Incorporating a Watershed-Based Summary Field Exercise into an Introductory Hydrogeology Course

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ABSTRACT

We have developed and implemented a summary field exercise for an introductory hydrogeology course without a laboratory section. This exercise builds on lectures and problem sets that use pre-existing field data. During one day in April, students measure hydraulic heads, stream and spring flow, and stream-bed seepage within the rural watershed of a third-order perennial stream in western Kentucky. Students calculate net specific discharge at various scales, map groundwater flow in the watershed, and calculate vertical hydraulic gradients at the mouth of the watershed, where the stream enters a reservoir (Kentucky Lake). Distinctive features of the exercise include hydraulic head measurements in large-diameter domestic wells and in piezometers installed in the reservoir embayment. Kentucky Lake is raised ~ 2 m shortly before the field trip, thus providing an analog of bank storage. Former students who responded to a questionnaire indicated that the exercise was worthwhile. The exercise was based at a biological field station but could be completed at any field site where long-term hydrologic monitoring is in place or could be initiated.

INTRODUCTION

During the past decade, field coursework in hydrogeology has proliferated within undergraduate and graduate Earth science curricula. An informal Web search found at least 10 institutions offering summer field courses in hydrogeology or hydrology as of 2005, and other institutions have integrated hydrogeology modules into conventional geology field camps (e.g., McKay and Kammer, 1999; Lautz et al., 2007). Some Earth science programs have instrumented watersheds or well fields on or adjoining their campuses, and have integrated data collection and interpretation from these sites into regular coursework (e.g., Woltemade and Blewitt, 2002; Salvage et al., 2004; Day-Lewis et al., 2006; Iqbal and Chowdhury, 2007). As noted by those authors, field exercises promote comprehension and retention of fundamental concepts, and they introduce students to techniques used by professional hydrogeologists (Sanders, 1998). Moreover, placing such exercises within a watershed framework facilitates understanding of the linkages between surface and subsurface hydrologic processes that are commonly decoupled in discussions of water resources (Winter et al., 1998). However, some students are not able to take summer field courses, and "not every university environment has opportunities for hands-on watershed-based activities within walking distance from the classroom" (Salvage et al., 2004, p. 147).

In this paper, we review a watershed-based, summary field exercise used in an introductory hydrogeology course (GLY 585) at the University of Kentucky (UK). GLY 585 is a 3-credit-hour lecture course that is typically offered during the spring semester and is taken by both undergraduate and graduate students. Total enrollment for each class ranged from 5 to 20 (average 13, median 12) between 1996 and 2009. Geology students have been a majority in most classes. However, because the only prerequisites are physical geology and first-semester calculus, students from other sciences, engineering, agriculture, and science education also have enrolled. Student performance is evaluated by midterm and final exams, several problem sets, a term paper, and a presentation, which is optional for undergraduates. During the first four times the senior author taught the course, field trips were 1-day tours of local karst features and clastic (alluvial) aquifers farther away. In 2000, we began a weekend trip as described below, which is analogous to trips for other upper-level geology courses at UK but with inclusion of numerical data collection and analysis.

STUDY AREA SETTING

The Ledbetter Creek watershed covers 24 km² in Calloway and Marshall counties in the Gulf Coastal Plain of western Kentucky (Figure 1a). The area features rolling land between sharply incised valleys, with land-surface elevations ranging from ~ 158 m above mean sea level (amsl) along the divide to ~ 109 m amsl at the mouth of the watershed. Cretaceous to Holocene sediments unconformably overlie Mississippian bedrock and dip gently westward. Land use in the watershed includes farms, rural residences, and parkland. Land cover is ~ 62% forest, 17% grassland, 15% cropland, 5% brush, and 1% water (MARC Associates, 1990, in Johnson, 1992).

