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Using an Applied Geophysical Imaging Course to Enhance Quantitative Reasoning and Problem-Solving Skills for Environmental Geography Students

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Quantitative reasoning and interdisciplinary skills are central to real-world environmental problem solving. Enhancing those skills for students in environmental programs will help them succeed as future environmental professionals. This paper describes an approach that uses an applied geophysical imaging course to enhance quantitative reasoning and interdisciplinary learning in an environmental geography program. To adapt the course to geography students, applied learning is emphasized through the high-impact educational practices (HEPs) of undergraduate research and service learning. Throughout the course, students learn the theories of, and utilize electrical resistivity (ER), ground penetrating radar (GPR), and electromagnetic (EM) induction methods to answer real-life environmental questions in the local community. Course evaluations indicate that the course produced positive learning outcomes consistent with the course objectives. Similarly, students appreciate the unique opportunity to learn and utilize these technologies that are not commonly found within geography programs. The teaching strategies described in this paper can benefit other faculty contemplating curricular integration for interdisciplinary learning and quantitative reasoning outcomes.

Introduction

Environmental challenges are increasing in complexity (Rodela & Alašević, 2017; Vogel, Scott, Culwick, & Sutherland, 2016), driven by both anthropogenic and natural stressors (Abernethy, Maisels, & White, 2016; Princiotta & Loughlin, 2014). Addressing these challenges often requires professionals to invoke interdisciplinary perspectives (Cantor, DeLauer, Martin, & Rogan, 2015; Ewel, 2001; Simon et al., 2013). Similarly, environmental problem solving requires the ability to manipulate and interpret large sets of data, some of which cut across disciplinary boundaries. These tasks demand a great deal of quantitative reasoning skills. Thus, helping environmental science students to build interdisciplinary and quantitative reasoning skills will prepare them for success as future environmental professionals (Cantor et al., 2015; Fortuin, Van Koppen, & Leemans, 2011; Lopatto, 2003). This paper discusses a rare curriculum integration approach that leverages the concepts and techniques of environmental geophysics to enhance both interdisciplinary and quantitative reasoning skills for environmental geography students. This is rare in the sense that geophysics is not commonly found in the corridors of geography. In fact, ordinarily, not many geography students will be excited by the term geophysics owing to their limited exposure to physics and mathematics coursework. However, as demonstrated by this course offering, geophysical concepts and methods can offer unique learning opportunities to environmental geography students. First, geophysics is interdisciplinary in nature, combining the principles of physics, geology, mathematics, and computer simulation. When put to use, it gives students the opportunity to embrace interdisciplinary perspectives to real-world problem solving. Second, the mathematical principles behind geophysical methods can help students sharpen their quantitative reasoning skills as they apply concepts to real-life problems. Lastly, geophysics provides subsurface imaging tools for engaging students in experiential learning that leads to characterizing several real-world environmental problems. For example, geophysical methods such as electrical resistivity (ER), ground penetrating radar (GPR), and microgravity, can be deployed to detect areas of groundwater pollution, unexploded ordnance (UXO), sinkholes and caves on construction sites, as well as soil and water contamination from landfill leakages (Reynolds, 2011; Van Dam, 2012).

To deliver this course successfully, two High-Impact Educational Practices (HEPs), i.e., field-based and service learning, are emphasized. In the following section, a brief literature on the merits of HEPS is presented. The remainder of the paper presents the specific geophysical methods taught, example field investigations and targeted skills, as well as the student learning outcomes, and the conclusions reached.

High Impact Educational Practices (HEPS) and Student Learning

HEPs are a collection of teaching and learning strategies including undergraduate research, collaborative learning, internships, and service learning, among others that have been found to enhance student learning, persistence, and engagement (Kuh, 2008). It has been suggested that students who participate in at least two HEPs tend to earn higher grades and retain, integrate, and transfer information at higher rates (Kuh, 2008). In a related study, Kilgo, Ezell Sheets, and

