Groundwater Flow and Reservoir Management in a Tributary Watershed along Kentucky Lake

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ABSTRACT
Understanding groundwater flow in tributary watersheds is important for evaluating water and solute storage and inputs into reservoirs. We delineated groundwater flow at various spatial and temporal scales within the watershed of Ledbetter Creek, a third-order tributary of the Tennessee River (impounded to create Kentucky Lake) in western Kentucky. We monitored hydraulic heads in wells (primarily in the upper watershed) and piezometers (in the lower watershed) and measured the flow of a spring along the embayment where the creek enters the reservoir. Manual measurements were made at least quarterly from July 1999 to March 2002 and were made annually each April from 2002 through 2006. From May 2000 to March 2002, hydraulic heads were recorded continuously in selected piezometers. At the watershed scale, groundwater flow followed the topography, with discharge occurring along the creek and in the embayment. Hydraulic heads in piezometers responded to large storms over periods of hours to days. Longer-term fluctuations in hydraulic head reflect reservoir management in the embayment (stage increased in early spring and decreased in late summer) and seasonal variability elsewhere in the watershed.

KEY WORDS: Ledbetter Creek, Tennessee River, bank storage, seepage, impoundment

INTRODUCTION
Despite the proliferation of research on groundwater/surface-water interactions during the past two decades (as reviewed by Winter et al. 1998; Jones and Mulholland 2000; Bencala 2005; and others) and the development of reservoirs as a dominant feature of the North American landscape during the 20th century, there have been relatively few studies of groundwater/reservoir interactions. Reservoirs have characteristics of both streams and lakes (Thornton et al., 1990; Winter et al. 1998; Wetzel 2001). As in the case of undammed streams, bank storage occurs when reservoir stage is raised and the hydraulic gradient is reversed, i.e., lateral infiltration is induced and the water table rises (Cady 1941; Coffin 1970; Simons and Rorabaugh 1971). A rise in stage also results in vertical infiltration of surface water. In effect, the zone in which infiltrating surface water and groundwater mix adjacent to a reservoir varies between hyporheic (the mixing zone adjoining and beneath a stream) and hypolentic (the mixing zone adjoining and underlying a lake) (Aseltyne et al. 2006). These zones can affect solute exports from groundwater to surface water and aquatic biological activity (White 1993; Winter 2001; Bencala 2005; Aseltyne et al. 2006).

One topic that has received limited attention is the extent of spatial and temporal changes in groundwater flow resulting from reservoir-stage manipulation. Changes in groundwater flow may be more pronounced adjacent to reservoirs than to undammed streams, for which the durations of stage rises are commonly shorter. In modeling flow where a creek enters a reservoir in the foothills of the California Coast Range, Rains et al. (2004) found that a “groundwater backwater effect... extends to portions of the terrace, but the most pronounced effects occur on the delta” of the creek. Aseltyne et al. (2006) ex-
amine infiltration where Ledbetter Creek enters Kentucky Lake, the terminal reservoir on the Tennessee River, in western Kentucky. Using “peepers” (multi-chamber passive-diffusion samplers) to track Cl and stable isotopes of H₂O, Aseltyne et al. (2006) showed that the depth of surface-water infiltration below the creek channel increased by 4 to 8 cm following a 0.65-m reservoir-stage rise over a 10-day period. Following release of water from bank storage into a reservoir, the rate of hydraulic-head change in the aquifer should decrease with distance and time (Guo 1997).

This paper expands on previous studies by delineating spatial and temporal patterns in groundwater flow both at the scale of a tributary watershed to a reservoir and in detail at the outlet of the watershed. In particular, this work complements that of Aseltyne et al. (2006) by providing hydraulic data from the same study area.

