Teaching Environmental Geochemistry: An Authentic Inquiry Approach

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ABSTRACT

A field-based environmental geochemistry course was developed at Western Michigan University for undergraduate geosciences and environmental studies students to (1) improve student understanding of complex environmental systems, specifically targeting lake systems; (2) facilitate student development of professional-level, field- and laboratory-based skills for lake water and sediment analysis; and (3) strengthen student teamwork and communication skills. In this course, students designed and completed a study of water quality in a local kettle lake. The instructor used short "question of the day" exercises, brief lectures, and in-class exercises to familiarize students with analytical and field techniques relevant to the posed problem. At the end of the semester, students presented their work in a public poster session and written report submitted to a local community association. The course was assessed using student work, a preinstruction experience survey, a postinstruction course evaluation, a pre- and postinstruction knowledge test, and a series of interviews with select students. Analysis of the full suite of assessment data suggests that students developed a significantly improved understanding of lake systems and the process of eutrophication and perceived that the course improved their analytical and interpersonal skills. However, lower-performing students (i.e., those with a lower grade point average) and students with weaker backgrounds in geochemistry tended to provide less sophisticated test responses and showed less ability to transfer knowledge gained in the course to other environmental systems. Overall, students reported a strong sense of satisfaction with the authentic inquiry and community-oriented nature of the course. Compared to students in the first year of the course, students in the second offering appeared to be somewhat less excited and engaged, which may reflect a perceived lack of novelty and new discovery about the field site and study question. Thus, to insure continued high levels of engagement of students in subsequent years, we recommend periodically shifting either the field site or the central research question addressed by the class. *© 2012 National Association of Geoscience Teachers*. [DOI: 10.5408/11-273.1]

Key words: eutrophication, teaching biogeochemistry, biogeochemical cycles, limnology, authentic inquiry

INTRODUCTION

According to the U.S. Bureau of Labor Statistics (2011), geosciences and hydrology employment opportunities will continue to expand at a faster rate than average for all occupations. Furthermore, geoscientists "must be inquisitive, able to think logically, and capable of complex analytical thinking, including spatial visualization, and the ability to infer conclusions from sparse data" (Bureau of Labor Statistics, 2011, "Other qualifications," para. 3). To prepare for these career opportunities, students need practical experience in designing field data collection and analysis protocols for complex, spatially and temporally heterogeneous environmental systems. However, traditional geochemistry courses that rely primarily on lectures and problem sets frequently employ decontextualized descriptions of data collection and analytical methods. Laboratory-based courses focused on analytical techniques do not typically consider the nuances involved in designing and carrying out field-based scientific investigations. Many students find the "cookbook" approach used in traditional, laboratory-based courses boring and disconnected from the natural world (e.g., Osborne and Collins, 2001).

In addition to gaining practical field and laboratory experience, students must learn to effectively communicate scientific results to peers and to the public to be adequately prepared for geoscience careers. According to the Bureau of Labor Statistics (2011), geoscientists entering the workforce need to be prepared to work in teams and must have excellent oral and written communication skills. Unfortunately, traditional undergraduate course work provides few opportunities for students to conduct authentic environmental field research or to communicate the findings of scientific investigations.

Developing a sophisticated understanding of complex, integrated environmental systems is also essential for students who will eventually work in geoscience careers that involve a plethora of societal issues (e.g., water resources, energy resources, air pollution, and climate change). We found little information in the literature regarding undergraduate student conceptions of complex environmental systems. Herbert (2006) suggests that students struggle to accurately and holistically conceptualize Earth systems because they lack three fundamental requisites necessary for understanding these systems: (1) accurate conceptualizations of processes that manipulate matter and energy transformations within systems and across system boundaries, (2) the ability to characterize the state of a system (variables that encompass the system) over space and time in both equilibrium and dynamic conditions, and (3)

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the competency to apply conceptual models to support problem solving. Sell et al. (2006) have investigated the development of student conceptual models of complex Earth processes, including coastal eutrophication, as a result of model-based inquiry instruction. Sell and colleagues suggest that inaccurate and incomplete conceptions of eutrophication persisted among students despite inquiry-based instruction (Sell et al., 2006; McNeal et al., 2008). Similarly, Hogan (2000) demonstrated that naïve conceptions, for example, that all pollutants kill aquatic species on contact, persisted among upper-level elementary students despite a monthlong ecosystems unit taught with hands-on materials. However, students in these classes did not visit field sites, nor did they collect their own field data.

We designed an environmental field geochemistry course for upper-level undergraduate students majoring in geosciences (GEOS) or environmental studies (ENVS) to help students (1) strengthen their understanding of complex environmental systems, specifically of lake systems and eutrophication; (2) develop professional-level skills in field investigations and laboratory analyses of lake water and sediment samples; and (3) improve communication skills. This problem-based, community-oriented course focused on assessment of water quality in a local urban lake. Students designed and implemented a field and laboratory study and disseminated their findings to the public via a written report and a poster session held at a local brewpub. The course was evaluated using data sources that included student work, a pre- and postinstruction knowledge test, a postinstruction course evaluation, and a series of interviews with select students enrolled in the course. We hypothesized that the community-oriented nature of the course would provide a significant incentive for students to produce high-quality "products" and to become more invested in the design and implementation of the authentic water quality assessment.

In the initial course offerings, we focused on a specific environmental problem: eutrophication of a local lake. Eutrophication, a widespread phenomenon in the U.S. and elsewhere, occurs when aquatic systems are impacted by excessive inputs of nutrients, typically phosphorus and nitrogen, resulting in the growth of large algal blooms and degradation of water quality (e.g., Wetzel, 2001). Understanding the causes, effects, and potential remediation options for eutrophic systems requires students to master complex ideas encompassing biological, chemical, and physical processes, including biogeochemical cycles and human impacts on integrated Earth systems. Prior work demonstrates that students often find the process of eutrophication conceptually challenging because it involves complex Earth systems (e.g., McNeal et al., 2008).

CONTEXT: COURSE DESIGN AND RATIONALE

The course was created using a "backward design" approach (Table I; Wiggins and McTighe, 2006). First, we identified three overall course goals and, within each of these, more specific objectives delineating the knowledge and skills we expected students to gain. We then designed course assessments to determine whether students met the learning objectives. Finally, we developed the day-to-day course instruction so that individual assignments, lectures, and in-class work would be aligned with course goals.

We chose to center the course on an authentic, local, field-based problem and to incorporate an element of service learning. The course was designed to have students complete an inquiry-based task intended to capture many subtleties of authentic scientific research: selecting variables to test, planning data collection procedures and analyses, assessing data quality, dealing with unexpected results, postulating mechanisms to explain data, representing data in multiple ways, and communicating results to stakeholders (NRC, 1996; Chinn and Malhotra, 2002). Although the instructor provided the research question ("Is Woods Lake eutrophic?") to guide the inquiry, students were responsible for the design, data collection, analysis, interpretation, and reporting of their investigations.