The region has a humid temperate climate, with moderately cold winters, warm summers, and no distinct wet or dry season (Humphrey et al., 1973). For the period 1971–2000 at Murray, Kentucky (~ 20 km southwest of the Ledbetter Creek watershed), air temperature ranged from an average minimum of –2.8 °C in January to an average maximum of 32.2 °C in July, and annual precipitation averaged 140.4 cm (Midwest Regional Climate Center, 2010).

Ledbetter Creek is a third-order perennial stream that drains to Kentucky Lake, the terminal reservoir on the Tennessee River that was formed when the Tennessee Valley Authority (TVA) constructed Kentucky Dam in 1945. Current TVA management practice is to raise the reservoir level ~ 2 m in March to summer pool, then lower it back to winter pool over a 3-month period beginning in August. Groundwater flows regionally toward Kentucky Lake and locally toward Ledbetter Creek and its

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embayment (the perennially flooded lower reach of the creek, which is an arm of the reservoir) (Morgan, 1965; Davis et al., 1973; Fryar et al., 2007). Fluctuations in reservoir stage can cause temporary reversals in hydraulic gradient adjacent to Ledbetter embayment (Fryar et al., 2007).

ACTIVITIES

Preparation for the summary exercise begins in the first half of the course, with discussions of groundwater/surface-water interactions more detailed than those in the textbook. Since 2003, these discussions have been tied to two problem sets involving data compiled by the senior author from elsewhere in the region (Fryar et al., 1999, 2000). The first assignment entails hydrologic balance calculations for a lake in the Ohio River floodplain during 1998. These include using: (1) climatic data to calculate the volume of precipitation falling on the lake and estimate evaporation from the lake during the monitoring period; (2) gauging data with an Excel spreadsheet to calculate discharge from a channel draining the lake; (3) Darcy's law to estimate seepage out of the lake; and (4) results of the preceding calculations to estimate seepage into the lake.