STUDY AREA SETTING

Kentucky Lake, impounded in 1944 by the Tennessee Valley Authority, is the farthest downstream and largest of nearly fifty reservoirs on the Tennessee/Cumberland River system. Typical of mainstem impoundments on the Tennessee River, it is narrow with a distinct deep main channel and a shallow floodplain that includes the drowned mouths of numerous small tributaries. Ledbetter Creek is a third-order perennial stream that drains a watershed of 24 km² in Calloway and Marshall counties, Kentucky (White et al. 2007) (Figure 1). The mouth of the Ledbetter Creek embayment is at Tennessee River mile 42.5, 68.4 km upstream of Kentucky Dam. Land cover in the watershed consists primarily of forests, fields, and rural development. Land surface elevations range from ~158 m above mean sea level (msl) along the watershed divide to ~109 m msl along the shoreline of the embayment. Similar to the site in the California Coast Range studied by Rains et al. (2004), impoundment of Kentucky Lake resulted in the formation of a delta, where Ledbetter Creek splits into multiple distributary channels at the head of the embayment.

The region is located along the northeastern margin of the Gulf Coastal Plain physiographic province, which is marked by rolling land between incised valleys (Fenneman 1938). Coastal Plain strata consist of unconsolidated Cretaceous to Holocene sediments, which dip gently to west and south toward the Mississippi River, overlying Mississippian bedrock. Units exposed in the Ledbetter Creek watershed include silicified Mississippian limestone (Ft. Payne Formation), Upper Cretaceous clays, silts, and sands (the McNairy Formation), Pliocene to Pleistocene clays, silts, sands, and gravels (the Continental Deposits), loess on uplands, and alluvium in valleys (Olive 1965). The surficial (water-table) aquifer lies within the Ft. Payne Formation, the McNairy Formation (except where absent in the northeastern part of the watershed), and alluvium (Figure 2). Regional groundwater flow in the study area is toward the Tennessee River (Morgan 1965).

The climate of the northern Gulf Coastal Plain is humid and temperate (continental), with moderately cold winters, warm summers, and no distinct wet or dry season (Davis et al. 1973; Humphrey et al. 1973). The closest meteorological stations with long-term records to the Ledbetter Creek watershed are Paducah, Kentucky (~66 km west-northwest), and Princeton, Kentucky (~49 km north-northeast). For the years 1972–2005, average air temperatures were 14°C at Paducah and 15°C at Princeton.
at Princeton, and annual precipitation averaged 123.5 cm at Paducah and 130.7 cm at Princeton (UKAWC 2006). Since 2000, the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) has maintained a monitoring station (KY99) in the Land Between the Lakes National Recreation Area, ~20 km north of the Ledbetter Creek watershed. Annual precipitation at KY99 from 2000 through 2005 averaged 118.4 cm (Illinois State Water Survey 2006). As of 1997, estimated annual average precipitation was 134.8 cm and estimated annual average pan evaporation was 125.0 cm for Calloway County (UKAWC 2006). Monthly estimates of pan evaporation exceeded monthly estimates of precipitation for May through October (UKAWC 2006).

METHODS

In this study, we collected data from domestic wells in the upper reaches of the watershed, piezometers in the floodplain, piezometers and a monitoring well in the embayment (the seasonally inundated mouth of the watershed, which includes the delta), and a perennial spring flowing into the embayment. During March 2000, Hancock Biological Station staff conducted a survey of domestic wells in and adjoining the watershed. We selected 8 of 35 inventoried wells (Figure 1b, Table 1) for long-term water-level monitoring based primarily on accessibility, including both landowner permission and ability to take measurements without becoming entangled in submersible-pump wiring or water-supply pipe. Wells 1, 2, and 4 through 8 had 2-ft (0.6-m) diameter concrete culvert pipe as casing because the driller used a bucket auger to excavate gravels. Well 3 consisted of PVC pipe without a pump installed; it and wells 1 and 6 were not in household use at the time of the study.

Two different sets of piezometers were used (Figure 1c, Table 1). A transect of three individual piezometers across the floodplain of Ledbetter Creek, each completed to 3 m below ground level (bgl), was installed in April 1999. A transect of five piezometer nests across the embayment, each containing two to
Table 1. Land-surface (LS) elevations for wells and piezometers (prefixed P), total depths for wells and piezometers, and screened depths (referenced to approximate midpoint of screened interval) for monitoring well and piezometers. Locations are shown in Figure 1.