It is widely recognized that undergraduate research experiences, including those embedded within undergraduate courses, are beneficial to students (Seymour et al., 2004). Authentic student research experiences lead to both student-reported and empirically observed gains in interest in science, career preparation, basic research skills, and understanding of the research process (Fitzsimmons et al., 1990; Alexander et al., 1996, 1998; Foertsch et al., 1997; Seymour et al., 2004). Additional studies report gains in interpersonal skills, including teamwork and communication (Gates et al., 1998; Mabrouk and Peters, 2000; Seymour et al., 2004). Several papers published in the past decade describe field- and inquiry-based investigations of environmental problems in geoscience courses, mostly focused on study of local surface water and groundwater (e.g., Woltemade and Blewett, 2002; Lev, 2004; Rodbell and Gremillion, 2005; Graney et al., 2008; Pearce et al., 2010). Rodbell and Gremillion (2005) describe a limnology/paleolimnology course in which students propose interdisciplinary research projects, design and carry out sampling plans, analyze data, read relevant literature, and report results of their investigations to their classmates. Although comparable in some aspects, in our course students work on a single research problem as a class. Furthermore, our course is community oriented, with students reporting their water quality results to members of the local watershed community. We anticipated that many of these reported gains would result from the authentic research framework developed for our course.

Service to the community as part of a class (service learning), in which the intellectual world of the classroom is clearly connected to the more practical "real" world, has been linked to both self-reported and empirically observed gains in students' personal development, interpersonal skills, civic engagement, and satisfaction with college (e.g., Eyler and Giles, 1999; Astin et al., 2000; Gray et al., 2000). Perhaps more importantly, service learning is reported to increase student engagement in the learning process and to motivate students to learn (Gray et al., 2000). The community-oriented approach employed in our course incorporates some elements of service learning, such as engaging students in a problem of local community concern and reporting results of the study to community stakeholders, and is similar to approaches reported in other capstone environmental science courses (e.g., Harbor, 2000; Liu et al., 2004). In contrast to these studies, our students carried out a field investigation as a class rather than as individuals or in small groups, our students presented results to the local community, and our content focus is geochemistry rather

TABLE I: Alignment between general course goals, specific objectives within each of these goals that describe what students should know or be able to do by the end of the course, course activities designed to meet the goals and objectives, and methods for assessing whether goals and objectives have been met.

<table>
<tr><th>Course Goals</th><th>Objectives
(Students Will Be Able To…)</th><th>Key Course Activities</th><th>Key Assessments
(of Learning)[1]</th></tr>
<tr><td rowspan="3">(1) Develop an understanding of complex environmental systems, specifically lake systems and eutrophication</td><td>(a) Describe spatial and temporal heterogeneity in lakes</td><td rowspan="3">- Fieldwork
- Analytical work
- QOD
- Minilectures
- Readings
- Homework
- Written interim and final reports</td><td rowspan="3">- Pre-/post geochemistry knowledge test
- Student interviews
- Individual and group QOD responses
- Written interim and final reports
- Graded homework
- Final exam</td></tr>
<tr><td>(b) Describe biogeochemical cycles in lakes (e.g., oxygen, nitrogen, phosphorus)</td></tr>
<tr><td>(c) Describe anthropogenic eutrophication in lake systems</td></tr>
<tr><td rowspan="4">(2) Develop an understanding of and skills in conducting professional-level field investigations and laboratory analyses of lake water and sediment samples</td><td>(a) Describe how modern surface water analytical data are collected and analyzed; recognize strengths and limitations of techniques</td><td>- Fieldwork
- Analytical work
- QOD
- Minilectures
- Homework</td><td>- Pre-/postgeochemistry knowledge test
- Individual and group QOD responses
- Graded homework
- Final exam</td></tr>
<tr><td>(b) Design and execute a field sampling strategy using appropriate instruments and techniques</td><td rowspan="3">- Written, presented, and conducted group research plan for water quality assessment of Woods Lake (field sampling and laboratory analysis)</td><td>- Graded homework</td></tr>
<tr><td rowspan="2">(c) Conduct analytical laboratory work using appropriate instruments and techniques</td><td>- Midterm group reports and class presentations of data collection and analysis</td></tr>
<tr><td>- Group posters and final written report</td></tr>
<tr><td rowspan="3">(3) Develop skills in teamwork and effective communication with peers and the public</td><td>(a) Work efficiently in teams</td><td>- Required group work throughout class</td><td>- Group grade on reports and poster</td></tr>
<tr><td rowspan="2">(b) Convey results to the public in both written and oral formats</td><td rowspan="2">- Final class public presentation and written report of research results</td><td>- Poster and community presentation</td></tr>
<tr><td>- Final class written report</td></tr>
</table>

[1]Italicized entries were used as data sources for research and course evaluation and were not part of graded student work. Remaining entries were typical, graded student work in the course.

than geophysics, geotechnical work, or engineering. We anticipated that students would self-report increased interest in the geosciences as a career, increased confidence in real-world problem solving, improved communication skills, and an enhanced sense of connection to the local community as a result of participation in this course, in agreement with findings of prior studies.

METHODS OF INSTRUCTION

Student Population

To date, the course has been taught twice (fall 2009 and fall 2010), both times offered as an upper-division elective to fulfill program requirements for undergraduate students majoring in GEOS or ENVS. ENVS students at Western Michigan University (WMU) are an academically diverse group. All ENVS students are required to have a second major; thus, many ENVS majors with a coordinate major in humanities and social sciences have only completed basic general education science courses prior to enrollment in our course. In contrast, GEOS students majoring in geology and geochemistry have the strongest math and science content preparation.

On the first day of class, demographic information and educational background of the students was collected via an experience questionnaire. Questions were designed to assess prior experiences of the students in (1) college-level science, technology, engineering, and math (STEM) course work; (2) field or laboratory work; and (3) collecting data, making public presentations, or both in other courses (Table II).

Field Site and Equipment

Woods Lake is an urban kettle lake with a maximum depth of ~14 m, a mean depth of ~8.2 m, and a surface area of 9.7 hectares (Koretsky et al., 2012). It is surrounded primarily by residential areas, together with two small city parks, and is accessible by boat via a sandy, manmade beach on the north side and a small dock located on the south side of the lake. There are no natural surface water inflows or outflows; however, five storm water sewers have channeled runoff into the lake since the 1960s. Kieser and Associates (1997) demonstrated that Woods Lake is eutrophic, primarily due to phosphorus loading from these storm water sewers. Water from the two sewers believed responsible for the greatest phosphorus loading was rerouted in 2002 and now flows through a retention pond and constructed

TABLE II: Self-reported demographic data from consenting students.