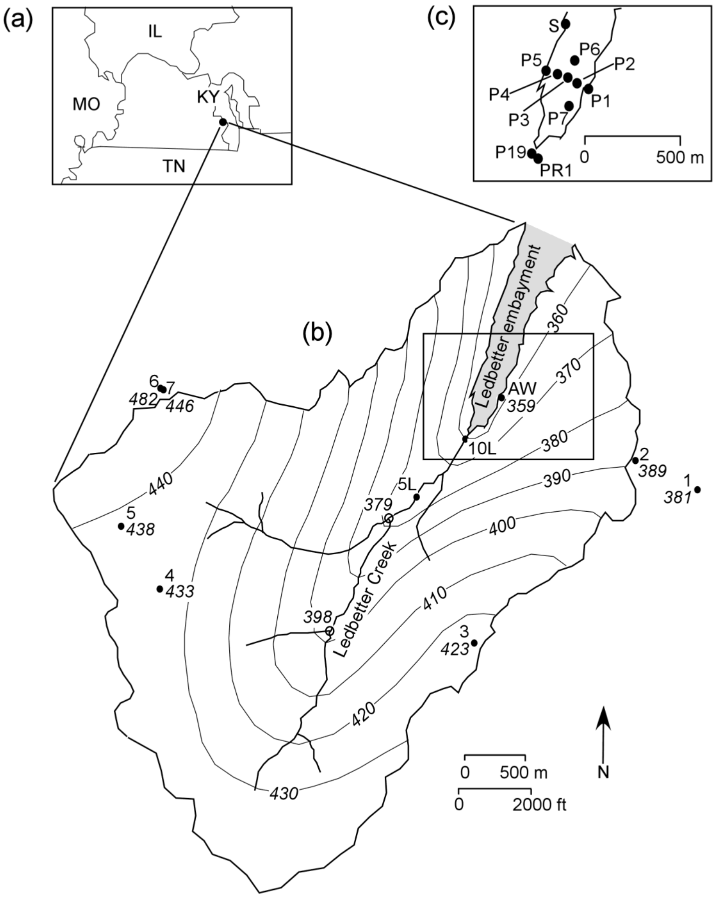

FIGURE 1. (modified from Fryar et al. [2007]).
a). Location of Kentucky Lake and the Ledbetter Creek watershed. IL = Illinois, KY = Kentucky, MO = Missouri, TN = Tennessee.
b) Ledbetter Creek watershed with wells (domestic wells numbered 1 through 7; AW = artesian well), gauging locations (5L and 10L), and inferred equipotentials for April 2006. Hydraulic heads (shown in italics for wells, stream confluences [open circles], and contours) are in feet amsl (1.000 ft = 0.3048 m). Box around mouth of Ledbetter Creek marks inset (c).
c) Upstream end of the Ledbetter embayment with piezometers (prefixed P; P1 through P5 are nests) and the spring (S) relative to summer pool. Within the accuracy of the map, nest P1 coincides with the location of the artesian well and floodplain piezometer P19 coincides with stream-gauging site 10L.

The second assignment includes hydrograph separation using daily streamflow data from a U.S. Geological Survey (USGS) gauging station in the region (Engel et al., 2004; USGS, 2010); calculating vertical hydraulic gradients for a nest of monitoring wells in an alluvial aquifer along the Ohio River; and mapping hydraulic heads in that aquifer. The data in this last problem were collected in September 1997, when the river's stage was relatively low. For comparison, to reinforce the concept of bank storage, students are subsequently shown the Ohio River hydrograph and hydraulic heads in monitoring wells from March 1997, when the largest flood in 47 years occurred. As a result, hydraulic heads were elevated and lateral hydraulic gradients were virtually stagnant as far as 5 km from the river (Fryar et al., 2000).

The summary trip is usually scheduled during a weekend in the latter half of April (i.e., during the last two weeks of the semester). Prior to departure, students are given an overview lecture on the study area and provided with maps and elevation data. The class is based during the exercise at Murray State University's Hancock Biological Station (HBS), which is located in an adjoining watershed that drains to Kentucky Lake, approximately a 5-hour drive from UK. Field activities typically take one day and focus on flow and water-level measurements.

At two locations on Ledbetter Creek (Figure 1b), we gauge stream flow by wading using the midsection method (Rantz et al., 1982) with an open-reel fiberglass measuring tape, top-setting rods, and a digital flow meter. We measure seepage from the stream bed at gauging sites using a homemade seepage meter (modified from the design of Lee [1977]) (Figure 2). A flattened condom is pulled over the larger rubber stopper and allowed to fill during a timed interval, after which the condom is pinched and removed, and the volume of water collected is measured in a 100-mL graduated cylinder. We also measure discharge of a small perennial spring flowing into the embayment (Figure 1c) using a bucket, stopwatch, and 2-L graduated cylinder.

Water-level measurements include observing an artesian monitoring well on the opposite side of the embayment from the spring (Figures 1b and 3). This well consists of 2-inch nominal (5.3-cm actual ID) PVC pipe, which was installed by a licensed driller with a truck-mounted hollow-stem auger rig through alluvium and into bedrock, to a depth of 12.2 m below ground level (bgl). The well is screened from 10.7 to 12.2 m bgl. Using an electric water-level indicator, we measure depths to water in several sets of piezometers in the alluvium (Figures 3 and 4). These consist of sections of 4-inch