<table>
<thead>
<tr>
<th>ID</th>
<th>LS elevation (m)</th>
<th>Total depth (m)</th>
<th>Screened depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well 1</td>
<td>137</td>
<td>29.3</td>
<td></td>
</tr>
<tr>
<td>Well 2</td>
<td>151</td>
<td>36.3</td>
<td></td>
</tr>
<tr>
<td>Well 3</td>
<td>155</td>
<td>42.7</td>
<td></td>
</tr>
<tr>
<td>Well 4</td>
<td>151</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>Well 5</td>
<td>155</td>
<td>27.4</td>
<td></td>
</tr>
<tr>
<td>Well 6</td>
<td>156</td>
<td>12.2</td>
<td></td>
</tr>
<tr>
<td>Well 7</td>
<td>157</td>
<td>29.9</td>
<td></td>
</tr>
<tr>
<td>Well 8</td>
<td>149</td>
<td>48.8</td>
<td></td>
</tr>
<tr>
<td>Monitoring well</td>
<td>109</td>
<td>12.2</td>
<td>11.4</td>
</tr>
</tbody>
</table>

We measured depths to water in domestic wells and piezometers using a 300-ft (91-m) electric tape graduated in 0.01-ft (0.003-m) increments. At elevated reservoir stage, we used a folding rule (also graduated in 0.01-ft increments) or measuring tape graduated in 1/16-inch (0.0016-m) increments to measure surface-water levels below the top of the casing for embayment piezometers. Water levels were measured manually beginning June 2000 in domestic wells, July 1999 in floodplain piezometers, and January 2000 in embayment piezometers. The measurements continued monthly to quarterly through April 2002 (with two sets of data for piezometers in July 2000) and annually each April thereafter through 2006. Depth to water or water level was converted to hydraulic head by adding land-surface elevation and subtracting casing height. Land-surface elevations were estimated for wells using the 1:24,000 Hico topographic map, which is accurate to within 5 ft (1.5 m) and were surveyed for piezometers using a GPS unit with an accuracy of 0.2 m. We used a folding rule or measuring tape to measure casing heights for domestic wells and embayment piezometers. In addition, pressure transducers connected to digital dataloggers were installed in piezometer nests P1 and P5 in January 2000. Pressure readings were recorded hourly until March 2002.

We measured discharge of the spring (S in Figure 1c) where it spilled over a ledge ~0.3 m high, ~10 m laterally from the orifice. We used a bucket, stopwatch, and 2-l cylinder graduated in increments of 20 ml. Discharge was measured monthly to quarterly from March 2000 through April 2002 and annually thereafter through April 2006. Beginning in May 2000, discharge measurements were made at least three times in succession and averaged.

RESULTS AND DISCUSSION

Hydraulic Heads at the Watershed Scale

Wells 1, 2, 6, 7, and 8 were determined to be just outside the watershed based on the divide inferred from the topographic map (although wells 2, 6, and 7 were within 100 m of the divide). The map of Morgan (1965) indicates that surface-water divides generally coincide with divides in the surficial aquifer in the area. Well 6 was perched, as indicated by ~9 to 12 m shallower depths to water than
those in the adjoining deeper well 7 located ~10 m away and by the sound of water flowing down the casing of well 7. Equipotential lines were contoured assuming (1) symmetry across the watershed divide, (2) all wells were completed in the surficial aquifer (excluding well 6), and (3) equipotentials were a subdued reflection of watershed topography, with hydraulic heads equal to land-surface elevations along the main stem of the creek (Figure 1b). Consequently, as inferred theoretically by Tóth (1963), groundwater was expected to flow away from the watershed divide and converge toward Ledbetter Creek and the embayment (Figure 2). Groundwater discharge in the lower watershed was corroborated by lateral hydraulic gradients in the floodplain piezometers (see below) by the existence of the spring along the embayment and by the observation that the monitoring well along the embayment flowed slowly. Because the top of casing in this well was flush with the concrete pad, the height of artesian rise above land surface was not measured. Therefore, we assumed conservatively that hydraulic head for the monitoring well equaled the land-surface elevation. This last assumption should not significantly affect the equipotential lines shown in Figure 1 nor, given the depth of the monitoring well, should it affect the delineation of groundwater flow directions within the embayment sediments.