Pascarella (2015) found the particular HEPs of active and collaborative learning, as well as undergraduate research, to have broad-reaching positive effects across multiple learning outcomes including critical thinking and metacognitive abilities. Further, there is evidence that students who are introduced to HEPs are better able to integrate ideas and apply same outside the classroom setting (Brownwell & Swaner, 2009). More specific to environmental problem solving, some researchers have observed that HEPs help students to develop the critical reasoning skills that enable them to understand better the complexities of real-world environmental problems (Whiley, Witt, Colvin, Arrue, & Kotir, 2017; Cantor, et al., 2015; Simon et al., 2013). In the geosciences particularly, a high premium is placed on field-based learning because it allows students to acquire multiple skills through data collection, processing, and interpretation (Mogk & Goodwin, 2012; Skop, 2008). From my personal experience, students show extra motivation and derive a sense of satisfaction when engaged in field learning that also helps them to solve a practical problem in their local community. Likewise, MacFall (2013) indicated that students engaged in environmental science service learning pedagogy reported long-term outcomes in commitment to civic engagement and environmental stewardship, as well as the ability to relate classroom principles to real-world issues. Field learning, integrated with service learning, can also help learners build interdisciplinary knowledge. For environmental studies, field learning often embeds a systems approach whereby learners must integrate information across different subsystems. Thus, Simon et al. (2013) advocate for environmental science education that integrates systems theory and service learning to better offer learners the breadth of knowledge that is required to synthesize ideas across disciplinary boundaries.

The range of useful skills that HEPs offer students can only be limited by the approach and depth of pedagogical implementation by individual faculty. For the course described here, another key target is to help students develop quantitative reasoning (QR) skills. QR, also referred to variably as quantitative literacy, fluency, or numeracy, has been identified as one of the must-have skills or competencies for all undergraduate students (AAC&U, 2010; Dingman & Madison, 2010; Jungck, 2012). It is at the heart of practical problem solving, especially in today's world where every sector, e.g., education, health, business, and government settings, is increasingly basing decision making on large quantitative datasets (Elrod, 2014). Several avenues exist for teaching QR to students, but one highly touted approach is the exposure of students to active learning situations with opportunities to integrate theory and practice. According to the Numeracy Infusion Course in Higher Education (NICHE), students often come to understand the relevance of quantitative reasoning skills when theory and data analysis are combined in an active learning setting (https://serc.carleton.edu/NICHE/best_practices.html). Pozo and Stull (2006) further note that contextualized use of data is central to teaching QR. The above ideas are leveraged to help students develop interdisciplinary and quantitative reasoning skills in the course described further.

Context to Course Offering

The course described is GEO 463 (Applied Geophysical Imaging), which is taught as part of the Geoenvironmental Studies curriculum at Shippensburg University (SU) of Pennsylvania. SU services a student population of over 6000, drawn primarily from rural Pennsylvania and neighboring states. The university strongly encourages its faculty to utilize high-impact instructional strategies that maximize students' life-long learning skills. For the Geoenvironmental Studies program in particular, a natural, outdoor laboratory exists in the local karst geology that surrounds the university campus. Within a 5 km radius of campus, karst features especially sinkholes, and caves are commonplace. Very often, students witness the hazards posed by sinkholes, as manifested in the delay of construction projects on or near campus. In this context, it was considered ideal to integrate techniques of environmental geophysics into the existing Geoenvironmental Studies curriculum for enhancing students' research-based, as well as service-based, learning opportunities. Thus, a National Science Foundation grant (the NSF-CCLI) was sought and used to purchase a range of geophysical equipment that are used to educate students in an applied geophysics course. It is noteworthy that this course adaption is greatly facilitated by the core requirements of our Geo-Environmental Studies students to take at least two introductory physics, chemistry, and computer science classes, as well as three introductory mathematics courses including algebra and statistics. These offer them the basic computational skills to build upon.

Course Structure and Implementation

The structure and delivery of this course leverages the identified five principles of learning (Merrill, 2002), i.e., 1) learners are engaged in solving real-world problems, 2) existing knowledge is activated as a foundation for new knowledge, 3) new knowledge is demonstrated to the learner, 4) new knowledge is applied by the learner, and 5) new knowledge is integrated into the learner's world. All five principles are woven into the various parts of the course and implemented. Overwhelmingly, the course seeks to engage students in practical problem solving, be it in the classroom or in the field. Practically, the course is taught in two parts: classroom and outdoor field learning environments. To better provide for the field learning emphasis, the course is offered in the spring semester so that students spend the cold winter months of January – mid-March learning in the classroom and embark on outdoor learning during the warmer spring months. The course is capped at 15 students to maximize participatory learning experiences.

