxes across Interfaces*, the Committee on Hydrologic Science of the US National Research Council (NRC) focused on seven questions to

---

[*] Corresponding author. Tel.: +1 859 257 4392; fax: +1 859 323 1938.
E-mail address: alan.fryar@uky.edu (A.E. Fryar).

0022-1694/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2008.06.026

address research gaps. The first of these was, ''What is the relative importance of diffuse versus focused recharge/discharge in various hydrogeologic settings?'' (NRC, 2004, p. 10). Understanding the nature of groundwater discharge to streams is important for several reasons. First, it provides baseflow to perennial streams (Holmes, 2000; NRC, 2004). Second, groundwater discharge can affect benthic habitats by regulating stream temperature, providing nutrients and carbon in the hyporheic zone, or introducing contaminants (including excess nutrients) (Holmes, 2000). Groundwater discharge can also affect the morphological evolution of stream channels via sapping (diffuse, intergranular flow) and piping (channelized flow) (Hagerty, 1991a,b; Pederson, 2001; NRC, 2004). Sapping or piping occurs when positive pore pressures create tension and shear stresses on exposed faces, thus causing undercut strata to slump. Erosion by stream-flow removes colluvium and thereby facilitates further slumping. This process is widespread, yet its significance in mass wasting has not been fully recognized (Hagerty, 1991a,b; Pederson, 2001; Wilson et al., 2007).

The purpose of this paper is to delineate and explain variations in groundwater discharge along a first-order perennial stream that has been modified by channelization. The study site is located on the northern margin of the Mississippi Embayment, a northward extension of the Gulf Coastal Plain. The Gulf and Atlantic Coastal Plains, which are located within the southern and eastern states, occupy a relatively large area of the contiguous 48 United States (14.2%, based on data from McNab and Avers, 1996). Coastal Plain streams have been extensively channelized for flood control and agricultural drainage (Shankman and Smith, 2004), among other purposes, but the relationship between such channelization and groundwater discharge has not been widely studied. This paper builds on prior work by Fryar et al. (2000) by focusing on a portion of the studied stream in greater spatial detail over a longer monitoring period. We examine geologic controls on groundwater discharge and its potential relationship with stream channel evolution. The relationships among groundwater discharge, stream-flow and the behavior of point-source contaminants at the study site are explored in a companion paper (LaSage et al., 2008).

Study area background

Little Bayou Creek is an 11-km long stream in McCracken County, Kentucky, in the lower Ohio River valley (Fig. 1). The creek's ~24-km^2 watershed includes part of the US Department of Energy's Paducah Gaseous Diffusion Plant (PGDP), which enriches uranium for use in nuclear reactors; the Tennessee Valley Authority's Shawnee Plant (a coal-fired generating station); the state-run West Kentucky Wildlife Management Area; and several small farms. Consequently, land cover in the watershed is a patchwork of industrial facilities, forests, and fields, although the stream banks are generally forested. The terrain is gently rolling, with land surface elevations ranging from 107 to 116 m above mean sea level (amsl) around PGDP to 88 m amsl (pool elevation) along the Ohio River.

Little Bayou Creek was originally a tributary of the Ohio River, but between 1953 and 1971, the creek was rerouted around ash ponds at the Shawnee Plant. Thereby, Little Bayou Creek was channelized along its lower 2.5 km and connected to Bayou Creek, a second-order perennial stream, 340 m southwest of the river. Little Bayou Creek itself has no perennial tributaries. Its flow is partly sustained by discharges from PGDP, which obtains at least 498 L/s of water from the river via two pipelines (BD Begley, Kentucky Division of Waste Management, personal communication, 2007). Cooling and scrubbing tower water is discharged from PGDP outfall K010 at an average rate of ~25 L/s (US Department of Energy, 2000). Additional releases come from sanitary sewers, storm sewers and plant runoff. Since October 1, 1990, the US Geological Survey (USGS) has maintained a gauging station on Little Bayou Creek ~3.9 km above its confluence with Bayou Creek (Fig. 1). For the period of record (through September 30, 2007), daily stream-flow rates ranged from values <11 L/s (primarily in August, September, and October) to a maximum of 14,300 L/s on March 1, 1997 (USGS, 2008).

The climate of the study area is humid-continental. For the period 1971–2000, average daily temperatures ranged from 0.5 °C in January to 25.7 °C in July at the Paducah station of the National Weather Service (NWS), 6 km southeast of PGDP (National Climatic Data Center [NCDC], 2004). Annual precipitation averaged 125 cm. Drier periods tended to occur during late summer–early autumn (with average minimum precipitation of 7.6 cm in August) and mid-winter, while precipitation was highest in April (average 12.6 cm) (NCDC, 2004). Using the method of Thornthwaite and Mather (1957) for 1969–1989 climatic data, CH2M Hill (1992) concluded that precipitation exceeded actual evapotranspiration for October through May. The tendency for precipitation and stream-flow to be greatest in late winter and early spring is evident elsewhere in the Mississippi Embayment (Shankman and Smith, 2004).

The Little Bayou Creek watershed is underlain at depths of ~91 to 122 m below land surface (bls) by Mississippian-era carbonate bedrock, which is locally mantled by a chert regolith (the Tuscaloosa Formation) (Clausen et al., 1992). This is overlain by the Upper Cretaceous McNairy Formation (sands, silts, and clays of fluvial-deltaic origin, subcropping at depths of 21–30 m bls), the Paleocene Porters Creek Clay (in the southern part of the watershed), the informally-named continental deposits of Miocene–Pleistocene age (fluvial cobbles and gravels grading upward into finer sediments), Pleistocene loess (windblown silt that generally mantles upland areas), and Holocene alluvium (Olive, 1980; Clausen et al., 1992). Following the more formal stratigraphic nomenclature of Nelson et al. (1999, 2002), which is used across the Ohio River in Illinois, the lower continental deposits are referred to here as the Mounds Gravel and the upper continental deposits as the Metropolis Formation. The Mounds Gravel in the vicinity of PGDP has been termed the regional gravel aquifer (RGA), which is semi-confined by the Metropolis Formation and loess. Groundwater moves predominantly vertically through the semi-confining unit and flows north–northeast in the RGA toward the Ohio River, except when the river is at flood stage (Clausen et al., 1992; Fryar et al., 2000) (Fig. 1).