Temporal plots of depths to water in domestic wells, normalized relative to the maximum depth to water in each well (Figure 3), showed broad seasonal and annual trends. In terms of seasonal variations from June 2000 through April 2002, water levels tended to peak in spring to summer, decrease to minimum values in fall to winter, then rebound. This behavior agreed with that observed in a previous study of groundwater flow in the 48-km² watershed of Bayou Creek, a second-order perennial stream near Paducah, Kentucky (Fryar et al. 2000). The water-level trends were consistent with groundwater recharge occurring from late autumn through early spring, when precipitation exceeded evapotranspiration as approximated by pan evaporation estimates. At the annual scale between April 2001 and April 2006, depths to water varied within 0.91 m on the west side of the watershed (wells 4–7) and varied by 2.07 to 2.29 m on the east side of the watershed (wells 1–3), with depths to water in wells 1 and 2 tracking each other. Annual-scale fluctuations

Figure 3. Depths to water in domestic wells monitored from 22 June 2000 through 22 April 2006, normalized against the maximum depth to water in each well. Note that monitoring of well 8 was discontinued after October 2001 at the landowner’s request.
in hydraulic head were less than seasonal fluctuations; excluding the August 2000 reading for well 3, which was anomalous and suspect, the maximum hydraulic-head fluctuation was 3.59 m (for well 2). It should be noted that water levels in domestic wells other than wells 1, 3, and 6 could have been affected by pumping, although no pumping was observed during measurements.

Hydraulic Heads in the Floodplain and Embayment

Hydraulic heads were typically higher in piezometer PR2 than in PR1 and higher in PR1 than in P19, which indicated groundwater flow toward Ledbetter Creek in the floodplain (Figure 4). Occasional reversals in hydraulic gradient appear to have coincided with the formation of a groundwater ridge between PR2, which was adjacent to an ephemeral channel, and PR1. As observed by Fryar et al. (2000) for Bayou Creek near Paducah, Kentucky, reversals also could have occurred from temporary increases in stream stage following rainfall in the Ledbetter Creek watershed or from seasonal water-table declines that led the stream to become temporarily losing in late summer. In particular, the higher hydraulic head for P19 relative to PR1 on 7 April 2001 could have resulted from rainfall during several days preceding the measurement. Rainfall of 2.8 cm was recorded at Princeton on 3 and 4 April (UKAWC 2006). By contrast, the gradient reversal from P19 to PR1 to PR2 on 17 September 1999 followed a month in which only 0.69 cm of rainfall was recorded at Princeton. In terms of seasonal trends, hydraulic heads in the floodplain piezometers tended to be lowest in late summer or early autumn and rebound to maximum levels in late winter or early spring before falling again (Figure 4). Hydraulic heads varied by as much as 1.95 m for PR2 between September 1999 and May 2000. At an annual scale, hydraulic heads measured each April between 2000 and 2006 tended to be relatively constant, with values varying by only 0.13 m for PR2 and 0.10 m for P19.

Hydraulic heads for piezometers in the Ledbetter Creek embayment varied spatially, but the most pronounced variations coincided with temporal changes in reservoir stage. The Tennessee Valley Authority (TVA) typically raises the level of Kentucky Lake 1.5 m in March and lowers it 1.5 m over 3 months beginning in August (Aseltyne et al. 2006), as shown for the period December 1999–April 2002 (Figure 5), which encompassed most of our monthly to quarterly monitoring. Vertical hydraulic gradients varied among piezometer nests: at nest P1, hydraulic heads in both piezometers were within 0.01 m (i.e., the vertical hydraulic gradient was negligible) for 18 of 22 measurements between January 2000 and

Figure 4. Manually-measured hydraulic heads in floodplain piezometers as a function of time from 16 July 1999 through 22 April 2006. Note that monitoring of PR2 was discontinued after April 2003 because the piezometer could no longer be located.
Figure 5. Daily precipitation at Princeton, Kentucky (UKAWC 2006) and hourly reservoir stage at Kentucky Dam (TVA, unpubl. data) for 22 December 1999 through 10 April 2002.