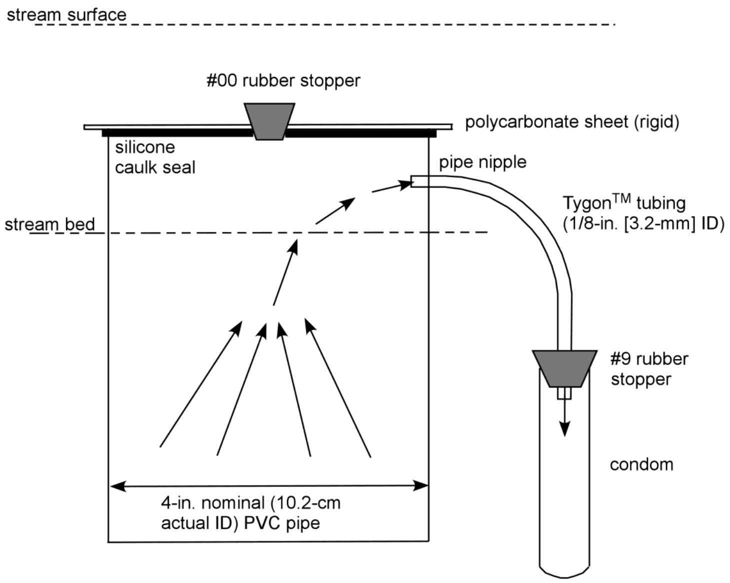

FIGURE 2. Schematic of seepage meter (not to scale; modified from Wallin [1998] and LaSage [2004]).

nominal PVC pipe, which were slotted or perforated along an interval of ~ 0.3 m, capped at the bottom, and emplaced in holes drilled with a gasoline-powered auger rig operated by two persons. The piezometers include two in a transect across the Ledbetter Creek floodplain (3 m bgl), two along the axis of the embayment (3 m bgl), and five nests (each containing two to three piezometers completed to depths of 0.6 to 3 m bgl) across the embayment (Figure 1c). With a folding rule, we measure surface-water levels relative to the top of casing for the embayment piezometers, which extend ~ 2 m above ground surface. Because the depth of water in the embayment can be > 1 m in April, we access offshore piezometers by wading or via pontoon boats.

Lastly, we measure casing heights and depths to water for seven domestic wells around the Ledbetter Creek watershed (Figure 1b). Six of these wells are amenable to water-level measurements because they were constructed of 2-ft (0.6-m) diameter concrete culvert pipe (a local driller used a bucket auger to excavate gravels and cobbles). Because of the relatively large casing diameter, the electric tape does not become entangled around the smaller-diameter PVC water-supply pipe or submersible-pump wiring within the well. The remaining well (#3), which is not in use, consists of PVC pipe without a pump installed. Depths to water vary from ~ 10 to 35 m bgl. One of the larger-diameter wells (#6) is perched, as indicated by water-level measurements ~ 9 to 12 m shallower than those in an adjoining deeper well (#7). To prevent cross-contamination between domestic wells, the bottom ~ 0.5 m of the electric tape is rinsed with bleach and distilled water after each measurement. Equipment and supplies used in the exercise are listed in an online supplement (Table S1).

DATA ANALYSIS AND ASSESSMENT

Following field work, the class meets to ensure that everyone has recorded the same data. Within 2 weeks after returning to UK, the class is given a set of multi-part questions that constitute half of the final exam (the take-home component). The format of the take-home has remained the same since 2003. In the first question, students are asked to (a) modify the Excel spreadsheet from the first problem set to calculate gauged discharge (in m^3/s) at the upstream and downstream sites along Ledbetter Creek, (b) determine the net discharge ΔQ between the sites, (c) estimate the distance ℓ between the sites from the topographic map (~ 686 m [2250 ft]), (d) calculate an average width w for the gauged transects, and thus (e) estimate specific discharge q for the stream reach between the sites ($q = \Delta Q/A$, where the cross-sectional area $A = \ell w$). Students are then given the cross-sectional area for the seepage meter (0.0079 m^2) in order to calculate specific discharge for the seepage meter at each site, and asked to compare the gauged and metered values. In the second question, students are given approximate land surface elevations for domestic wells and, using their field data and the topographic map, asked to draw equipotentials and flow lines for the watershed. (The question does not refer to either a potentiometric-surface map or a water-table map because the main aquifer occurs within different strata and probably is semi-confined.) In the third (last) question, students are asked to calculate the vertical hydraulic gradient between various embayment piezometers and the lake, then asked whether the observed directions of flow are qualitatively consistent with the presence of the spring along the embayment and with their answers to questions 1 and 2.