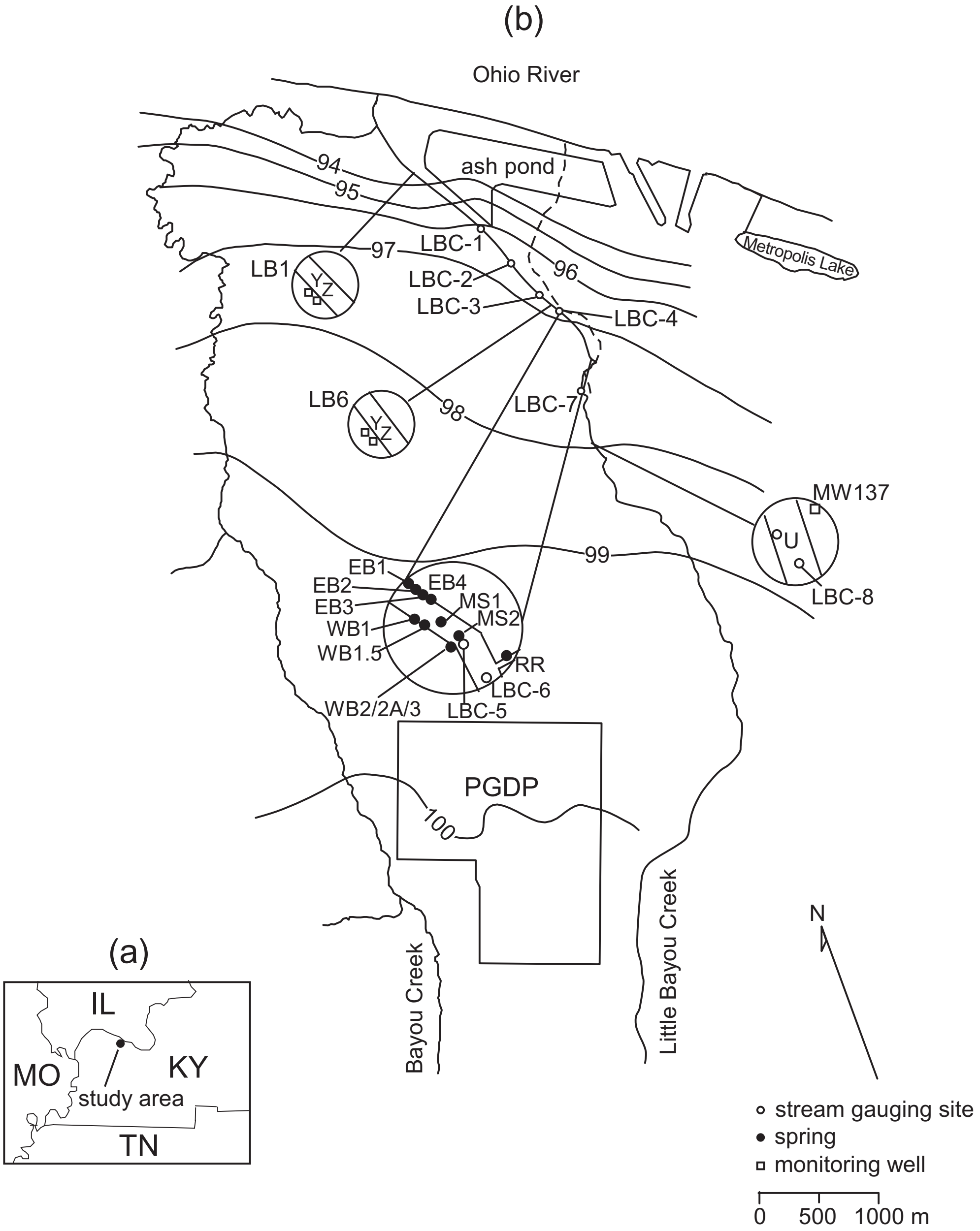

Figure 1 (a) Inset showing regional location of study area (modified from Fryar et al., 2007). IL = Illinois; MO = Missouri; KY = Kentucky; TN = Tennessee. (b) Site map showing monitoring locations for this study and hydraulic-heads in the regional gravel aquifer on September 24–25, 1997 (contour interval 1 m; modified from Fryar et al., 2000). Insets (not to scale) along Little Bayou Creek show relative positions of the stream channel, springs, selected gauging locations (including the USGS gauging station [U]), monitoring wells at sites LB1 and LB6 of Fryar et al. (2000), and PGDP monitoring well MW137. Dashed line marks perennial channel of Little Bayou Creek as shown by USGS (1932).

Methods

Groundwater discharge was assessed using several techniques. At the reach scale (stream distances of tens to hundreds of meters), between the USGS gauging station and the present Shawnee Plant ash pond, we measured stream-flow by wading along transects across the channel with a digital current meter and top-setting rods (Marsh-McBirney, Frederick, MD, USA). Flow rates were calculated according to the mid-section method of Rantz (1982) and net discharge (attributable to seepage and/or tributary inflow) between gauging sites was determined. We measured stream and air temperatures at gauging sites using a YSI T-L-C meter (YSI, Yellow Springs, OH, USA) or an Orion electrical conductivity meter (Thermo Electron, Waltham, MA, USA). Where we observed springs on the banks or in the bed, we also measured temperatures using one of the meters or a YSI stainless-steel temperature probe connected to a digital thermometer. Relatively constant water temperatures can indicate groundwater discharge, since stream temperatures are typically cold in winter and warm in summer (Fryar et al., 2000; Conant, 2004). Groundwater discharge rates were estimated by using a stopwatch and transferring a collected volume to a graduated cylinder. Groundwater was collected from bank springs using a bucket and from channel springs using a seepage meter made from 4-in. nominal (10.2-cm actual inside diameter) PVC pipe (Fryar et al., 2000). From June 1999 through May 2001, at 3- to 4-month intervals, stream-flow was gauged at as many as eight sites (LBC-8 through -1), and groundwater temperatures and discharge rates were measured for springs (Fig. 1). In January, June, August, and October 2002, we again gauged stream-flow at sites LBC-4 through -1. Using the hydrograph separation program iSep (Muthukrishnan et al., 2003) with daily stream-flow data from the USGS gauging station, we confirmed that Little Bayou Creek was at baseflow (i.e., runoff was negligible) at times when we took measurements.

During August 9–12, 2002, we used a temperature probe and digital thermometer to measure stream-bed temperatures along a channelized reach extending 286 m upstream from site LBC-4. Following White et al. (1987) and Conant (2001, 2004), we measured temperatures on transects across the creek. In general, each transect was separated by 10 feet (ft) (3.0 m) along the stream, and probing occurred at 3-ft (0.9-m) intervals along each transect, thus resulting in a grid of 683 points. The grid was deformed because there were two bends along the reach. Like Becker et al. (2004), we measured the temperature at the maximum depth to which the probe could be pushed by hand, beneath the veneer of loose sediment in the bed. This semi-quantitative approach enabled us to pinpoint anomalously cold and deep areas relatively rapidly. In addition, we probed visible springs that were not on the grid. Temperatures and depths were contoured using the program Surfer® version 8 (Golden Software, Golden, CO, USA). Along the same reach where probing occurred, we measured orientations of presumed fracture traces in bed and bank sediments using a Brunton® compass. These linear features were ~1–2 cm wide, several meters long, and marked by apparent iron oxide or manganese oxide cementation. We also collected bed sediment samples at three locations for particle-size measurements via sieve and hydrometer analyses.

In part to complement hydrologic investigations and observations of stream morphology, a stratigraphic framework model was developed for an area including the Little Bayou and Bayou Creek watersheds. We obtained 400 lithologic logs for monitoring wells and geotechnical borings (at PGDP and the Shawnee Plant) and for borings used in geologic maps of the Heath and Joppa quadrangles (Olive, 1966; Finch, 1967). Exposures of the Mounds Gravel, Metropolis Formation, loess, and alluvium were mapped along streams, drainage ditches, and borrow pits. Bank sediment samples were also collected at several sites along Little Bayou Creek for sieve analyses. Mapped exposures were spatially referenced against 1:24,000 topographic maps using a hand-held global positioning system with ~4.6-m horizontal resolution. Elevations of selected bedding contacts were measured using a total station electronic surveying device and a stadia rod equipped with a prism. These elevations were referenced to the closest monitoring wells with known top-of-casing elevations. Grid models for structural elevation and isopach maps were created by kriging lithologic data in Surfer® version 7. Sexton (2006) provides additional details on development of the overall framework model.

Results and discussion

Stream-flow and evidence of groundwater discharge

During each monitoring period, stream-flow increased between the farthest upstream and downstream gauging sites, with a maximum rate of 89 L/s at LBC-1 in June 2002. Likewise, Evaldi and McClain (1989), who gauged Little Bayou Creek on August 15–16, 1989, reported that flow tended to increase with distance downstream beginning ~4.1 km above the confluence with Bayou Creek. Stream-flow at gauging locations along Little Bayou Creek tended to fluctuate seasonally (Fig. 2), with maximum values in May or June and minimum values in autumn or winter. These observations agree with those of Fryar et al. (2000), who gauged stream-flow at two locations along Little Bayou Creek (our site LBC-3 and their site AP, ~30 m downstream of LBC-1) monthly to bimonthly between July 1996 and October 1997.