	2009 Class ($N = 16$)[1]	2009 Interview Subjects ($N = 4$)	2010 Class ($N = 13$)[2]	2010 Interview Subjects ($N = 4$)
Gender				
Male	11	3	7	2
Female	5	1	6	2
Age				
Range (y)	21–45	21–22	21–43	21–24
Mean (y)	24.1	21.7	23.6	22.5
GPA (on 4.0 scale)				
Range	2.70–3.93	2.95–3.93	2.60–3.92	2.90–3.50
Mean	3.36	3.44	3.27	3.23
Major				
Geology[3]	7	2	2	1
Geochemistry[3]	2	1	3	0
ENVS/STEM[4]	2	0	4	1
ENVS/social science[5]	3	0	5	2
ENVS/humanities[6]	2	1	0	0
Prior Experience				
Original field research	2	1	0	0
Original lab research	3	1	1	0
Collected data for a course	10	3	5	1
Gave external presentation	7	3	5	0
Postgraduation plans[7]				
Graduate school—geoscience	4	2	3	1
Graduate school—other	7	1	4	1
Job—geoscience or environmental job	6	1	6	2
Job—other	7	1	1	1

[1]In 2009, all 16 students enrolled in the course consented to participate in data collection.
[2]In 2010, 13 of 15 students enrolled in the course consented to participate in data collection. Thus, data are reported only for the students who gave consent to participate.
[3]Includes double majors.
[4]Includes biology and Earth science as the second major.
[5]Includes geography, psychology, and economics as the second major.
[6]Includes Spanish as the second major.
[7]Responses could fall into multiple categories (i.e., some students indicated plans to attend graduate school and obtain a job).

wetland before discharging into the lake. Subsequent work completed at Woods Lake (Koretsky et al., 2012) demonstrates that there is also substantial sodium and chloride accumulation in the lake, presumably related to road-salt runoff from the residential areas surrounding the lake.

Available field equipment included two canoes; a vertical point water column sampler (Aquatic Research Instruments); Secchi disks; portable dissolved oxygen, temperature and pH probes; a Russian peat corer (Aquatic Research Instruments); a small benthic grab sampler; and a dip water sampler.

Analytical Facilities and Equipment

Laboratory equipment included four ultraviolet/visible light (UV/Vis) spectrophotometers, two pH meters, a centrifuge, a water purification system, a heating oven, a muffle furnace, an electronic balance, a Rigaku X-ray diffractometer, an OI Analytical total organic carbon/total inorganic carbon analyzer, and a Dionex ion chromatograph. The facility also contained analytical grade glassware, plasticware, digital pipettors, and other general aqueous geochemistry laboratory accessories. Students were allowed to analyze a limited quantity of samples for major or trace elements on a Perkin Elmer inductively coupled plasma–optical emission spectrometer in a WMU research facility.

Course Structure and Instructional Methods

The class met for 3 h once per week for 14 weeks (fall semester) and was taught by the first author in both 2009 and 2010. Students were graded based on a combination of homework assignments (20%), in class assignments (10%), an initial written report and in class oral presentation (25%), a final written report and public poster presentation (25%), and a written final exam (20%). The course was designed to become progressively more student driven as the semester

TABLE III: Weekly class activities, Question(s) of the Day, and homework assignments. In fall 2010 (second offering), students were also required to work a full day in the lab or the field on a Saturday or Sunday in weeks seven and ten.

Week	In Class Activities	QOD(s)	Homework Assignment(s)
1	- Course introduction - Tour analytical laboratory and introduce equipment - Lab and field safety information	- What is eutrophication? - How do you know if a lake is eutrophic? - What types of measurements might you make to determine whether Woods Lake is eutrophic?	- Reading and questions: Eutrophication processes
2	- Hands-on tasks with lab equipment - Running Fe(II) and Mn(II) calibrations with UV/Vis	- How do you know whether analytical data are of high quality?	- Reading and questions: Basic analytical chemistry
3	- Running NH_3, PO_4^{-3}, and alkalinity on UV/Vis - Visit field site	- Do samples change when they are removed from a water body for analysis? If so, how? - Will in situ and ex situ measurements differ? If so, can this be prevented or accounted for?	- Prepare initial sampling and analysis strategies
4	- Analyze peepers	- Does the temperature in a lake change with depth? Does it change with season? Draw a diagram(s) to illustrate your answer.	- Prepare peeper presentations
5	- Peeper presentations - Discussion of sampling and analysis plan	- None	- Reading and questions: Box models - Prepare final sampling and analysis strategy
6-10	- Independent group work on sampling and analysis	- *Week 7:* Draw graphs to show how the concentration of dissolved oxygen changes as a function of depth in an eutrophic lake during fall, winter, spring, and summer. Do the same for an oligotrophic lake. - *Week 8:* Draw profiles of total dissolved phosphorus as a function of depth in a eutrophic lake during fall, winter, spring, and summer. Do the same for an oligotrophic lake. - *Week 10:* Using a simple box model, show the different chemical forms of nitrogen found in lake ecosystems and the processes that convert one form of nitrogen to another.	- Readings and questions: Organic carbon, dissolved oxygen, phosphorus, inorganic carbon, and nitrogen species and cycling
11	- Discussion of analytical results - Prepare posters	- Draw depth profiles of temperature, dissolved oxygen, dissolved phosphorus, and dissolved ammonia for a eutrophic lake in fall, winter, spring, and summer.	- Reading and questions: Remediation of eutrophic lakes
12	- Finalize data analysis - Finalize posters	- Can a eutrophic lake be remediated? - What are the costs/benefits of eutrophication remediation and/or prevention strategies?	- Prepare final posters and written report
13	- Final exam		- Finalize written report
14	- Public poster session		

progressed (Table III; course syllabi available in supplementary materials, which are available at: http://dx.doi.org/10.5408/11-273s1.).

During class, "questions of the day" (QODs, Table III) and very short lectures ($\leq$15 min) were used to stimulate thinking and convey basic content information regarding lake systems and water quality issues. Many of the lectures and QODs focused on temporal heterogeneity in lake systems (e.g., seasonal changes in the depth profiles of temperature, dissolved oxygen, phosphorus, and ammonium in oligotrophic and eutrophic system), because these are a key aspect of lake systems that is not easily observed or measured in a single semester course. During the QOD, students first spent approximately 10 min writing out individual answers to the best of their ability (Fig. 1[A]), aware that grading was based on the quality of their