To be successful, students enrolling in the course are expected to have foundational knowledge of physics and algebra. Our students acquire these basic skills through core course requirements. Although foundational knowledge of calculus would be beneficial, it is not required as calculus is not a required course in our curriculum. The goal of this course is to help students build higher order quantitative reasoning skills through a combination of classroom and field-based learning modules.

The Classroom Learning Part

This primarily involves providing the theoretical concepts behind several geophysical methods. Further, students get an overview of the disciplinary connections of geophysics and learn important foundational mathematical principles while building critical quantitative reasoning skills. The overriding goal is to provide students with the foundational knowledge that is necessary to apply geophysical techniques to practical environmental problem solving.

Overall, the classroom learning part kicks off with a discussion of case studies. Because geophysics is not typical for the students in this course, and many may have physics and math phobia, it is considered better to provide some foundation knowledge, consistent with Merrill's learning theory 2, before exposure to the theoretical geophysics principles. Thus, we begin by examining case studies and videos that highlight the environmental problem-solving capabilities of geophysics. Particular attention is given to cases similar to local issues that the students are familiar with. In this way, not only is the intimidation of perceived course content lessened, but students gain a level of familiarity with geophysical methods prior to the introduction of the theoretical concepts. Moreover, I found that this approach generates students' interest and enthusiasm in the subject, possibly instilling the confidence that is needed for successful learning. From the learner's perspective, this approach is also consistent with the assertion by Khalil, Nelson, & Kibble (2010) that students who lack foundational knowledge should be given some relevant experience as a foundation for the new knowledge to come. Indeed, student feedback via course evaluations justify the approach as exemplified by these sample comments: (1) "I never imagined myself liking geophysics but now, I think I am in love with it but having those case studies/videos at the beginning really helped my focus"; and (2) "Geophysics proved to be manageable-thanks to the many case studies and videos. The lawn mower in the videos became GPR and I could relate and even felt more accomplished as I was personally using it to collect data."

Emphasizing the Interdisciplinary Nature of Geophysics. The complexity of environmental issues often challenges professionals to integrate knowledge across disciplinary boundaries. Thus, it is critical that students understand clearly the importance of interdisciplinary perspectives in resolving environmental problems. To help students appreciate this, class time is dedicated to highlighting the interdisciplinary nature of geophysics. It begins with a reflective assignment on the meaning of geophysics. Students are given Figure 1 to examine at home and reflect on the many disciplinary connections to geophysics. The figure is further discussed in class with reflections on some practical problems. For example, students are guided to reflect on how a practical environmental problem involving soil and water contamination may require the investigating scientist to acquire, analyze, and integrate soils, water, biological, and human health data in order to draw a remediation plan. Lastly, students are urged to keep this interdisciplinary image in focus throughout the course, especially as it evolves into practical field investigations.

Focusing on Quantitative Reasoning. Quantitative reasoning (QR) is critical to coping with geophysics and to solving most environmental problems. It entails the ability to reason critically and apply basic mathematics/statistics skills to evaluate and interpret data and solve problems within a disciplinary or interdisciplinary context (Elrold, 2014). To be successful as environmental scientists, students need to attain quantitative fluency. To foster this skill, students are aided to solve basic mathematical problems repeatedly, first in groups, and then individually. QR learning begins with identification of equation types and variables in an equation. Students are handed Figure 2 showing equations and guided to learn the nature of formulas and how to use them. By the end of this exercise, most students verbally confess to how easily their fear of formulas have evaporated. Throughout the classroom problem solving part of the course, student use data in Excel to solve basic practical math problems, as well as method-specific quantitative geophysics problems. Following these, students become more easily adapted to the theories of the individual geophysical methods.

Geophysics Theory. Students are introduced to the theoretical frameworks behind individual geophysical methods. To begin, a broad introduction to the