Visual observations and stream-flow increases between gauging sites were complementary indicators of groundwater discharge. As noted above, following Fryar et al. (2000), we observed multiple springs along the upper ~400 m of the artificial channel (between our sites LBC-6 and -4), as well as seeps farther downstream along the channel adjoining the closed (original) and current ash ponds. Except during January 2001, when ice cover may have interfered with gauging, stream-flow always increased between our sites LBC-5 and -4 (Table 1), where most of the springs were observed. The maximum gain (net discharge) measured along this reach was 18.7 L/s in May 2000. Groundwater discharge is consistent with an upward hydraulic gradient between paired monitoring wells (LB6Y and LB6Z) located on the west bank of the creek ~10 m downstream of LBC-4 (Fryar et al., 2000, and unpublished data). The well screens are 0.76 m long and are vertically offset by 1.4 m; the top of the shallower screen (in LB6Z) is ~3.0 m below the bed of the creek. Furthermore, groundwater discharge is consistent with detections of the contaminants trichloroethene and technetium-99, which occur in springs and wells, downstream of LBC-6 (LaSage et al., 2008). Except during January 2000 and August 2000 (when gauging was not performed downstream of LBC-3 or upstream of LBC-6), gauged stream-flow also always increased between sites LBC-3 and -1, along the closed ash pond. Fryar et al. (2000) measured an increase in stream-flow along essentially the same reach on seven of eight occasions. However, two ephemeral tributaries, which were not gauged in either study, may have contributed to the increase.

Because errors in gauged stream-flow values at each of two stations could result in large uncertainties in net discharge calculations, we examined the effects of varying reported velocities and depths at each measuring point on net discharge. Following Mukherjee et al. (2005), velocity was varied by ±0.01 ft/s (±0.003 m/s, the precision of the current meter) and depth by ±0.05 ft (±0.015 m, half the increment of the top-setting rod). In the field, depth was visually

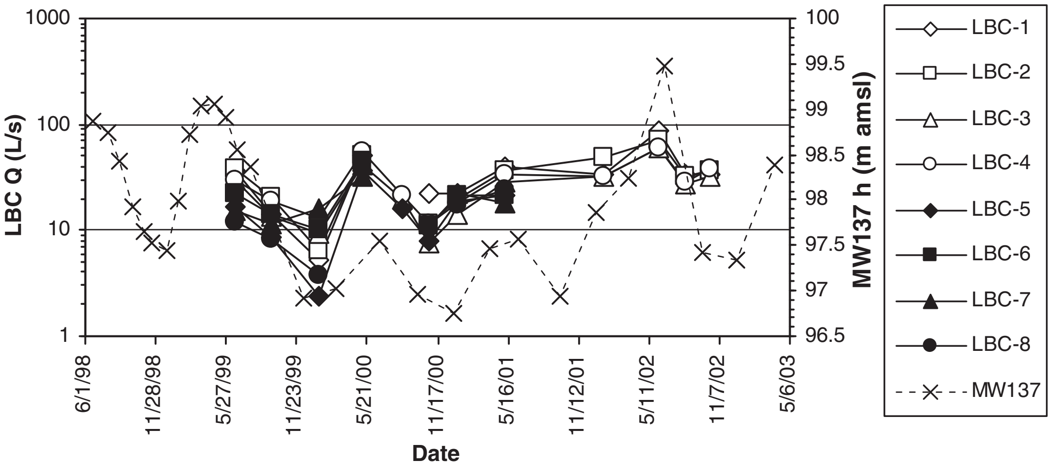

Figure 2 Stream-flow at gauging locations along Little Bayou Creek, June 1999—October 2002, and hydraulic-heads in well MW137, June 1998—March 2003 (Bechtel Jacobs, unpublished data).

Table 1 Discharge of springs to Little Bayou Creek, stream-flow rates at gauging locations LBC-5 and -4, and gain between those locations (in L/s), as well as ratio of total discharge (minus RR) to gain for June 1999 through May 2000. Blank indicates no or insufficient data

Date measured								
Spring	6/19/99	9/17/99	1/22/00	5/8/00	8/12/00	10/27/00	1/5/01	5/9/01
RR	0.17	0.084	0.035	0.026			0.103	
WB3				2.8				
WB2A		0.040						
WB2	1.68	0.812	0.079	0.031				
MS2		0.003		0.005				
MS1				0.006				
WB1.5								
WB1	0.24	0.320		0.105				
EB4	0.32	0.208	0.069	0.14	0.10	0.049	0.060	0.11
EB3	0.25			0.071				
EB2	0.39	0.160	0.090	0.486				
EB1	0.85	0.627	0.33	**1.04**	0.511			
Total	3.9	2.3	0.60	4.7				
Total − RR	3.7	2.2	0.57	4.6				
Stream site								
LBC-5	16.9	8.48	2.37	36.9	16.1	7.84	19.0	21.6
LBC-4	29.4	18.6	12.9	55.6	21.3	11.4	18.1	33.2
Gain	12.5	10.1	10.6	18.7	5.20	3.56	−0.874	11.6
Discharge/gain	0.30	0.21	0.054	0.25				

estimated to within 0.01 ft (0.003 m). In estimating error, negative (physically nonsensical) values were taken as 0 (Mukherjee et al., 2005). Estimated errors were within ±30% for 55 of 73 stream-flow measurements. Errors >30% occurred at times of low stream-flow (September 1999, January 2000, October 2000, and January 2001). The minimum net discharge between points LBC-5 and -4 and between LBC-3 and -1 for each measurement period was then estimated by subtracting the maximum possible stream-flow at the upstream point from the minimum possible at the downstream point. This resulted in negative (i.e., apparent losing) values between LBC-5 and -4 at four of eight times (May 2000, August 2000, October 2000, and January 2001) and between LBC-3 and -1 at nine of 11 times (all but October 2000 and June 2002). Conversely, by subtracting the minimum possible stream-flow at the upstream point from the maximum possible at the downstream point, we obtained positive values of maximum net discharge for all times along both reaches. We thus find that inferences of gaining conditions are reasonable between LBC-5 and -4 but may be tenuous between LBC-3 and -1.

Groundwater discharge was measured at various times for 12 springs. Stream stage or the shape of an orifice sometimes precluded measurements, and the channel springs were not always visible. In general, discharge was greatest at springs WB3, WB2, and EB1 (Table 1). During the period from June

1999 through May 2000, when most of the discharge measurements were taken, the total measured discharges (excluding RR, which was upstream of LBC-5) accounted for 5.4% to 30% of the gauged increase in stream-flow between LBC-5 and -4 (Table 1). For several springs, the measured discharge decreased from June 1999 through January 2000, then rebounded in May 2000. This apparent seasonality is broadly consistent with seasonal fluctuations in stream-flow along Little Bayou Creek and in hydraulic-head for PGDP monitoring well MW137 (Fig. 2), completed in the RGA adjacent to site LBC-8, as observed previously by Clausen et al. (1995). Fryar et al. (2007) noted similar fluctuations in discharge for a Coastal Plain spring located ∼70 km east-southeast of PGDP. In general, for shallow groundwater flow systems in humid settings, ''recharge and discharge fluctuate in a relatively predictable way in response to seasonal changes in precipitation and evapotranspiration'' (NRC, 2004, p. 16). However, discharge for springs WB2 and RR did not rebound between January and May 2000 (Table 1). By May, flow at WB2 had almost ceased, and a new spring, WB3, had emerged along the bank ∼5 m upstream (Fig. 1 and Plate 1a).

Temperatures of springs between LBC-6 and -4 tended to vary over a limited range, consistent with groundwater discharge. For the eight springs with at least four seasons' worth of data, the average temperature varied from 13.9 °C at EB4 to 14.6 °C at WB3. The temperature range (i.e., the difference between maximum and minimum temperatures) for these eight points varied from 1.4 °C at WB3 to 8.8 °C at RR. The range was ⩽4.3 °C for six of the eight points; the greater ranges for RR and MS2 (6.5 °C) suggest discharge from shallower depths and/or mixing with stream-water. Seasonal temperature ranges reported by Fryar et al. (2000) for monitoring wells along Little Bayou Creek were comparable (from 1.8 °C at LB1Y to 8.8 °C at LB6Z). As expected, our stream temperature range was much broader, varying from 22.3 to 27.1 °C at sites LBC-6

Plate 1 (a) Spring WB3 in Metropolis Formation, August 2002. Width of orifice (marked by folding rule) is 0.9 m. (b) Bank collapse in Metropolis formation adjoining spring WB2, May 2000. Excluding handle, cooler on bank at lower left has dimensions (width × height) of 0.2 × 0.2 m.

through -1 (the gauging locations with at least four seasons' worth of temperature data).