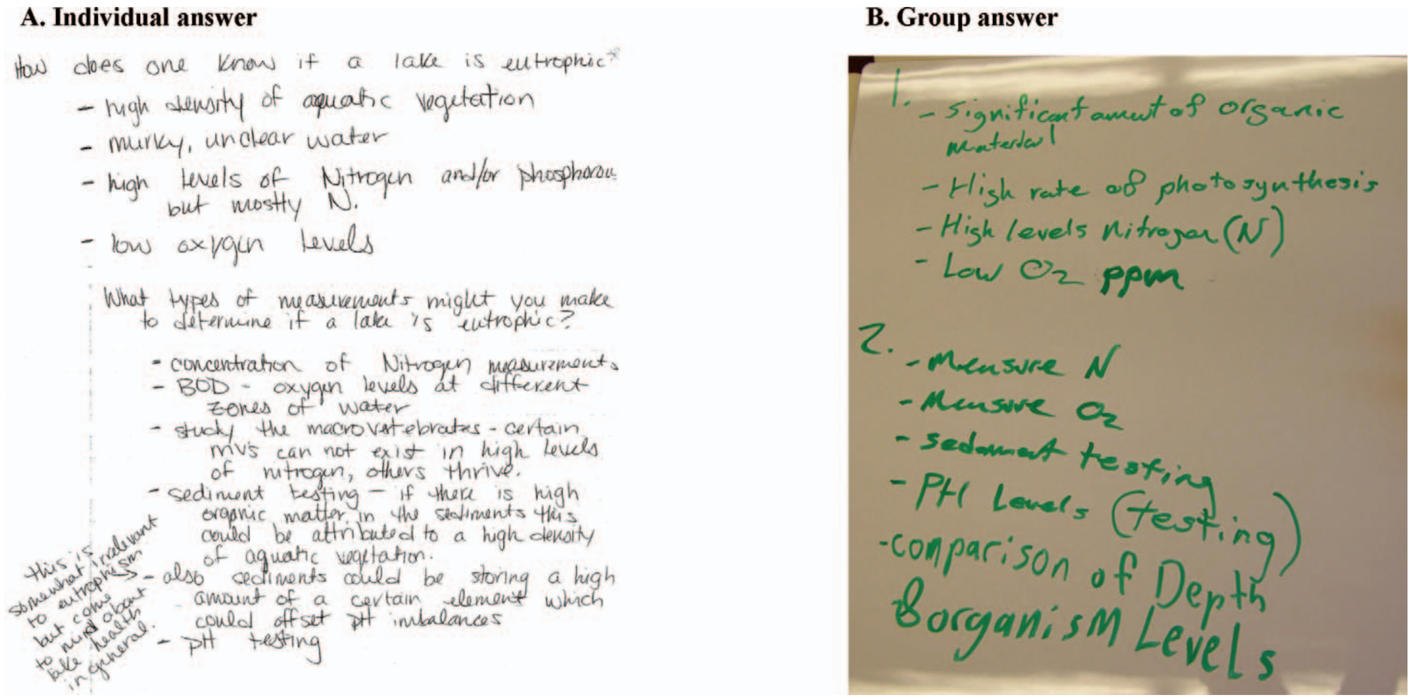


FIGURE 1: Example of (A) an individual and (B) a group answer to a "question of the day (QOD)."

reasoning as opposed to whether they achieved a "correct" answer. Next, groups of about four students spent 10 to 15 min discussing their individual responses and then illustrating their consensus answer on a whiteboard (Fig. 1[B]) and explaining it to the rest of the class. As each student group described their ideas, the instructor asked probing questions to understand the rationale behind the illustrations or answers without revealing "correct" answers. After this discussion, the instructor provided a brief lecture addressing the QODs and related content.

Homework assignments, mainly consisting of supplemental reading and questions about the readings, were used primarily to convey additional content knowledge, because in-class time was devoted to working on the water quality investigation (Table III). These readings covered basic concepts regarding eutrophication (eutrophic versus oligotrophic lake systems), basic analytical chemistry (dilutions, standards, and quality controls), field-sampling methods, redox stratified systems, box models, biogeochemical cycles (carbon, phosphorus, nitrogen, and sulfur), and remediation and pollution prevention strategies for eutrophic lakes. Directed in-class exercises near the beginning of the semester were used to teach basic laboratory safety and analytical skills and to introduce students to the field setting. Midterm class presentations and written reports were used to give students feedback regarding their initial conceptualizations of the field system and their field data collection and analysis plans. These were also intended to give students practice and feedback regarding formal oral and written presentation techniques.

Because many students in the course were not well versed in analytical chemistry or field geochemistry procedures, the course was structured to progressively teach these skills such that students became more independent over the semester (Table III). The course was organized as follows:

- Week 1: The instructor led demonstrations of equipment.
- Week 2: Students were divided into teams of three to five (in the first year, groups were instructor chosen such that each included a balance of strong and weak students; in the second year, groups were self-selected by the students). Student groups practiced using laboratory equipment.
- Week 3: Students completed a structured laboratory assignment (analyzing a set of calibration standards for dissolved Fe(II) or Mn(II); see supplementary materials). Students visited Woods Lake.
- Week 4: Students analyzed samples from a retention pond adjacent to the lake (see supplementary materials).
- Week 5: Each student team produced a written report and gave an oral presentation to the class, describing and interpreting their data from week 4.
- Week 6 to end of semester: All field and analytical work was student driven, with the instructor and teaching assistant offering assistance and answering questions as needed. Each student teams turn in a weekly report detailing all sampling completed to date and including descriptions of methodologies, results, and discussion/interpretation of data.
- Final week: Students turned in final posters and a final written report after a cycle of two to five drafts and revisions completed in prior weeks. Students decided how to complete the final written report, with each team taking responsibility for one or more report sections.

During the initial field trip to Woods Lake, the instructor informed students that complaints made by several neighborhood associations to the City of Kalamazoo about turbidity and algal blooms led to a study of lake water quality in 1997. In response to this report, a small constructed wetland and retention pond were built in 2002 with the goal of decreasing nutrient loading into the lake and improving the water quality. The instructor pointed out each of these features at the field site, described their intended purposes and provided handouts including a bathymetric map of the lake and a subset of the data collected in 1997. The instructor then posed the research questions guiding the students' work: is the lake currently eutrophic, and has water quality changed substantially since 1997?

To address these questions, students first developed an initial field-sampling strategy as an individual homework assignment (week 3). Each student produced a list of field parameters to measure, including planned spatial and temporal resolution of sampling, appropriate analytical techniques, and justifications for each choice. This assignment was graded, and instructor feedback was provided. In week 5, all students in the class collaboratively developed a consensus plan for sampling and analysis, with instructor feedback mainly in the form of suggestions regarding feasibility and logistics of the planned work. From week 6 onward, each group turned in a weekly report describing the group's completed measurements, interpretations of these data, and any modifications to the group's initial sampling plan. In year 1, the formal report of water quality completed by Kieser and Associates (1997) was provided to the students in week 6 of the course. A deliberate decision was made to provide the students with this report only after they had formulated their own sampling and analyses strategy to insure that they did not simply duplicate the measurements reported from 1997. In contrast, students in year 2 were able to access information from year 1 throughout the semester, because this information was already readily available on the Internet.

METHODS OF ASSESSMENT

A combination of data sources was used to assess student learning in the course, to evaluate whether the course met the stated goals, and to improve the course for future offerings (Table I). Student work (described in the previous section), a pre- and postinstruction knowledge test, and semistructured interviews with selected students were used to determine the extent to which students met learning objectives. A postcourse evaluation survey and interviews were used to determine the extent to which students perceived that the course was effective in developing their content knowledge, analytical skills, and interpersonal skills. All data were collected with informed consent of participating students, under an approved Human Subjects Institutional Review Board protocol.

Pre- and Postinstruction Knowledge Test

During the first offering of the course (2009), a 25-question multiple choice test was administered in class on the first and last days of the semester (see supplementary materials). Questions were based on the key concepts shown in Table I and were designed to assess students' basic understanding of analytical and field methodologies, limnology, biogeochemical cycles, and anthropogenic eutrophication. Items were mostly drawn from a final exam used in an entry-level environmental systems class taught by the first author and another instructor. Questions were predominantly at the knowledge/understanding level of the modified Bloom's taxonomy (Anderson and Krathwohl, 2001), requiring mainly recall of vocabulary and understanding of basic geochemical concepts. Items were reviewed for content, wording, and face validity by five external experts, including three geochemists and two experts in test design and geoscience education research. The test was also reviewed with interview subjects during their first interview to determine whether any of the items or response options required clarification. Test items were scored +1 for a correct response, −1 for an incorrect response, and 0 for an "I don't know" response, resulting in a maximum score range of +25 to −25.