Apart from minor errors in arithmetic, unit conversions, and data entry into the spreadsheet, students typically obtain reasonable values of specific discharge. Net discharge is positive between the gauging locations, which is assumed to reflect baseflow. As students are told in the field, inflow into the seepage meter may be affected

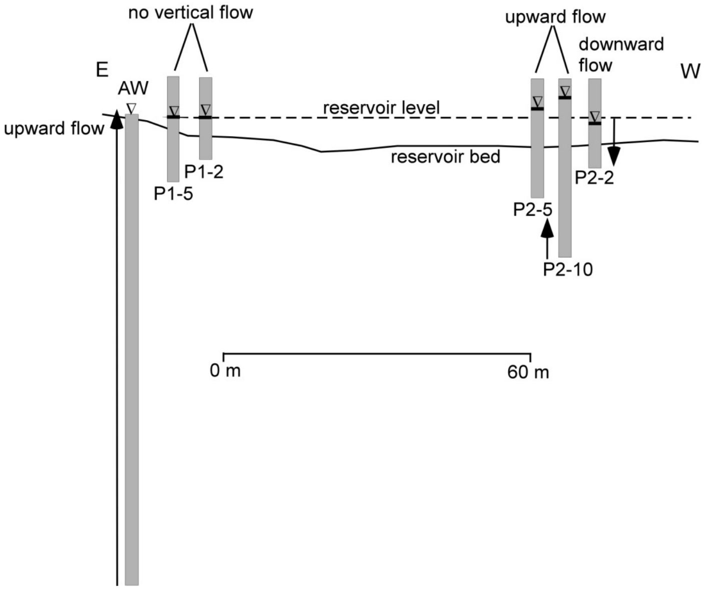

FIGURE 3. Schematic cross-section depicting artesian well (AW) and piezometer nests 1 and 2 (not to scale). Suffixes for individual piezometers refer to the approximate depth of the piezometer below the reservoir bed in feet (e.g., P1-2 is completed 2 ft [0.6 m] below the bed at nest 1). Inverted triangles denote hydraulic heads.

FIGURE 4. Student sketch in field notebook of reservoir stage and hydraulic heads in piezometers at nests 4 and 3.

by stream-water advection through the bed (Fryar et al., 2000) or elastic response of the condom (Schincariol and McNeil, 2002). Although the values of specific discharge measured using different techniques are commonly within an order of magnitude of each other, students tend to recognize that the values obtained by gauging and by seepage meters represent different scales of measurement.

Mapping groundwater flow in the watershed is constrained by the paucity of data points and the fact that well #1 is actually located ~ 500 m beyond the divide. The perched well is excluded from contouring. Students are instructed to use the topographic map to infer hydraulic heads where wells are absent and to assume isotropic conditions, so that flow lines are perpendicular to equipotentials. For consistency with the topographic map, equipotentials are contoured in feet rather than in meters. Most students calculate hydraulic heads properly, correcting for casing stick-up (which is actually within the precision of the land-surface elevations estimated from the topographic map), and they draw flowlines away from the watershed divide and toward the embayment (where hydraulic head for the artesian well is assumed to be at land surface). Errors result where flow lines are not drawn converging toward the creek as well as the embayment, and where equipotentials do not approximate the topography of the watershed (e.g., because Ledbetter Creek is a gaining stream, hydraulic heads should be approximately equal to land-surface elevations along the creek) (Figure 1b).