Temperature probing in August 2002 generally corroborated previous temperature measurements for individual springs. Relatively cold zones tended to be localized where probe penetration depths were greatest, although the converse was not always true, particularly for the farthest upstream segment of the probed reach (Fig. 3). Notwithstanding considerable scatter ($r^2 = 0.36$), a linear regression for all data points shows a decrease in temperature with increasing depth. We chose 16.5 °C as an upper limit for delineating cold zones, since that value was within one standard deviation of the average temperatures for the eight springs mentioned above. Although we did not monitor stream temperatures during probing, hourly air temperatures measured simultaneously at the Paducah NWS station ranged from 16 to 34 °C (University of Kentucky Agricultural Weather Center, 2007). Zones colder than 16.5 °C occupied ~7.5% (138 m^2) of the probed reach by area, including ~8.2% of the downstream segment, ~9.8% of the middle segment, and none of the upstream segment. Taken together with direct measurements of spring-flow and net discharge between LBC-5 and -4, these percentages indicate that a disproportionate amount of groundwater discharge is focused.

Channel morphology and sedimentary geology

Comparisons of the most recent topographic maps of the study area (USGS, 1978, 1982) with the last topographic map prior to channelization (USGS, 1932) shows that the unchannelized main stem of Little Bayou Creek migrated <100 m laterally in the interim. The creek lacks a well-developed floodplain and large woody debris has been stranded above the stream at its baseflow stage. At the head of the channelized reach, where the stream gradient changes, a 1.4-m-deep knickpoint pool has formed. These morphological characteristics are associated with moderately unstable streams that undergo deepening and widening as they re-establish equilibrium in response to changes in stream-flow (National Water and Climate Center, 1998). Based on visual inspection, Little Bayou Creek below LBC-8 is an F5 stream type (Rosgen and Silvey, 1998), characterized by entrenchment, meanders, a low gradient, riffle/pool morphology, and a high width/depth ratio. The gradient downstream of LBC-4 was ~0.0015 (Mukherjee et al., 2005). Stream width at sites LBC-5 through -1 ranged from 5.4 to 8 m for 51 of 54 gauging runs, while stream depth was ⩽0.62 m. Along the probed reach, stream depth was ⩽0.98 m, while the maximum sediment depth penetrated below the stream-bed was 1.21 m.

From LBC-8 to -1, Little Bayou Creek is incised ~2 to 5 m below the surrounding landscape. Stream-bank exposures of white to tan silty sand and overlying massive silt between LBC-8 and -3 were identified as the upper Metropolis Formation and loess, respectively. Particle-size analyses of a bank sample from LBC-7 and stream-bed samples collected between LBC-5 and -4 indicated fine to silty sand. Where not mantled by sand, the bed consists of hard, mottled, light gray clay. Oxide-cemented zones were noted occasionally in the banks and, between LBC-6 and -4, in the bed along fractures in the clay. Eight linear features in the bed and banks (including three ridges) were oriented between N3°W and N41°E, while five linear features (generally joints) were oriented between N55°W and N80°W. Beginning ~30 m downstream of LBC-3 and continuing to within ~300 m of the confluence with Bayou Creek, the Mounds Gravel was

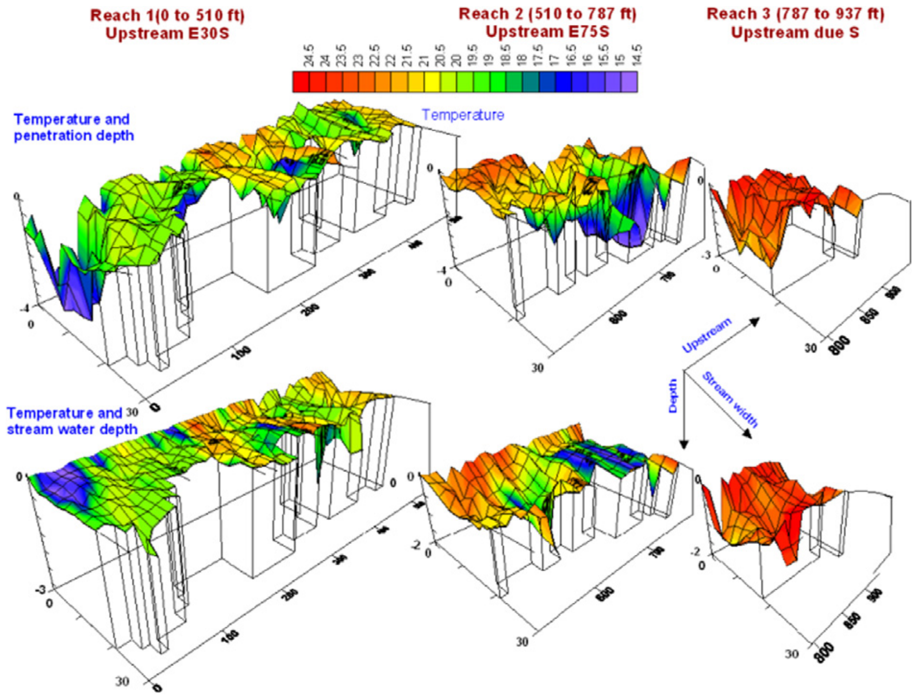

Figure 3 Temperature (in °C) draped over penetration depth (top) and stream-water depth (bottom) along probed stream channel upstream of gauging location LBC-4. Length, width, and depth are shown in ft (1.00 ft = 0.305 m). Note that horizontal and vertical scales vary between subreaches, which are demarcated by bends in the channel.

identified on both banks of Little Bayou Creek. Gravel- to cobble-sized chert clasts with a characteristic patina (Nelson et al., 1999, 2002) occur within a poorly-sorted sandy matrix. This unit is reddish-brown (iron-stained) and weakly to well cemented. Cementation has resulted in irregular bed topography at LBC-2 and a waterfall ~0.5 m high, which may represent a secondary knickpoint, ~25 m downstream. In stream banks, the Mounds Gravel is overlain by the Metropolis Formation (consisting of orange and gray silty sand and weathered brown chert gravel [Nelson et al., 1999, 2002]) or loess. Near the confluence of the creeks, the Mounds Gravel has been reworked by modern fluvial processes, as indicated by a lack of cementation.

Structural elevation and isopach maps indicate variable thicknesses of the Mounds Gravel and Metropolis Formation (Figs. 4–6), which appear to reflect paleotopographic and possibly structural controls. The uppermost elevation of the Mounds Gravel ranges from 412 ft (126 m) amsl southwest of PGDP to 265 ft (81 m) amsl in the Ohio River floodplain (Fig. 4). Thickness of the Mounds Gravel varies from 80 to 2 ft (24 to 0.6 m), with an elongate thickness trend oriented northwest–southeast (NW–SE) across the study area and subordinate trends oriented northeast–southwest (NE–SW), incised into the underlying McNairy Formation (Fig. 5). The larger NW–SE trend parallels a feature delineated by Jacobs EM Team (1997) as the ''terrace slope'', which appears to be a buried erosional scarp coinciding with the valley wall of the ancestral Tennessee River.

The Metropolis Formation thickens on the north slope of the paleoterrace defined by Jacobs EM Team, similar to the underlying Mounds Gravel (Fig. 6). The Metropolis also exhibits several narrow, elongate thickness trends to the northeast (Fig. 6), at least one of which overlaps with an elongate thickness trend in the Mounds Gravel (Fig. 5). Numerous upward-fining sequences have been noted in the Metropolis Formation, but spatially variable deposition means that tracing intraformational units laterally is difficult.