The knowledge test was substantially revised for the second course offering (2010) to create a more conceptually, and less factually, oriented test. Version 2 of the knowledge test was modeled after development of the Geoscience Concept Inventory (Libarkin and Anderson, 2006, 2007). Alternative conceptions evident in the course work, QOD responses, and interviews from the 2009 offering of the course formed the basis for incorrect response options. Questions were then checked for good alignment with course objectives, reviewed by the same five external experts as in the previous year, and clarified with students during interviews. Test items were scored using the same +1, 0, −1 system as in 2009, resulting in a maximum score range of +26 to −26.

Postinstruction Course Evaluation

A survey was administered on the last day of class in both years and included a combination of five-point Likert and open-ended questions designed to gather student perceptions regarding efficacy of the course design and instructional methods. Because formative course evaluation was the primary purpose of this survey, it was not externally validated. However, questions were clarified with student interviewees.

Semistructured Interviews

In each year, four students were selected from among consenting volunteers to participate in a series of interviews designed to more deeply probe student thinking related to the course content. Interviewees were selected to represent the prior experience, age, and gender distribution of the class, as obtained from the student experience questionnaire (Table II). Selected students participated in four or five 30- to 50-min audio-recorded interviews. Interviews were semistructured, with questions drawn from QODs and student work. Interviews were retrospective; that is, students were asked to reflect back on their individual and group QOD work and to further explain their thinking on each subject. They were also asked whether their ideas had evolved in the time since the content was covered in the course. In the final interview, students also provided general feedback on the course.

Interviews were transcribed and coded using emergent techniques (e.g., Patton, 2002), and all coded interviews were checked by all three authors and discussed until full agreement was reached. Codes naturally fell into larger themes that were closely aligned with course content goals and revealed student ideas related to the process of eutrophication, biogeochemical cycling, and spatial/temporal heterogeneity in lake systems.

RESULTS

Student Investigation of Water Quality in Woods Lake

In 2009, students collected and analyzed water column samples at ~1-m intervals at five sites in the lake (forming an "X" transect). They also collected surface water samples at three storm water inlets, including during a significant rain event; pore waters from the retention pond; and peat core samples from the retention pond and several other sites around the lake. In 2010, students mostly concentrated on a site in the deepest part of the lake, sampling it on three occasions. The data collected by the students clearly demonstrates that the deepest part of the lake water column is anoxic, with no detectable oxygen at depths below 9.5 m, as late as mid-November (e.g., Fig. 2). At depths below 8 m, dissolved oxygen levels dropped dramatically, pH decreased, and the concentrations of dissolved iron, manganese, ammonium, and sulfate all pointed to significant degradation of organic matter via anaerobic pathways and to persistent eutrophic conditions in the lake. Furthermore, conductivity and chloride increased with depth to levels that exceeded the chronic toxicity threshold for freshwater aquatic organisms. Data from the retention pond also demonstrated very high levels of chloride, consistent with significant runoff and retention of chloride from road-salt deicers in the surrounding watershed.

Students in both years were successful at collecting high-quality analytical data, from which they concluded that eutrophic conditions persist at Woods Lake. In 2009, the students came to the unexpected finding that the lake might have become monomictic (once per year mixing) or even meromictic (persistently chemically stratified) due to high loadings of road salt. Students in 2010 followed up on this finding, comparing their data to that collected in the previous year; they concluded that the lake water chemistry was substantially similar in fall 2009 and 2010. Students in both years recommended reduction of phosphate use in the watershed (detergents and especially fertilizers), proper disposal of leaves and lawn clippings, and reduction of suspended solid input into the lake to help slow eutrophication. However, they noted that such changes would have little impact on road salt–related changes to the lake chemistry and biology and that there seem to be few options for remediation of salinized lakes.

Student Work: Final Exam, Written and Oral Presentations

The same written final examination was given during both 2009 and 2010. Final exam scores were lower in 2010 as compared to 2009 (2009: median 95%, average 88%; 2010: median 82%, average 81%). The exam consisted of 20 multiple-choice questions and four open-ended discussion questions. Students mostly performed well on an open-ended discussion question concerning eutrophication, providing complex and generally well-reasoned answers. Most students listed multiple indicators of eutrophication (e.g., phosphorus and nitrogen concentrations, algal blooms, turbidity, low dissolved oxygen, and high biological oxygen demand), but some students tended to focus on just one or two indicators (e.g., phosphorus concentration or presence of algal blooms) or on parameters that are not generally indicators of eutrophication (e.g., pH or conductivity). Most students were able to draw qualitatively correct depth profiles for most parameters; students tended to struggle most with dissolved oxygen profiles in oligotrophic lakes and with ammonium profiles in both eutrophic and oligotrophic systems.

Another open-ended discussion question asked students to interpret real pore water data from a different field site. To correctly answer this question, students needed to demonstrate a high level understanding of the relationships among anoxia, accumulation of reduced solutes in aqueous solutions, Fe(III) oxyhydroxide reductive dissolution, ammonification, and pH. Although many students produced remarkably thorough and correct answers to this question, some struggled. Common difficulties included confusing the redox chemistry of Fe(III) and Fe(II) and understanding the primary controls on pH.

A final open-ended discussion question was intended to assess whether students could use the knowledge gained in this course to develop a reasonable sampling strategy for another site with a different environmental problem. Students were asked to make a prioritized list of measurements, including when, where, and how many samples would be taken to determine the effects of atmospheric trace element deposition on lake and sediment chemistry in an urban lake located downwind of a coal-fired power plant. Most students produced a reasonable list of parameters, with solid plans for assessing spatial variability. Students, especially in 2010, struggled more to justify their choice of parameters. In both years, lower-performing students and those with weaker backgrounds in geochemistry tended to focus on the same parameters that they had measured in class to assess lake eutrophication. In contrast, higher-performing students and students with strong geochemistry backgrounds tended to include more "problem-specific" parameters, such as heavy metal and mercury content in lake waters, sediments, and fish tissue, in their sampling plans.

Preliminary written and oral reports (week 5) suggested that redox chemistry was a common source of misconceptions. Many students also had trouble understanding detection limits and uncertainty (e.g., reporting negative concentrations). Other difficulties included preparation of professional-quality graphics (e.g., color schemes, font sizes, and choice of axes). Substantial feedback from the instructor was provided regarding all of these issues so that students could improve their understanding of concepts and produce a more polished final product.