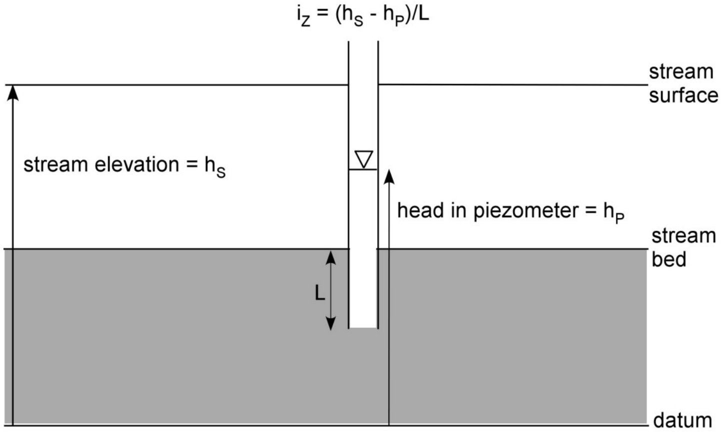

FIGURE 5. Conceptual diagram of the vertical hydraulic gradient (i_Z) between groundwater and a stream or other surface-water body.

Calculating the vertical hydraulic gradient (i_Z) between groundwater and surface water is mathematically simple but conceptually subtle. Students are given a diagram in the lecture notes during the first half of the course (Figure 5) illustrating that the hydraulic head of a stream or lake, similar to that of groundwater, is merely the water-level elevation above some datum, and the distance L over which the head drop occurs is the depth of the well or piezometer intake below the stream or lake bed. For simplicity in the final problem, students are told to assume that the intake is at the bottom of the piezometer, as shown in Figure 4. Students typically calculate the head difference correctly, but some forget to divide by L. In late April, vertical hydraulic gradients are often near zero or downward in the shallow piezometers and upward in the deeper piezometers near the axis of the embayment (Figure 3). As some students note, upward hydraulic gradients are consistent with other evidence of groundwater flow toward the embayment. However, only a few have recognized that near-zero or downward hydraulic gradients are probably a temporary artifact of recent reservoir-level rise, analogous to bank storage.

Each take-home exam is scored out of 50 points and returned to the student after the semester. For 2003-09 classes, minimum values ranged from 18 to 30, maximum values from 43 to 49, and medians from 36 to 43. We examined tendencies in scores on 2003-09 take-home exams by level of education (undergraduate [UG] versus graduate/ post-baccalaureate [G/PB]) and by discipline (geology majors [undergraduate and graduate] versus others). Minimum, maximum, and median scores were greater for G/PB students than for UG students in most classes (Table 1). Maximum and median scores for geology majors were greater than values for other students in all but two instances. However, in four out of six classes, minimum scores for geology majors were less than for other students. Maximum and median scores for the four populations in the 2003-09 classes fluctuated within 12-point ranges (Table 1), thus suggesting that student performance and grading have been reasonably consistent over time.

STUDENT EVALUATIONS

Introduction of the summary exercise coincided with a general improvement in student ratings on standardized, end-of-semester teacher-course evaluations (TCEs; UK Office of Institutional Research, Planning, and Effectiveness [OIRPE], 2010). We compared ratings for classes prior to the exercise (in 1996, 1997 [spring and summer], and 1998) with those from 2000 through 2009 (note GLY 585 was not offered in 1999 and 2007). Averaged minimum, maximum, and median scores increased for five key items:

16. Increased my ability to analyze and evaluate;
17. Course helped ability to solve problems;
18. Gained understanding of concepts and principles;

20. Overall value of the course;
21. Overall quality of teaching.

However, the increased scores cannot be attributed solely to the summary exercise. Other changes included the textbook (Domenico and Schwartz [1990] during 1996–98, Domenico and Schwartz [1998] during 2000–02, and Schwartz and Zhang [2003] from 2003 onward); lecture delivery (use of a blackboard in 1996 and 1998, a document camera in spring 1997, video broadcast in summer 1997, overheads from 2000 through 2002, and PowerPoint with handouts plus a whiteboard from 2003 onward); and introduction of term-paper presentations in 2002 and the western Kentucky problem sets in 2003. Separating the TCE responses further into 2000-02 and 2003-09 cohorts, we saw an increase in median scores coinciding with post-2002 instructional changes, although there were fluctuations in maximum and minimum scores with time (Table 2).