Evidence of possible structural controls on stratigraphy and, thereby, groundwater flow includes orientations of the NE–SW thickness trends in the Mounds Gravel and Metropolis Formation. These orientations are broadly parallel to faults mapped across the Ohio River in southern Illinois (Nelson et al., 1999, 2002; Nelson and Masters, 2006). Nelson et al. (1999) delineated narrow, steep-sided grabens as part of the fluorspar area fault complex (FAFC), with vertical displacement of >100 m for upper Tertiary strata, 10–30 m for Illinoisan and older Pleistocene strata, and ⩽1 m

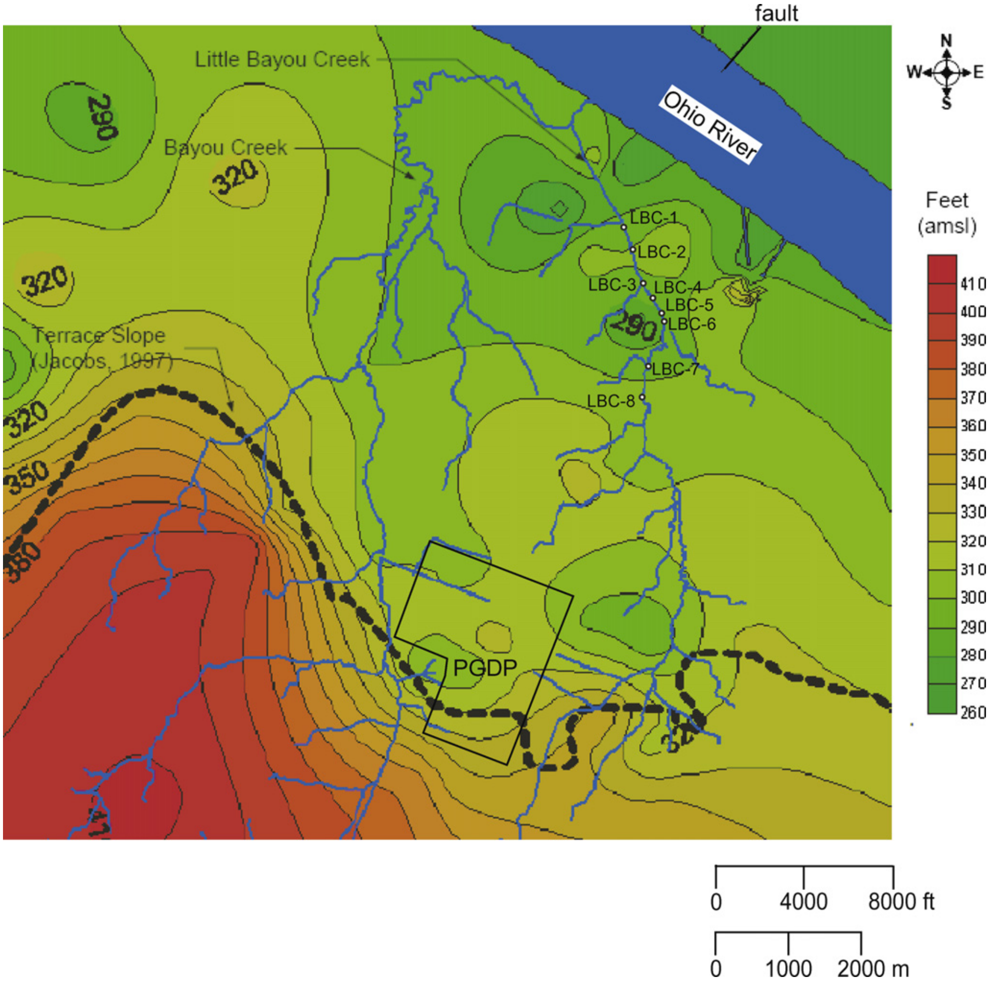

Figure 4 Structural elevation map of the Mounds Gravel upper surface. Each contour interval represents 10 ft (10 ft = 3.05 m). Thick dashed line represents terrace slope inferred by Jacobs EM Team (1997).

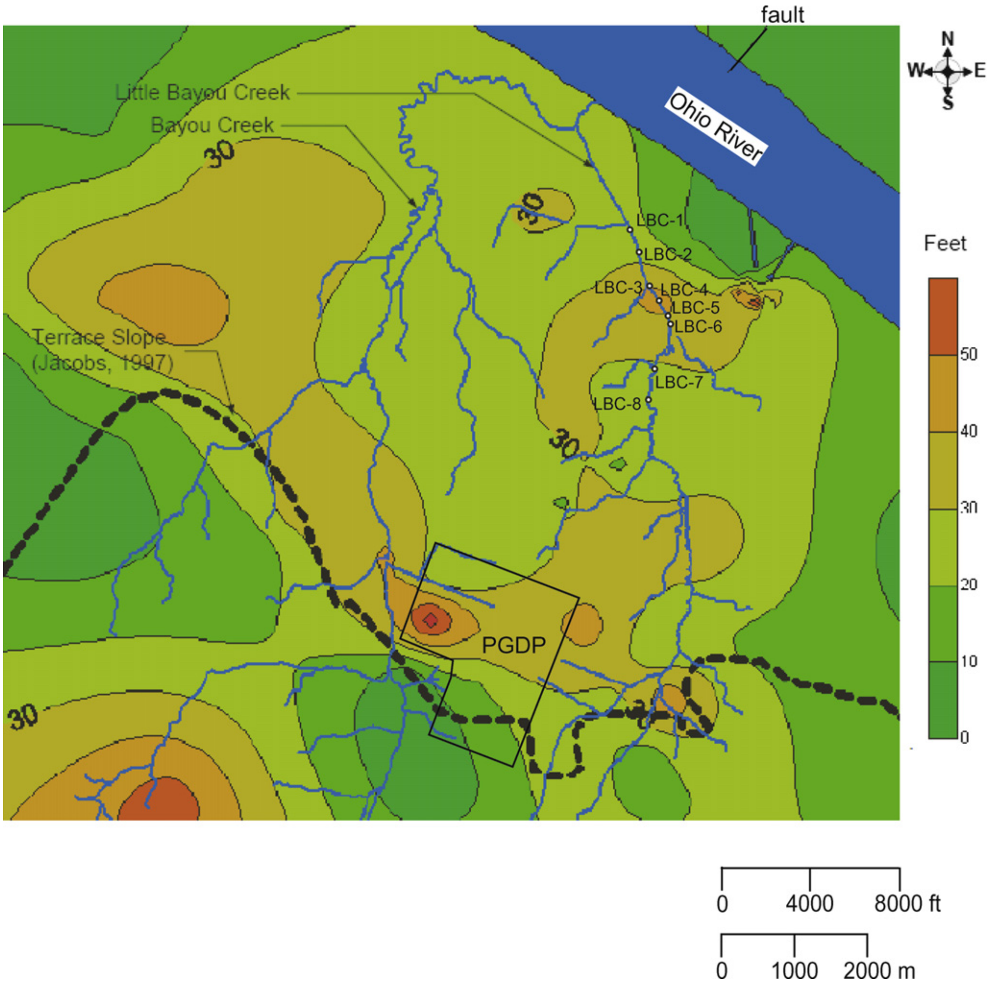

Figure 5 Isopach map of the Mounds Gravel. Each contour interval represents 10 ft thickness (10 ft = 3.05 m). Thick dashed line represents terrace slope inferred by Jacobs EM Team (1997).

for Wisconsinan deposits. Reported strikes of tectonic features, including joints and clay veins in the bed of Barnes Creek, range primarily from N10°E to N50°E, with subordinate orientations of N—S and N10°W to N55°W (Nelson et al., 1999). Nine of 13 linear features mapped in the bed and banks of Little Bayou Creek (~14 km SW of the Barnes Creek site) have strikes within these ranges. However, we did not observe vertical displacement of the Metropolis Formation along Little Bayou Creek. Geophysical surveys in our study area, including shear-wave seismic reflection and electrical resistivity imaging, have identified fault traces co-linear with the FAFC, with offsets decreasing from 15—25 m at the top of bedrock to 2—5 m at 20—25 m below land surface (Langston et al., 1998; Blits et al., 2008).