In both years, the students produced a coauthored final report, which was distributed to leaders of the Woods Lake Association with the executive summary posted on a local neighborhood association Web site. In 2009, each group (four teams total) chose to tackle specific sections of the report (introduction, field site, methodology, results/discussion, and conclusions/suggestions), with each group contributing to one subsection of the results/discussion section. Contributions to the subsections were based on the written reports that each group submitted weekly beginning in week 6. In 2010, each group (four teams) produced a separate report; these were bundled by the course instructor into a single report. In both years, the final poster presentation was held at a local brewpub; local community groups, including neighborhood associations, environmental groups, and members of the academic community, were invited to

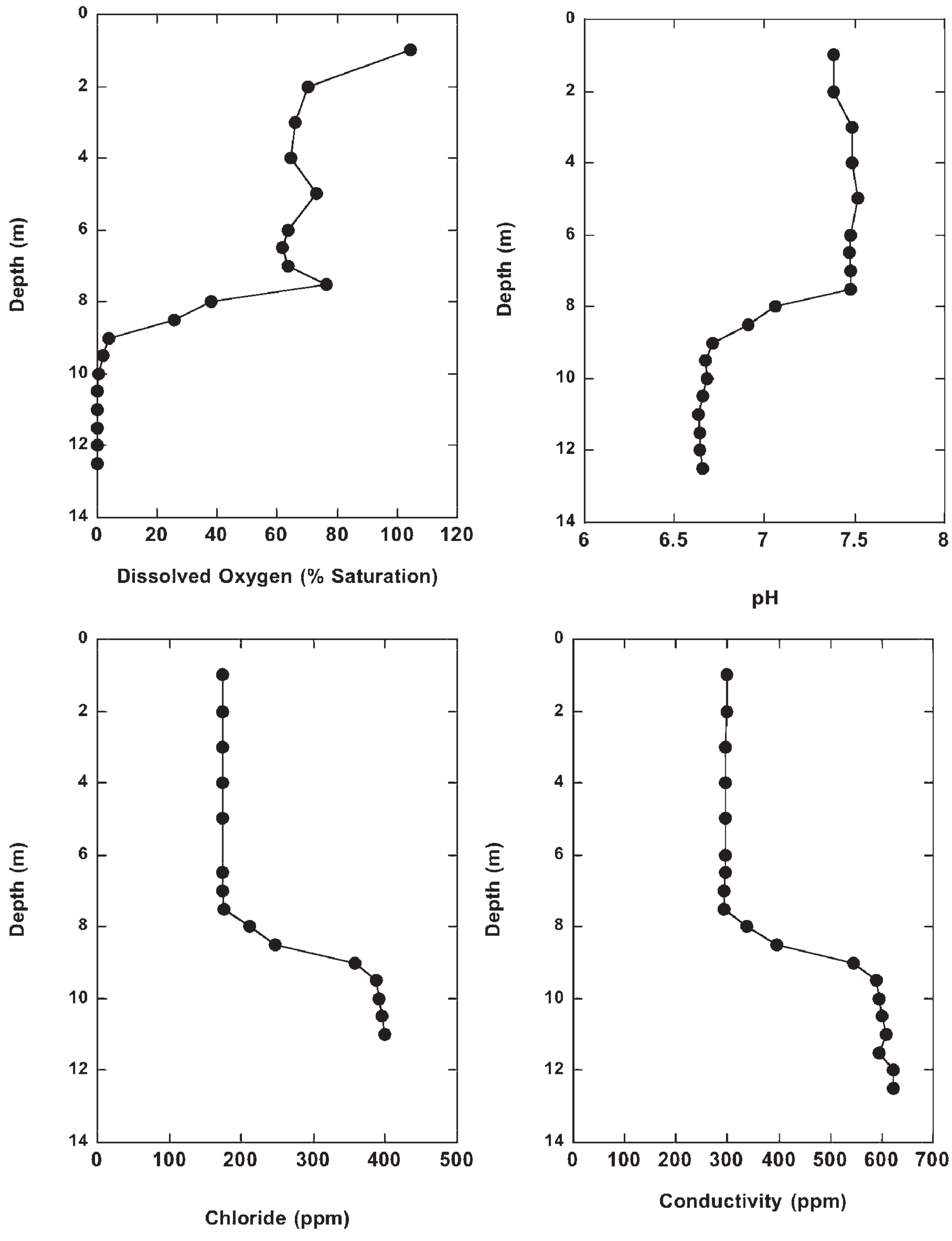
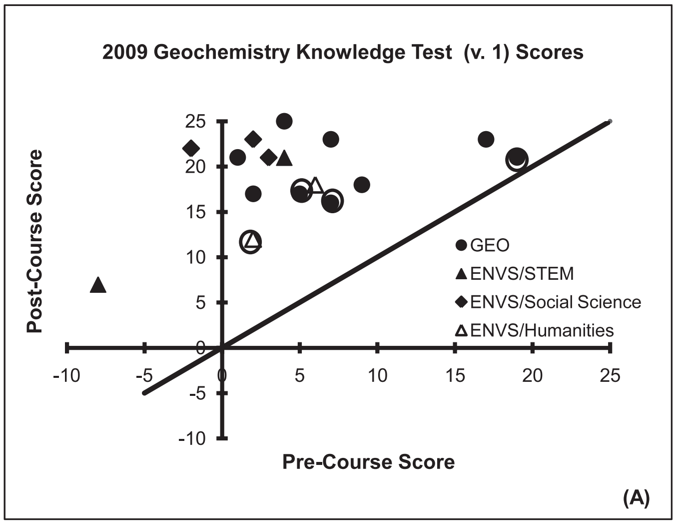


FIGURE 2: Selected results of student investigation of Woods Lake water chemistry. These data were collected November 21, 2009, and demonstrate that the lake remains unmixed and anoxic at depths below ~9 m even in late fall. High levels of conductivity and chloride are likely the result of road-salt inputs.

attend. Students spent approximately 3 h engaged in discussions with the public, with their results displayed on four large posters. Examples of draft and final posters are provided in supplementary materials.

Environmental Geochemistry Knowledge: Knowledge Test and Interview Results

Mean preinstruction scores on the geochemistry knowledge test were 4.88 out of a possible range of −25



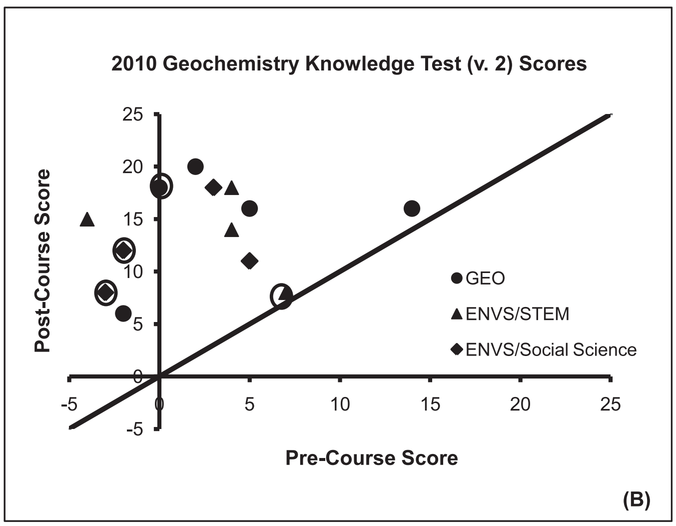


FIGURE 3: Results of the pre- and postinstruction geochemistry knowledge test for (A) 2009 and (B) 2010. Open circles indicate interview subjects.