Figure 1
Disciplinary connections of geophysics

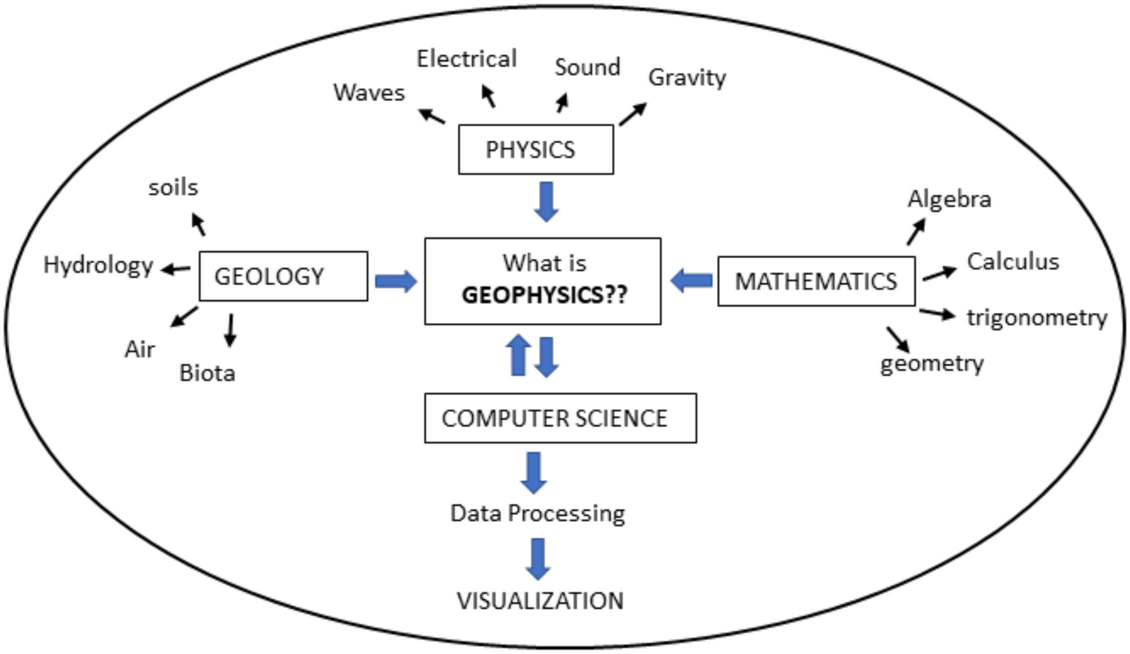


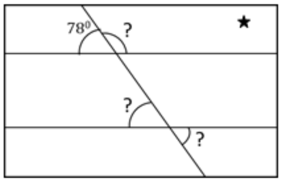
Figure 2
Introductory equation box for QR exercises

$$\rho = \frac{2\pi\delta}{V_{MN}I}\left\{\left[\frac{1}{AM} - \frac{1}{MB}\right] - \left[\frac{1}{AN} - \frac{1}{NB}\right]\right\}^{-1}$$

$$\rho = a\varphi^{-b} f^{-c} \rho_w$$

$$\cos\alpha + \cos\beta = 2\cos\frac{1}{2}(\alpha+\beta)\cos\frac{1}{2}(\alpha-\beta)$$

$$g(\lambda) = gc(1 + \alpha \sin 2\lambda + \beta \sin 4\lambda$$



$$Cos^2\theta + Sin^2\theta = ? \quad \bigstar$$

$$F = G\frac{m_1 m_2}{r^2} \longrightarrow g = \frac{4\pi G\rho R}{3}$$

$$a^2 + b^2 = c^2 \quad \bigstar$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad \bigstar$$

$$t = \left(t_0^2 + \frac{4x^2}{v^2}\right)^{1/2}$$

$$Z_c = \frac{X_c}{2}\sqrt{\frac{V_{p2} - V_{p1}}{V_{p2} + V_{p1}}}$$

$$gt = gobs - gn + 0.3086\,h - 0.04193\,r\,h + TC\ (mgal)$$

$$f(x) = a_0 + \sum_{k=1}^{\infty}\left(a_k \cos\frac{n\pi x}{L} + b_k \sin\frac{n\pi x}{L}\right)$$

$$\left(\frac{H_s}{H_p}\right)_v = \frac{2}{(\beta S)^2} * \{9 - [9\beta S + 4(\beta S)^2 + (\beta S)^{3]*e^{-\beta S}}\}$$