Groundwater discharge and implications for present-day channel evolution

Diffuse groundwater discharge is evidenced by observations of seeps and increased stream-flow where the Mounds Gravel is exposed along Little Bayou Creek. Some of this discharge originates from the closed and current ash ponds, as indicated by elevated electrical conductivity values for some east-bank seeps (Sexton, 2006) and concentrations of boron (characteristic of ash leachate) in stream-water at sites LB1 and LBC-1 (Fryar et al., 2000; LaSage, 2004). In contrast to wells LB6Y and LB6Z, paired monitoring wells on the west bank of the creek at LB1 have not generally shown an upward hydraulic gradient (Fryar et al., 2000 and unpublished data). However, seeps along the west bank of Little Bayou Creek and in exposures of the Mounds Gravel along Bayou Creek upstream of the confluence with Little Bayou Creek (Sexton, 2006) indicate that diffuse groundwater discharge occurs from the RGA and not just from the ash ponds downstream of LBC-3.

Focused groundwater discharge between LBC-6 and -4 appears to be stratigraphically and perhaps structurally controlled. An isopach map indicates that the NE—SW trend of the Mounds Gravel, which is as much as 40 ft (12 m) thick, extends beneath this reach (Fig. 5). The Metropolis Formation is mapped as ~20 ft (6 m) thick (Fig. 6), but the head of the channelized reach is incised 2—3 m below the Ohio River floodplain (i.e., the Mounds Gravel may lie 3—4 m below the bed of the creek). Extrapolating from lithologic logs for nearby PGDP monitoring wells MW146 and MW152, Science Applications International Corporation (2001) concluded that the RGA lies

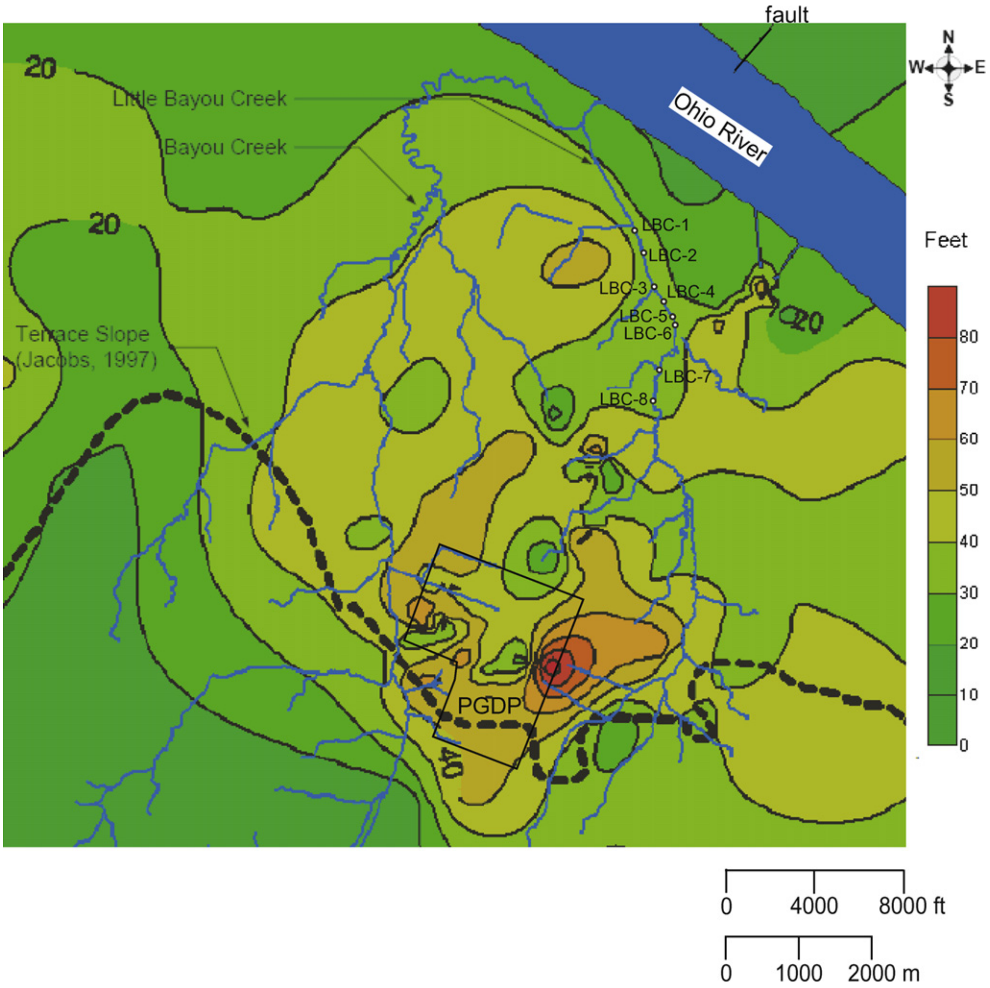

Figure 6 Isopach map of the Metropolis Formation. Each contour interval represents 10 ft thickness (10 ft = 3.05 m). Thick dashed line represents terrace slope inferred by Jacobs EM Team (1997).

<1 m below Little Bayou Creek, separated from the channel bed by a thin (0.6—0.9 m) layer of sandy clay to silty sand. The zone of relatively thick Mounds Gravel could indicate the existence of a fault-bounded graben, as observed by Nelson et al. (1999) in southern Illinois. However, the observation that the adjoining thick zone of the Metropolis Formation overlaps, rather than coincides with, the thick Mounds Gravel, and preliminary indications that the McNairy Formation subcrops shallowly beneath the Shawnee Plant (Steve Hampson, Kentucky Research Consortium for Energy and Environment, personal communication, 2008), make the inference of a gravel-filled graben speculative. Nonetheless, temperature probing and observations of clay in the stream-bed indicate that the confining unit (i.e., the Metropolis Formation), even if thin, is still largely intact along the reach where springs are observed. Groundwater discharge may be localized along meter-scale heterogeneities (e.g., sand stringers) or fractures in the clay. The occurrence of oxide-cemented fractures suggests that groundwater flowed along those features at one time, although not necessarily at present (Hagerty, 1991b). Similarly, sites with probe penetration depths >0.5 m but without temperature anomalies, such as upstream of LBC-5 (Fig. 3), could represent abandoned foci of groundwater discharge.

The thickness of the Mounds Gravel, the occurrence of springs on both banks, and the detection of groundwater contaminants downgradient (north—northeast) of the creek (Clausen et al., 1992) are consistent with interactions between an intermediate to thick aquifer and the riparian zone in a humid temperate landscape (Hill, 2000, Table 1). In this conceptual model, the water table exhibits moderate to small fluctuations, and there is continuous but variable baseflow via spring-discharge, as well as deep bypass flow beneath the stream.

Groundwater discharge between LBC-5 and -4 is similar in some ways to that along two other humid temperate streams where spatially intensive temperature measurements were made. For a reach of the Pine River in southern Ontario (Canada), Conant (2004) found that ~4.6—7.0% of the streambed contributed 20.6—23.5% of total groundwater discharge. Focused discharge was attributed to zones where conduits (e.g., fractures, sand stringers, or root holes) or high hydraulic-conductivity deposits connect the aquifer to the stream. Along the artificial Schachtgraben channel in eastern Germany, Schmidt et al. (2006) found that 20% of the reach length accounted for 50% of total groundwater discharge. Morphologically, the probed reach of Little Bayou Creek is generally intermediate between the studied reaches of the Schachtgraben and the Pine River. At all three sites, the streams are incised into Quaternary alluvial sediments. The Schachtgraben had a gradient of 0.0008, a channel width of 2—3 m, and mean annual stream-flow of ~20 L/s (Schmidt et al., 2006). The studied reach of the Pine River is a type E5 stream (less incised than type F5 [Rosgen and Silvey, 1998]), with a gradient of 0.0007, a channel width of ~11 to 14 m, an average depth of 0.5 m (maximum 1.1 m in the summer), and summer stream-flow of 120—170 L/s (Conant, 2001, 2004).