to 25 (SD = 6.49) for the 2009 version, and 2.54 out of a possible range of −26 to 26 (SD = 4.91) for the revised 2010 version (Fig. 3). Pretest scores varied widely for all groups of students, with GEOS students scoring highest in both 2009 and 2010. Preinstruction results demonstrate that students have higher levels of prior knowledge regarding mechanisms of eutrophication-related death, nutrient loading, and the lake turnover process, whereas they have lower levels of prior knowledge regarding factors regulating dissolved oxygen, phosphorus, and ammonia levels. All students scored higher on the postinstruction test compared to the preinstruction test in both years. Mean posttest scores were 19.1 (SD = 4.63) in 2009 and 13.8 (SD = 4.49) in 2010. A repeated measures paired *t*-test suggests that the pre- to postinstruction gains in both years are statistically significant ($p < 0.001$; data met assumptions of normal distribution). The largest pre- to postcourse knowledge gains occurred for questions related to definitions of terms (Secchi disk, epilimnion, hypolimnion, and dimictic) and for concepts regarding factors that influence dissolved oxygen levels, nitrogen conversion processes, and phosphorus binding and release from sediments.

Preliminary results of the interview analysis reveal that although many students initially appeared to use terminology related to eutrophication and lake systems appropriately, upon probing they were unable to further explain their responses. Overall, however, students gained a more sophisticated understanding of the process of eutrophication, as illustrated by the following interview excerpts:

Preinstruction

INTERVIEWER: *So, what is eutrophication? [In your QOD response,] you said, "It is when nutrient levels in a body of water promote accelerated aquatic plant growth." So let me first ask what does that mean, "nutrient levels"?*

STUDENT F10-01: *Like phosphorus or nitrogen levels, ... they're fertilizers for terrestrial plants. Aquatic plants are technically no different than terrestrial ones. So [it's] ... basically fertilizing the little plants and critters and stuff in the water.*

INTERVIEWER: *Then it says, "All those [little plants] grow, die and remove dissolved oxygen from the water." How do they [do that]?*

STUDENT F10-01: *...I know that when they die, it removes dissolved oxygen. I don't know [how] exactly, I just know that it does....*

Postinstruction

INTERVIEWER: *So what is eutrophication as a process?*

STUDENT F10-01: *Eutrophication basically is when limiting nutrients such as phosphorus or nitrogen are added unnaturally to a lake system—be it from fertilizers, from runoff, from storm drains—it gets in there somehow and it causes heavy algal growth or plant growth in the lake. And then when those algae die they sink to the bottom and they decompose. And the process of decomposition removes oxygen from the water. Where you have higher than normal algal growth, you have higher than normal death rate [and] you have higher than normal decomposition, so it removes all the oxygen from the bottom [of the water column] and creates these dead zones where nothing can live—no fish, no crappie, no mollusks, no nothing....*

In the postinstruction interview, the student is able to elaborate on his reasoning about processes leading to eutrophication. The student understands that increased phosphorus or nitrogen levels catalyze the eutrophication process because they are limiting nutrients in natural systems. The student also recognizes that the reduction in dissolved oxygen levels that results from the eutrophication process negatively affects aquatic heterotrophic organisms.

Student Perceptions of Course Efficacy: Post Course Evaluation and Interview Results

Written course evaluation data from all consenting students indicate that most of the students ($N = 10$ in 2009, $N = 9$ in 2010) felt that their prior course work had adequately prepared them for the course. A minority of students, all in the ENVS/social sciences or ENVS/humanities groups, ($N = 5$ in 2009; $N = 3$ in 2010) felt inadequately prepared. Students self-reported that as a result of this class they had gained a better understanding of biogeochemical cycles and of water quality laboratory analytical methods and felt better prepared for future careers. Most students ($N = 11$ in 2009, $N = 13$ in 2010) reported that the course improved their knowledge of water quality issues, provided relevant hands-on experience, and increased their interest in pursuing a career in environmental or geological sciences. In both the open-ended survey items and in the interviews, students reported that they particularly enjoyed spending time doing practical, hands-on research in the laboratory and especially in the field. They also enjoyed the challenge of collecting and analyzing their own data and working independently on a "real-world" problem. For example:

> *I like the field work, I like doing the stuff ourselves. I appreciated not having tests every two weeks. It was beneficial to see the trends yourself rather than just being told. (Student F09-08, interview #4)*

On 2009 postinstruction course evaluations many students commented that they felt rushed and needed more time for lecture, laboratory, and especially fieldwork. In particular, they reported needing more time to work out roles among group members for collecting and analyzing the field data. To address these concerns, two single-day weekend sampling trips were required in 2010. The addition of required weekend workdays in 2010 alleviated some time constraint problems experienced in 2009:

> *I think the work weekend was a really good idea.... We got all of our data, the two days we were able to complete a profile each day so it worked really well, helped make everything a lot easier, less rushed. (Student F10-01, Interview #5)*

Students also voiced concerns about the group work required in the course. They reported that the logistics of coordinating many schedules for group work, particularly outside of class time, was daunting. Some also noted that the logistics of getting group members to agree on data management (e.g., sample naming conventions and roles and responsibilities of group members) was a challenge. However, many students enjoyed the group work, reporting that it was necessary to complete their detailed field and laboratory analysis plans. Many students also found it helpful to share ideas with peers and believed it was useful training for work as an environmental professional:

> *I think [the group work] was a really good idea because in an environmental consulting firm I would imagine they're not just going to make you do it all by yourself.... They would make you a part of a team. And it adds a certain skill to be able to work together towards one goal.... I mean there was a lot of debate and stuff in the beginning trying to hash out the ideas, but I mean that happens everywhere. (Student F10-01, Interview #5)*

Because students in 2009 reported difficulty sharing all data among group members, in 2010, the instructor set up a class Google Docs site as a data repository. Some students used this successfully to share data, but other students struggled to use the site or simply did not attempt to do so.