April 2006. Moreover, manually-measured reservoir stage was within 0.01 m of hydraulic heads in nest P1 piezometers for 9 of 11 measurements at summer pool between 2000 and 2006. In contrast, at nest 2, hydraulic head for P2–10 was always greater than for the shallower P2 piezometers and was always higher than manually-measured reservoir stage (Figure 6). Vertical hydraulic gradients varied in direction at nests P3 and P4. At nest P5, hydraulic head for the deeper piezometer (P5–5) was typically greater than for the shallower piezometer and higher than manually-measured reservoir stage except when the stage was being raised in April.

Hydrostratigraphic cross-sections illustrate differences in hydraulic-head distributions across the embayment between summer and winter. Because of imprecision in surveying, values of manually-measured reservoir stage, which should have been virtually identical for a given date, varied by as much as 0.5 m among piezometer nests. Therefore, the stage value measured at each nest on 22 June 2000

Figure 6. Manually-measured hydraulic heads and summer-pool reservoir stage at nest P2 for 28 January 2000 through 22 April 2006.
was adjusted to the simultaneous value at Kentucky Dam after correcting for the approximate slope of the reservoir surface (following Thompson 2002). Hydraulic heads likewise were adjusted for piezometers in each nest on 22 June 2000 and 7 January 2001, then contoured (Figures 7a–b). In June, when the reservoir was at summer pool, the hydraulic gradient was typically downward from the surface to 0.6 m depth and upward from 3 m depth to 1.5 m depth (Figure 7a). In January when the piezometers were not in standing water, the hydraulic gradient beneath the embayment was upward except in the top 1.5 m of the profile at nests P1, P3, and P4 (Figure 7b).

For piezometers equipped with transducers and dataloggers, raw transducer readings were plotted against hydraulic heads measured manually at approximately the same time (within a period of several hours). Beginning with 7 May 2000 data for P1–2 and beginning with 22 June 2000 data for P1–5, P5–2, and P5–5, plots of measured heads versus pressures were strongly linear ($r^2 = 0.987$ to 0.999, $n = 10$ to 12 for each piezometer). We therefore used the regression equations obtained to convert raw transducer readings to hydraulic heads for nests P1 and P5 starting with the aforementioned dates. We suspect that prior non-linear responses resulted from errors in setting or recording the depths at which the transducers were suspended. Because we were comparing hydraulic heads within a given piezometer nest, rather than between nests, we did not attempt to correct continuous data (or the manually-measured data shown in Figure 6) for imprecision in surveying.

As with manual measurements, continuous data showed that hydraulic heads at nests P1 and P5 tracked reservoir stage, rising in March and falling in August. Continuous data also indicated, however, that water levels in the embayment piezometers responded to storms over shorter time scales. In seven instances between December 2000 and December 2001, five for nest P1 (Figure 8) and five for nest P5 (Figure 9), hydraulic head in piezometers rose at least 0.4 m before falling again over a period of several days to weeks. In five of these instances, precipitation of at least 9.3 cm was recorded at Princeton, Kentucky, within a week prior to the start of the hydraulic-head rise (UKAWC 2006). Four of the instances when piezometer water levels rose at least 0.4 m coincided with even greater stage rise at Kentucky Dam during winter pool.

This indicated that the piezometers may have responded to temporary back-flooding in the embayment resulting from regional rainfall in addition to local precipitation. Comparing responses among piezometers for episodes in January 2001, February 2001, and November 2001, hydraulic-head rises were greatest for P5–2, were approximately equal for P1–2 and P1–5 and were smallest for P5–5 (Figures 8, 9). Coincidentally, the timing of hydraulic-head peaks was nearly simultaneous (within 5 hours) for P1–2, P1–5, and P5–2. In contrast, the peak for P5–5 lagged behind the peak for P5–2 by 2 to 4 days, except for an instance in June 2001 (during summer pool) when both piezometers peaked simultaneously. Temporary reversals in hydraulic gradient from upward to downward at nest P5 during reservoir low-stand were thus evident. Differences in the responses at nest 1 and nest 5 may have been a consequence of stratigraphic heterogeneities. Nest P1 was within ~10 m of one of the main distributary channels of Ledbetter Creek, which had relatively coarse, permeable bed sediments, whereas nest P5 was emplaced in mud at the edge of the valley.