Comparing locations of the perennial channel of Little Bayou Creek circa 1932 (USGS, 1932) and the current channelized reach (Fig. 1) indicates that baseflow (i.e., groundwater discharge) upstream of the Mounds Gravel exposures is not solely a consequence of channelization. However, channelization and other activities may have enhanced groundwater discharge, in contrast to the comment of Pringle and Triska (2000, p. 182) that ''channel straightening...drastically reduce(s) contact zones between surface and subsurface waters''. Although data on stream-flow in Little Bayou Creek prior to 1989 are unavailable, outfall discharges and runoff from impervious surfaces at PGDP should have increased stream-flow, which, along with channelization, would promote incision (Schueler, 1994; Shankman and Smith, 2004). In turn, downcutting into the Metropolis Formation is likely to promote further groundwater discharge. Along Little Bayou Creek, observations of spring-flow, meter-scale temperature anomalies (Fig. 3), and cavities approaching 1 m in diameter (Plate 1a) constitute multiple lines of evidence for piping (Hagerty, 1991b). Clays in the stream-bed and banks tend to resist erosion, but may be weakened along joints associated with release of confining pressure (Hagerty, 1991a; Simon and Thomas, 2002). Consistent with Hagerty (1991a), some sites of piping have migrated following bank collapse, as shown for springs WB3 and WB2 (Plate 1a and b). Groundwater discharge thus appears to act as a positive feedback to stream erosion.

Recent studies elsewhere in the Mississippi Embayment have variously noted the roles of channelization in promoting bank failure (Simon and Thomas, 2002; Shankman and Smith, 2004), groundwater discharge in promoting bank failure (Simon et al., 2000; Fox et al., 2007; Wilson et al., 2007), and breaches of confining units in promoting groundwater discharge (Urbano et al., 2006; Neilans and Urbano, 2006). Along incised (meandering or channelized) streams in non-cohesive sediments, banks become oversteepened and fail, thus causing significant mass wasting. These failures have been attributed at least in part to seepage from perched permeable strata in the banks and exfiltration during stormflow recessions (Simon et al., 2000; Fox et al., 2007; Wilson et al., 2007). However, groundwater can discharge at the foot of a slope in the absence of perched conditions or bank storage (Freeze and Cherry, 1979, pp. 470—471). Local breaches of confining units along channelized streams result in focused groundwater discharge, which may control the position of the thalweg (Urbano et al., 2006; Neilans and Urbano, 2006). None of these previous studies appears to have identified the potential linkages among channelization, breaches of confining units, enhanced groundwater discharge, and bank erosion. Little Bayou Creek appears to be analogous to the channelized Yalobusha River basin in northern Mississippi, where resistant bed materials such as clays and ironstone outcrops have ''restricted advancement of knickpoints and knickzones in certain reaches and have caused a shift in the focus of channel adjustment to bank failures'' (Simon and Thomas, 2002, p. 716).

Conclusions

We have documented focused and diffuse groundwater discharge along different reaches of Little Bayou Creek, a first-order stream in western Kentucky modified by channelization. Springs tend to coincide with thermal anomalies in the stream banks and bed, and springs contribute a disproportionate amount of baseflow along the reach where they emerge. At least some of these focused discharge points appear to be located along meter-scale heterogeneities or fractures in the fine-grained Metropolis Formation, which semi-confines the Mounds Gravel. Based on their alignment with faults observed across the Ohio River in southern Illinois, the fractures and trends in gravel thickness may be of tectonic origin. Diffuse groundwater discharge occurs where the Mounds Gravel is exposed farther downstream along Little Bayou Creek. Temporal variability in groundwater discharge and baseflow appears to reflect seasonal variability in recharge, although infiltration from lagoons and leaking pipes at PGDP may be a non-seasonal component of recharge (Jacobs EM Team, 1999).

The occurrence of groundwater discharge along Little Bayou Creek has more than local relevance in part because of its geomorphic implications. At other sites in the Coastal Plain, particularly where streams breach confining units, groundwater discharge may be an unrecognized contributor to channel instability. In its Finding 1, NRC (2004, p. 56) stated, ''A key science question is how landscape heterogeneity controls spatial and temporal variability of recharge and discharge.'' The results of this study suggest that spatial variability in groundwater discharge can also affect landscape heterogeneity via channel evolution in unlithified sediments.

Acknowledgements

The research described herein was funded by the US Department of Energy (DOE) via the Agreement-in-Principle with the Commonwealth of Kentucky (through a Contract from the Kentucky Division of Waste Management to the University of Kentucky, UK) and via the Kentucky Research Consortium for Energy and Environment. However, the contents of this paper do not necessarily reflect views and policies of the US Government or the Commonwealth of Kentucky. Supplemental funding was provided by Grants from the Geological Society of America Southeastern Section, the UK Graduate School, and the UK Department of Earth and Environmental Sciences Brown-McFarlan Fund to LaSage and Mukherjee. We thank DOE and the Tennessee Valley Authority for providing data and access to their properties and the Kentucky Department of Fish and Wildlife Resources for providing access. Brian Begley, Gaye Brewer, Lee Gatterdam, Andrea Hougham, Michael LaSage, Janet Miller, Karen Thompson, David Vance, and James Ward helped with field work. We particularly appreciate the assistance of

John Nelson (Illinois State Geological Survey) and Steve Hampson (Kentucky Research Consortium for Energy and Environment) during mapping and development of the conceptual stratigraphic model. John Nelson, Brian Begley, Bruce Phillips, and two anonymous reviewers provided helpful comments on drafts of this paper.

References

Becker, M.W., Georgian, T., Ambrose, H., Siniscalchi, J., Fredrick, K., 2004. Estimating flow and flux of ground water discharge using water temperature and velocity. Journal of Hydrology 296, 221–233.

Blits, C.A., Woolery, E.W., Macpherson, K.A., Hampson, S., 2008. Integrated geophysical imaging techniques for detecting neotectonic deformation in the Fluorspar Area Fault Complex of western Kentucky. Geological Society of America Abstracts with Programs 40 (5), 80.

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 US Department of Energy under Subcontract to DOE Contract DE-AC05-76OR00001.

Clausen, J.L., Douthitt, J.W., Davis, K.R., Phillips, B.E., 1992. Report of the Paducah Gaseous Diffusion Plant groundwater investigation phase III. Report KY/E-150, Prepared by Martin Marietta Energy Systems Inc., for the US Department of Energy, 147p.

Clausen, J.L., Zutman, J.L., Pickering, D.A., Farrow, N.D., 1995. Final report on drive-point profiling of the northwest plume and analysis of selected data. Document KY/ER-66, Prepared by Martin Marietta Energy Systems Inc., for the US Department of Energy, 173p.

Conant, Jr., B., 2001. A PCE plume discharging to a river: investigations of flux, geochemistry, and biodegradation in the streambed. Ph.D. Dissertation. University of Waterloo, Canada, 543p.

Conant Jr., B., 2004. Delineating and quantifying ground water discharge zones using streambed temperatures. Ground Water 42 (2), 243–257.

Evaldi, R.D., McClain, D.L., 1989. Streamflow, specific-conductance, and temperature data for Bayou and Little Bayou Creeks near Paducah, Kentucky, August 15 and 16, 1989. US Geological Survey Open-File Report 89-582, 19p.

Finch, W.I., 1967. Geologic map of part of the Joppa quadrangle, McCracken County, Kentucky. US Geological Survey Map GQ-652, 1 sheet.

Fox, G.A., Wilson, G.V., Simon, A., Langendoen, E.J., Akay, O., Fuchs, J.W., 2007. Measuring streambank erosion due to ground water seepage: correlation to bank pore water pressure, precipitation and stream stage. Earth Surface Processes and Landforms 32, 1558–1573.

Freeze, R.A., Cherry, J.A., 1979. Groundwater. Prentice-Hall, Englewood Cliffs, NJ, 604p.

Fryar, A.E., Thompson, K.E., Hendricks, S.P., White, D.W., 2007. Groundwater flow and reservoir management in a tributary watershed along Kentucky Lake. Journal of the Kentucky Academy of Science 68 (1), 11–23.