The QOD and brief lecture format was novel for most students in the course. Many students reported that this format stimulated their curiosity about the course subject matter and helped them develop a conceptual understanding of the material. For example:

> *It [the class format] wasn't just straight-out-of-the-book details.... It was nice to be able to do some thinking on your own about it. It generally tends to increase your knowledge and interest in what's going on.... So I like the minilectures [and] the question of the day and the group work. One of the best ways generally to learn is to be wrong at first. (Student F09-08, interview #4)*

Finally, students reported that knowing that their results would be disseminated to the local community added a sense of responsibility and importance to their project. It also generated a feeling of connection to the community members who live near the lake. For example:

> *It gave us validation.... Instead of just writing up a report and getting graded on it and then it just gets recycled, ... it added more to [the class] to be able to say, "Okay this is an actual presentation versus just a group-think in front of the class [where] everybody [just] claps politely." ... I talked to this little old lady [from the community] for a little while.... I wanted to be able to explain to her as much as I could, to [say], "This is what we did and this is what we looked at, and unfortunately your lake is in deep trouble but there is hope." ... Yeah, it was cool talking to that little old lady, like a little grandma. (Student F10-01, interview #5)*

DISCUSSION AND IMPLICATIONS

Course evaluation and assessment data suggest that course goals were generally achieved. Students developed professional-level laboratory and field skills, as evidenced by their collection of high-quality data. Student teamwork and communication skills, both written and oral, were enhanced by participation in the course. A third goal was to improve GEOS and ENVS students' understanding of complex environmental systems, specifically concepts related to lake systems. Students in both years made significant gains in the geochemistry concept test (Fig. 3), even on the more conceptual 2010 version of the test. Probing during student interviews generally revealed that students, especially students with more STEM preparation prior to the course, made significant gains in their ability to explain biogeochemical cycling and temporal/spatial heterogeneity in lake ecosystems. Furthermore, a final exam question requiring students to consider a different complex system (a lake influenced by atmospheric deposition of heavy metals) demonstrated that many students, especially those with a strong STEM background, were able to transfer ideas regarding spatial and temporal heterogeneity, as well as connectivity among atmosphere–water–sediment–biota, to a different complex system. We found that students who struggled most on the final exam had taken fewer prior courses in STEM and tended to be lower-performing students.

Our analyses also suggest several "best practices" for other faculty who may wish to implement a similar course at their institution. The assessment data indicate that both the authentic inquiry and the community-oriented aspects of the course were critical to the success of the course. The authentic investigation of water quality in Woods Lake kept students curious and highly engaged in the work that they completed. Students in both years believed that the format of the class (QOD, minilecture, and water quality investigation) enabled them to develop their own knowledge and ideas, in turn helping them learn:

> *I like the format of the teaching and I like the idea that we kind of had to come up with stuff ourselves in terms of conclusions.... You can bounce stuff around off [the instructor], but having to figure it out yourself is pretty cool.... Doing stuff yourself is probably the best part, [because] you're not going to learn otherwise. Especially lab work; you're not going to learn if you don't screw up. (Student F09-02, interview #4)*

Results of the pre- or postinstruction geochemistry knowledge test and the final exam support these perceptions. In both years, students performed significantly better on the knowledge post-test than on the pretest and were able to demonstrate the ability to transfer knowledge of analytical methods to new environmental situations on the final exam. Analysis of the interview data also suggests that students developed more sophisticated conceptions of eutrophication and lake systems over the course. Furthermore, as reported elsewhere (e.g., Seymour et al., 2004), our students stated that the research experience improved their interpersonal skills and prepared them for future environmental careers.

Most students reported that the community-oriented aspect of the course left them with a strong sense of responsibility to "get the answer right" and produce a high-quality report for local community members. They felt that this was an essential aspect of the course and recognized that communicating research results is an important part of the scientific process. Some students even viewed the community poster presentation as the "reward" for the work they put into the course. For example:

> *[The class is] obviously designed to be very hands-on and introduce you into the world of research—doing your own research, not just reading about it. Part of that is presenting your findings to an audience, so without [that], you'd be losing a little bit some of the real-world research experience. (Student F10-04, interview #5)*

The element of service learning in our course provided additional motivation for students to engage in the learning process, as reported elsewhere (Gray et al., 2000).

One lesson learned from this course is that purposefully structuring student groups appears to be important for course success. In 2009, groups were assigned by the instructor and were shuffled periodically throughout the semester. This ensured that students with different backgrounds (ENVS versus GEOS) and high- and low-performing students participated in groups together. In 2010, students chose their own groups at the beginning of the semester, which resulted in less mixing of students with different backgrounds. This may have led to some of the issues regarding poorer overall performance in 2010. We recommend structuring groups deliberately to mix students of different backgrounds and abilities.

In the second offering of the course, students were generally aware of the findings from the previous year, which had been broadly disseminated and were posted online. Students were therefore asked to follow up on these findings, rather than answer the more "novel" research questions posted in the first year. We suspect that this led to a diminished level of engagement, as observed by the course instructor. However, another factor that may have contributed to lower achievement on posters and final exams in year 2 was likely the greater number of lower-performing students with a weaker background in STEM, compared to year 1 (nine geology/geochemistry majors in 2009, compared to three in 2010; Table II). We therefore recommend two changes to the course structure: (1) implementing a prerequisite of a minimum of one semester of college-level chemistry and (2) rotating the course field setting, primary research question, or both each year, if possible. If access to a second field site is not possible, we recommend significantly changing the focus of the central question, such as by having the students focus on a mass balance of nutrient or salt inputs into the lake or on groundwater monitoring, rather than surface water monitoring.

Many valuable aspects of this course can be readily adapted for use in a variety of courses. For example, public presentations regarding water quality in a local surface water or groundwater body could be given to local community organizations, environmental groups, or K–12 school groups. Eutrophic lakes are common and can be found in urban and rural communities throughout the U.S. Road-salt impacts are more limited to snowy regions, but other water quality issues, such as acid mine drainage or salinization of rivers due to irrigation withdrawals, are common in many regions. Such issues could easily be used as the focus of a course similar in general structure to the one described here.

Our course benefited tremendously from ready access to a well-equipped aqueous geochemistry laboratory and a range of field equipment. However, many aspects of the course could be completed with a more limited range of equipment and laboratory access. Portable field probes (dissolved oxygen, pH, conductivity, and pH and temperature) are available for relatively little cost, as is the vertical point sampler used to collect water column samples (Aquatic Research Instruments). Without boats, water samples could be collected from a bridge or dock or simply by using a dip sampler to collect surface water samples around the perimeter of a lake, along or across streams or rivers, or at lake outlets and inlets. Without access to a fully equipped geochemistry lab, many analyses could be completed with readymade colorimetric kits (e.g., Hach Company) at relatively low cost. Without the ability to use peepers, sediments could be collected from accessible marshy or sandy areas using simple and inexpensive PVC tubes, extruded, sliced, and centrifuged to obtain pore water samples for analyses.

CONCLUSIONS

Our course is unique in the geoscience education literature in that it focuses on lake water geochemistry and incorporates authentic inquiry, in addition to being community oriented. Our students were responsible for designing, carrying out, and reporting all parts of their investigation to the local watershed community in both a written report and a public poster session. Authentic inquiry has already been linked to content gains, increased interest in science careers, and better understanding of the scientific process. We conclude that the service-learning aspect of our course provided a significant incentive for students to produce a high-quality "product" and to become more invested in the outcome of their authentic scientific research. This combination of authentic inquiry and a community-oriented approach appears to play an important role in achieving the goals of the course.

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Supplemental Materials:

The following materials are available in a supplementary document: (1) course syllabi, (2) laboratory protocols for UV/Vis spectrophotometric tests, (3) a brief description of peepers, (4) the preinstruction experience survey, (5), the geochemistry knowledge test used in 2009 and the modified version used in 2010, (6) the postinstruction course evaluation questionnaire and (7) examples of student posters. Available at http://dx.doi.org/10.5408/11-273s1.