Spring Discharge along the Embayment

Discharge for the spring along the embayment showed both seasonal and annual-scale variability. Flow rates peaked in April and decreased to minimum values in autumn or early winter before rebounding (Figure 10). The seasonality was similar to that observed for springs along Little Bayou Creek near Paducah, Kentucky (LaSage 2004), and for hydraulic heads in domestic wells and floodplain piezometers in this watershed. Measured flow rates ranged from 0.0858 L/s on 20 October 2001 to 1.95 L/s on 12 April 2003; these values probably underestimated actual discharge because of the likelihood that not all flow was captured in the bucket. Values measured each April between 2000 and 2006 varied within a factor of 2.5 and decreased progressively from 2003 to 2006. However, April flow rates appear not to have varied systematically either with short-term precipitation (during the pre-
Figure 7. (a) Generalized hydrostratigraphic cross-section across Ledbetter Creek embayment for 22 June 2000 (see Figure 1(c) for map of piezometer locations). Piezometer diameters are not shown to scale; reservoir stage (109.6 m msl) and piezometer stick-ups above land surface are not depicted. Hydraulic heads for each piezometer are in m msl. Note that the hydraulic head for piezometer 4-10 had not yet equilibrated following drilling, so it was not contoured.

(b) Generalized hydrostratigraphic cross-section across Ledbetter Creek embayment for 7 January 2001 (see Figure 1(c) for map of piezometer locations). Piezometer diameters are not shown to scale and piezometer stick-ups above land surface are not depicted. Hydraulic heads for each piezometer are in m msl.
Figure 8. Continuous hydraulic heads for nest P1 (from 7 May 2000 through 10 April 2002 for piezometer P1-2 and from 22 June 2000 through 10 April 2002 for piezometer P1-5). Instances of hydraulic head rises ≥ 0.4 m (noted in text) are marked with arrows. Occasional data gaps resulted from datalogger battery failures or loose wiring connections. Flat-line intervals from 22 May through 28 July 2001 resulted from water levels rising beyond the dynamic range of the transducers.

Figure 9. Continuous hydraulic heads for nest P5 from 22 June 2000 through 10 April 2002. Instances of hydraulic head rises ≥ 0.4 m (noted in text) are marked with arrows. Occasional data gaps resulted from datalogger battery failures or loose wiring connections. May 2001 data for P5-2 are suspect and may reflect an equipment malfunction.

Summary and Conclusions

Using manual, monthly to annual measurements of hydraulic head and spring flow over a period of 6 years, as well as continuous, automatic measurements of hydraulic head over a period of 22 months, we documented that groundwater flow within the Ledbetter Creek watershed tended to converge toward the creek and its embayment. Furthermore, we showed that hydraulic heads and spring flow...
rates fluctuated over various time scales. Above the embayment, including the Ledbetter Creek floodplain and the valley slope where the spring discharges, hydraulic heads and spring flow varied seasonally, probably in response to groundwater recharge, as noted elsewhere in the region. In the floodplain, hydraulic heads also varied over shorter time scales, probably as a result of precipitation and flooding. Interannual variability in hydraulic heads was less than seasonal variability. In embayment sediments, hydraulic heads fluctuated with precipitation over periods of hours to weeks, but the most pronounced changes were in response to reservoir-stage manipulation. The effects of such manipulation on groundwater flow were spatially localized. Reservoir-stage rise resulted in temporary reversals of hydraulic gradients from upward to downward to depths of 1.5 m in parts of the embayment, but Kentucky Lake management did not appear to affect the floodplain piezometers and the spring, for which land-surface elevations are within 2 m of the land surface in the embayment.

The results of this study are generally consistent with the limited number of prior studies on groundwater-reservoir interactions. In particular, as observed by Rains et al. (2004) for the East Park Reservoir in California, hydraulic-gradient reversals in the Ledbetter Creek watershed were most pronounced beneath the delta where the creek enters the reservoir. The depth of surface-water infiltration resulting from reservoir-stage rise may only be a few tens of centimeters, as indicated by stable-isotope and chloride analyses of porewater at piezometer nest P1 (Aseltyne et al. 2006). However, this study has shown hydraulic gradient reversals propagating to greater depths at other sites in the Ledbetter Creek embayment. Such reversals are likely to perturb solute distributions in sediments below the boundary of the hyporheic-hypolentic zone.

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