Fryar, A.E., Wallin, E.J., Brown, D.L., 2000. Spatial and temporal variability in seepage between a contaminated aquifer and tributaries to the Ohio River. Ground Water Monitoring & Remediation 20, 129–146.

Hagerty, D.J., 1991a. Piping/sapping erosion. I: basic considerations. Journal of Hydraulic Engineering 117, 991–1008.

Hagerty, D.J., 1991b. Piping/sapping erosion. II: identification-diagnosis. Journal of Hydraulic Engineering 117, 1009–1025.

Hill, A.R., 2000. Stream chemistry and riparian zones. In: Jones, J.B., Mulholland, P.J. (Eds.), Streams and Ground Waters. Academic Press, San Diego, CA, pp. 83–110.

Holmes, R.M., 2000. The importance of ground water to stream ecosystem function. In: Jones, J.B., Mulholland, P.J. (Eds.), Streams and Ground Waters. Academic Press, San Diego, CA, pp. 137–148.

Jacobs EM Team, 1997. Ground-water conceptual model for the Paducah Gaseous Diffusion Plant, Paducah, Kentucky. Report Prepared for the US Department of Energy under Contract DE-AC05-93OR22028 by Jacobs Environmental Management, Kevil, KY.

Jacobs EM Team, 1999. Transport modeling results for the northeast plume interim remedial action and the northwest plume at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky. Report DOE/OR/07-1803&D1, Prepared for the US Department of Energy by Jacobs Environmental Management, Kevil, KY, 100p.

Langston, C., McIntyre, J., Street, R., 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, pp. 878–880.

LaSage, D.M., 2004. Natural attenuation along a first-order stream recharged by contaminated ground water. Ph.D. Dissertation, University of Kentucky, USA, 238p.

LaSage, D.M., Fryar, A.E., Mukherjee, A., Sturchio, N.C., Heraty, L.J., 2008. Groundwater-derived contaminant fluxes along a channelized Coastal Plain stream. Journal of Hydrology 360 (1–4), 265–280.

McNab, W.H., Avers, P.E., 1996. Ecological subregions of the United States. US Forest Service Report WO-WSA-5. <http://www.fs.fed.us/land/pubs/ecoregions/index.html> (accessed June 2007).

Mukherjee, A., Fryar, A.E., LaSage, D.M., 2005. Using tracer tests to assess natural attenuation of contaminants along a channelized Coastal Plain stream. Environmental & Engineering Geoscience 11 (4), 371–382.

Muthukrishnan, S., Harbor, J., Lim, K., Engel, B.A., 2003. iSep: automated, web-GIS based hydrograph separation tool – application in studying hydrological changes due to urban sprawl. Geological Society of America Abstracts with Programs 35 (6), 156.

National Climatic Data Center (NCDC), 2004. Paducah Barkley Regional Airport, Kentucky. Climatography of the United States, No. 20, 1971-2000, 6p.

National Research Council (NRC), 2004. Groundwater Fluxes across Interfaces. National Academic Press, Washington, DC, 85p.

National Water and Climate Center (NWCC), 1998. Stream Visual Assessment Protocol. US Department of Agriculture, Natural Resources Conservation Service, NWCC Technical Note 991, 42p.

Neilans, D.A., Urbano, L., 2006. Geomorphic effect of groundwater flux on the channelized Loosahatchie River, Shelby County, Tennessee. Geological Society of America Abstracts with Programs 38 (7), 233.

Nelson, W.J., Denny, F.B., Devera, J.A., Follmer, L.R., Masters, J.M., 1999. Quaternary grabens in southernmost Illinois: deformation near an active intraplate seismic zone. Tectonophysics 305, 381–397.

Nelson, W.J., Masters, J.M., 2006. Geology of Joppa quadrangle, Massac County, Illinois. Illinois State Geological Survey, preliminary map, 2 sheets.

Nelson, W.J., Masters, J.M., Follmer, L.R., 2002. Surficial geology, Metropolis quadrangle, Massac County, Illinois. Illinois State Geological Survey, Illinois Geologic Quadrangle Map IGQ-Metropolis-SG, 2 sheets.

Olive, W.W., 1966. Geologic map of the Heath quadrangle, McCracken and Ballard Counties, Kentucky. US Geological Survey Map GQ-561, 1 sheet.

Olive, W.W., 1980. Geologic maps of the Jackson Purchase region, Kentucky. US Geological Survey Miscellaneous Investigations Series Map I-1217, 1 sheet and 11p.

Pederson, D.E., 2001. Stream piracy revisited: a groundwater-sapping solution. GSA Today 11 (9), 4—10.

Pringle, C.M., Triska, F.J., 2000. Emergent biological patterns and surface—subsurface interactions at landscape scales. In: Jones, J.B., Mulholland, P.J. (Eds.), Streams and Ground Waters. Academic Press, San Diego, CA, pp. 167—193.

Rantz, S.E., 1982. Measurement and computation of streamflow, volume 1, Measurement of stage and discharge. U.S. Geological Survey Water-Supply Paper 2175, 284p.

Rosgen, D., Silvey, L., 1998. Field Guide for Stream Classification, second ed. Wildland Hydrology Books, Ft. Collins, CO, 193p.

Schmidt, C., Bayer-Reich, M., Schirmer, M., 2006. Characterization of spatial heterogeneity of groundwater-stream water interactions using multiple depth streambed temperature measurements at the reach scale. Hydrology and Earth System Sciences 10, 849—859.

Schueler, T., 1994. The importance of imperviousness. Watershed Protection Techniques 1 (3), 100—111.

Science Applications International Corporation, 2001. Seeps along Little Bayou Creek northwest groundwater plume. Draft Report Prepared for the US Department of Energy, Office of Environmental Management, under Subcontract 23900-BA-YT001U.

Sexton, J.L., 2006. Lithologic and stratigraphic compilation of near-surface sediments for the Paducah Gaseous Diffusion Plant, McCracken County, KY. M.S. Thesis, University of Kentucky, USA, 250p.

Shankman, D., Smith, L.J., 2004. Stream channelization and swamp formation in the US Coastal Plain. Physical Geography 25 (1), 22—38.

Simon, A., Curini, A., Darby, S.E., Langendoen, E.J., 2000. Bank and near-bank processes in an incised channel. Geomorphology 35, 193—217.

Simon, A., Thomas, R.E., 2002. Processes and forms of an unstable alluvial system with resistant, cohesive streambeds. Earth Surface Processes and Landforms 27, 699—718.

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

US Department of Energy, 2000. Phase II independent investigation of the Paducah Gaseous Diffusion Plant, environment, safety, and health practices 1952—1990. Office of Oversight, Environment, Safety and Health, 76p.

US Geological Survey (USGS), 1932. LaCenter quadrangle, Kentucky—Illinois, 1:62,500-scale topographic map, 1 sheet.

USGS, 1978. Heath quadrangle, Kentucky, 1:24,000-scale topographic map, 1 sheet.

USGS, 1982. Joppa quadrangle, Kentucky—Illinois, 1:24,000-scale topographic map, 1 sheet.

USGS, 2008. National Water Information System, USGS 03611900 Little Bayou Creek near Grahamville, KY. <http://nwis.waterdata.usgs.gov/nwis/dv/?site_no=03611900> (accessed April 2008).

University of Kentucky Agricultural Weather Center, 2007. Climatology data, hourly weather observations, Paducah. <http://wwwagwx.ca.uky.edu/climdata.html> (accessed June 2007).

Urbano, L., Waldron, B., Larsen, D., Shook, H., 2006. Groundwater—surfacewater interactions at the transition of an aquifer from unconfined to confined. Journal of Hydrology 321, 200—212.

White, D.S., Elzinga, C.H., Hendricks, S.P., 1987. Temperature patterns within the hyporheic zone of a northern Michigan river. Journal of the North American Benthological Society 6 (2), 85—91.

Wilson, G.V., Periketi, R.K., Fox, G.A., Dabney, S.M., Shields, F.D., Cullum, R.F., 2007. Soil properties controlling seepage erosion contributions to streambank failure. Earth Surface Processes and Landforms 27, 447—459.