$$B = \mu_0 H + \mu_0 k H = (1 + k)\mu_0 H = \mu_R \mu_0 H$$

★ :Students expected to identify with ease

commonly used geophysical methods for environmental investigations, e.g., gravity, electrical resistivity (ER), seismic refraction (SR), electromagnetic induction (EM), and ground penetrating radar (GPR) are discussed. In furtherance of QR skill development, class time is further dedicated to hands-on solutions to basic problems specific to individual geophysical methods. These also enable students to conceptualize some theoretical parameters as they apply in the context of field investigations. For example, students process seismic refraction data in Excel to determine subsurface layers and depths. Similarly, for ER, they hand-solve numerical problems involving the geometric factor and electrode separations. For ground penetrating radar (GPR), students solve simple problems involving common GPR parameter settings such as determining optimum time windows for desired depths of investigations with given antenna frequencies. They practice velocity-distance-time calculations, frequency-wavelength relations, dielectric permittivity, sampling frequency, etc. Additionally, students practice converting the unit of wave velocity from m/s to m/µs to m/ns. All calculations involve important parameters that students must understand clearly when deploying equipment in the field. Course evaluation comments indicate positive learning outcomes with respect to strengthening quantitative reasoning skills.

The Outdoor Component of the Course

Introduction to the Geophysical Methods Implemented. Although a suite of geophysical methods (e.g. gravity, seismic, magnetics, etc.) exist for a range of applications, several factors including costs, availability, suitability, specific site conditions, among others, often compel investigators to use only a few for a given project. However, it is a common best practice to use at least two geophysical methods at a site so that results obtained with one could be corroborated with the other. In this course, field investigations are limited to the methods for for which we have equipment, e.g., electrical resistivity (ER), ground penetrating radar (GPR), and electromagnetic (EM) induction. As of the time of this writing, a magnetics system has just been acquired. For now, students are exposed to Electrical Resistivity (ER), Ground Penetrating Radar (GPR), and Electromagnetic (EM) Induction methods. For environmental monitoring and characterization, these methods are complementary, but each also has its specific advantages in different environments and study targets. The ER method works by sending electrical currents underground and recording the resistances offered to the current flow by different subsurface materials. In simple terms, those resistances help to determine which features are good and bad conductors of electricity. GPR, on the other hand, works by sending radar pulses underground via a transmitter and receiving the reflected (signals bouncing off of subsurface features) waves via a receiver unit. It produces a real-time image of the subsurface along the path traversed, allowing subsurface features to be identified. Lastly, the EM method works by transmitting a primary electromagnetic field into the subsurface via a transmitter dipole, which induces an electrical current in subsurface features. The induced currents, in turn, induce a secondary electromagnetic field in the features which is received at the receiver dipole on the surface. Thus, practically, the EM method measures the conductivity of earth materials. Note that the working principles described for all three methods have been oversimplified for a general audience.

For all methods, acquired field data are processed using specialized software to obtain 2- or 3-dimensional models of the subsurface. All methods can be used to detect and map several man-made and natural features underground. It should be noted that although geophysical methods are not typical for geography students, the applied methods are adaptable owing to advancements in equipment and processing software. These have made it relatively easy for those with less rigorous physics and mathematics preparation to be successful at learning and applying geophysical technology. For this course in particular, the emphasis is on active learning via field application rather than the theoretical rigor. The integration of theory and practice via field engagement of students has been a cherished HEP in the geo and environmental sciences (Anđelković, Dedjanski, & Pejic, 2017; Garner & Gallo, 2005; Scott et al., 2012). Appendix D shows students with equipment at field sites.

Example Outdoor Learning Projects and Outcomes

This course has been offered five times since its inception, and students have investigated various local sites with practical environmental issues. A selected site offers students the opportunity to solve a real-world problem while also rendering a service to the local community. This section describes two such sites as examples and summarizes the outcomes of student investigations. For each field project, students are divided into three groups, with each group starting off using one geophysical method to collect data. Afterwards, the methods are swapped until each group has had experience with each method. One site is visited repeatedly throughout the outdoor portion of the course for thorough investigations, as well as to maximize student's practice with equipment and methods. For each project, the students are tasked with the following: (1) collect data using appropriate methods; (2) process and produce 2-D models from the raw data collected; (3) identify anomalies on the model visualizations; (4) interpret anomalies in terms of physical subsurface features, providing justifications for the interpretations; and (5) produce reports and make classroom presentations. To further reinforce the interdisciplinary nature of environmental issues and geophysics, the students are guided to explore exhaustively the geology, soils, and hydrology, as well as land use/cover for each site to be surveyed. Students access online databases such as those of the U.S. Geological Survey (USGS), Environmental Protection Agency (EPA), and U.S. Department of Agriculture (USDA), to locate relevant resources, and they are also tasked with producing geologic sketches including strikes/dips/outcrops on sites. They must integrate information from these resources to reflect on their field survey design requirements and any potential impacts on their geophysical results. For presenting their results, report writing is individualized while class presentation is still done in pairs. Specific instructions that form the basis for evaluation, including formatting the final reports, are given to the students to follow. Appendix A and B show example results produced by students at the two sites. The figures are picked from student submissions and intentionally left in their original formats. Similarly, detailed written interpretations by individual students are omitted for brevity.