To obtain feedback specifically on the summary exercise, we sent a questionnaire (online Table S2) to 71 former students (out of 96 who took GLY 585 for credit between 2000 and 2006) for whom we had valid e-mail addresses in summer 2007. Forty of those students replied. Anonymity was maintained to the extent possible by not asking when the respondent took the class and by requesting that questionnaires be returned to the department's administrative assistant, who removed identifying information before printing the responses. However, several former students responded directly to the senior author. Slightly more former graduate students than undergraduates replied, and most replies came from geology majors (online Table S2). Of the 15 respondents who had subsequently been employed in hydrogeology, seven had not pursued further studies in hydrogeology beyond GLY 585.

All of those who had attended the field trip (39 of 40 respondents) said it was worthwhile, and 36 of 40 said the field exercise and previous class activities gave adequate preparation for the take-home exam (online Table S2). When asked the most and least useful parts of the exercise, 12 respondents said all were most useful and 19 said none were least useful; the most common recommended change was "none". Among respondents who specified one or more techniques as being most useful, the most common answer was hydraulic-head measurements in piezometers and wells (online Table S2). Responses about useful parts of the exercise did not vary systematically by level of education (UG versus G/PB), discipline (geology majors versus others), or having experience in hydrogeology after GLY 585 (coursework, research, or employment). Most additional comments (17 out of 28; online Table S3) were positive. Criticisms included the need for more time in the field, visits to other field sites, and more measurements by students.

INSTRUCTIONAL EFFECTIVENESS AND LIMITATIONS

Assessing the effectiveness of the summary exercise is complicated by the nature of the available data. Exam scores do not provide information about performance on individual questions and TCE scores do not specifically address the summary exercise. However, since 2003, ranges of take-home and TCE scores have been relatively consistent (Tables 1 and 2) and TCE scores have usually exceeded college means (UK OIRPE, 2010). We therefore infer that the instructional approach underpinning the exercise is reliable. According to Wiggins and McTighe

TABLE 1. ENROLLMENTS IN GLY 585 CLASSES (2003-09) AND SCORES ON TAKE-HOME EXAM

	2003		2004		2005		2006		2008[1]		2009	
	enroll.	score[2]	enroll.	score	enroll.	score	enroll.	score	enroll.	score	enroll.	score
UG[3]	9		8		5		17		2		8	
G/PB	6		4		6		3		7		5	
GLY[4]	8		10		6		16		2		10	
other	7		2		5		4		7		3	
UG min.[5]		30		21		29		21		18		25
G/PB min.		36		40		37		31		38		35
GLY min.		30		21		29		24		42		25
other min.		31		32		35		21		18		31
UG max.[5]		45		39		46		43		43		47
G/PB max.		47		47		49		41		47		45
GLY max.		47		47		49		43		44		47
other max.		45		40		43		41		47		35
UG med.[5]		37		35		31		40		30.5		34.5
G/PB med.		43.5		43		41.5		38		44		42
GLY med.		43		36		41		40		43		38
other med.		37		36		38		38.5		42		33

[1] course was not offered in 2007;
[2] score out of 50 points;
[3] educational level: UG = undergraduate, G/PB = graduate/post-baccalaureate;
[4] discipline: GLY = geology major; other = non-geology;
[5] min. = minimum, max. = maximum, med. = median.

TABLE 2. CLASS-AVERAGE SCORES ON TEACHER-COURSE EVALUATION (TCE) QUESTIONS FOR GLY 585

	TCE questions[1]				
Class scores	#16	#17	#18	#20	#21
min. 1996-98[2]	2.9	2.9	3.0	2.8	2.8
min. 2000-02	3.3	3.4	3.4	3.4	3.3
min. 2003-09	3.2	3.2	3.5	3.4	3.5
max. 1996-98	3.6	3.4	3.4	3.2	3.5
max. 2000-02	3.6	3.4	3.6	3.5	3.7
max. 2003-09	3.7	3.7	3.7	3.7	3.8
med. 1996-98	3.2	3.3	3.4	3.1	3.1
med. 2000-02	3.5	3.4	3.6	3.4	3.6
med. 2003-09	3.6	3.6	3.7	3.5	3.7

[1] question numbers are keyed to the text; scores are referenced to 4 = excellent, 3 = good, 2 = fair, 1 = poor;

[2] statistics (min. = minimum, max. = maximum, med. = median) are determined for three groups of classes: 1996-98, 2000-02, and 2003-09.

(2005), the validity of an exercise hinges on student understanding of concepts and not simply recall of formulas. In this case, the tendencies of students to recognize differences in scales of groundwater discharge (question 1), to infer directions of groundwater flow from contouring hydraulic heads (question 2), and to articulate plausible explanations for vertical hydraulic-head drops (question 3) represent a fundamental level of conceptual understanding. Moreover, survey comments indicate that former students found the exercise worthwhile not merely because "the performance is complex and the task interesting" (Wiggins and McTighe, 2005, p. 183), but also because it was useful, practical, and like a professional project (online Table S3).

Notwithstanding the apparent reliability and validity of the exercise, there are several limitations and opportunities for enhancement. In part, these stem from the limited time available for the exercise, which is a consequence of the site's distance from campus. Additional time would facilitate activities such as installing new piezometers, surveying their elevations, conducting pumping tests, and sampling water for chemical analyses. Because of limited time and equipment, the instructor typically performs stream gauging while students record data. In addition, estimates of groundwater inflow have assumed that runoff is negligible between gauging sites. We think this assumption is tenable because rainfall at the nearest National Weather Service station (Paducah, Kentucky, ~ 66 km west-northwest) was ≤ 1.0 cm for at least 24 hours prior to each time Ledbetter Creek was gauged (UK Agricultural Weather Center, 2010). However, interpretation of gauging results following heavier rainfall should account for the possibility that the stream was not at baseflow. Slug testing (Schwartz and Zhang, 2003) of piezometers in the floodplain would permit calculation of horizontal hydraulic conductivity (K) and thus estimates of specific discharge ($q = K \times (\Delta h/L)$, where Δh is the hydraulic-head difference and L is the distance between the piezometer and the stream) at a scale between seepage meters and stream gauging.

CONCLUSIONS

The summary exercise described in this paper addresses concepts and skills, including measurement of hydraulic heads and mapping of groundwater flow, that are fundamental to hydrogeologic research and professional practice. In the process, the exercise focuses on groundwater/surface-water interactions, a commonly underemphasized topic in hydrogeology classes (Siegel, 2008). Students engage in hands-on collaborative learning through field data collection and interact with local stakeholders (residents whose wells are monitored). Important quantitative skills utilized in data interpretation include unit conversion, dimensional analysis, and calculation of gradient (Manduca et al., 2008). Moreover, students can observe effects of reservoir management on groundwater flow. Since the 1940s, reservoirs have proliferated across much of the USA, yet standard hydrogeology texts do not usually consider them (one exception is Freeze and Cherry [1979]). Although students have not been asked to compare their results with those obtained by previous classes, the opportunity exists to assess year-to-year variability in parameters such as stream flow, spring discharge, and hydraulic heads.

The techniques and materials used in this exercise are broadly transferable to other times of year and other locations, including natural lakes. Less expensive alternatives exist for some equipment (e.g., using a hand auger instead of a gasoline-powered rig to drill holes for piezometers). Having both a spring and existing wells available for monitoring within the Ledbetter Creek watershed, as well as a nearby fixed-base camp, is serendipitous but not unique. Use of a chalked steel tape, rather than an electric tape, should be considered to avoid entanglement during hydraulic head measurements in standard diameter (e.g., 4-inch nominal) domestic wells.

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