Site 1: The Old Shippensburg Travel Plaza. This site is roughly a 5- to 7-minute drive from the Shippensburg University campus. The Pennsylvania Department of Environmental Protection (PADEP) had concerns about possible gas leakage from a buried tank at an abandoned travel plaza that posed the risk of soil and groundwater contamination. I was contacted for help and decided to use it as a service-learning opportunity for students. Consequently, students used geophysical methods to image the tank and evaluate the risk of soil contamination. First, the class conducted a preliminary study of the site geology, soils, hydrology, and site-specific conditions before deciding on the suitability of ER and GPR for detailed investigation. Appendix A (Figures i and ii) show the results of the ER and GPR interpretations respectively. On A (i), the buried gas tank is clearly visible as the zone of very low resistivity with pronounced boundaries (indicated on the figure). There was evidence of gas leakage as well. Similarly, the buried gas tank is clearly indicated by the hyperbola on the GPR radargram in A (ii).

Site 2: An Abandoned Landfill Site Associated with the Property Disposal Office at the Letterkenny Army Depot, near Chambersburg, PA. This site is one of the EPA's superfund sites, added to the National Priorities List on March 22, 1989. Areas on the site are associated with the storage and disposal of industrial chemicals and petroleum. Soils, groundwater, sediments, and surface water around the sites are known to be contaminated with hazardous chemicals. Students investigated this site with the goal to detect and map zones of subsurface soils and groundwater contamination from the migrating landfill leachate. Shown in Appendix B (Figure i) is the final ER model produced on one of the transects at the site. The circled areas of very low resistivities are the suspected groundwater contamination zones. Students learned that the composition of leachate material makes it highly conductive; thus, they are captured as very low resistivity anomalies on the 2-D ER model. Figure ii of Appendix B shows the corresponding GPR anomalies on the same transect. Because conductive zones absorb GPR signals, the lack of strong reflections near the end of the transect were interpreted to be due to groundwater contamination, and they compare well with the ER anomalies in Figure i.

Throughout the outdoor field component of the course, students work both collaboratively and independently to achieve their final outcomes. In the process of executing their research tasks, students come face to face with the interdisciplinary nature of environmental issues. First, the nature of geophysics requires that they review information on the soils, geology and, in some cases, the hydrology of the study site. Next, they must draw upon theoretical concepts learned in class to decide on both the suitability of a particular geophysical method and the data collection strategy to use. For example, students must know that GPR surveys won't be successful at sites with clay overburden because clay soils are highly conductive and easily attenuate GPR signals rather than allowing them to penetrate deeper into the ground. This understanding draws upon physics, geology, and soil science, reinforcing interdisciplinary perspectives. Additionally, students learn the empirical mathematical relationships between soil conductivity and the electrical and magnetic properties of the propagating radar waves. All the learning is done hands-on and collaboratively with group peers and the instructor. The experiential component lies in the entire learning process where the students learn by direct experience and having to reflect repeatedly upon their research methodology and findings. Many times, students also experience the frustrations of equipment temporally malfunctioning in the field due to practical field conditions and learn coping/backup strategies. These all add to the overall learning experience and students' problem-solving capabilities.

Assessment and Student Feedback

Students' learning achievements in the course are gauged on the basis of performance on different testing areas. Specifically, besides exams and homework assignments, a concept quiz (CQ), interactive questioning sessions in the field, written project reports, classroom presentations, and an end of semester course evaluations are used. To assess students' mastery of basic quantitative reasoning skills, a CQ consisting of 20 MCQs, all basic math problems, is given at the end of the classroom learning portion of the course. Performance on the CQ is rated on the scale of "Very High (≥ 90%); High (≥ 80 < 90%); Average (≥ 70 <80%); low (≥ 60 < 70%); and poor (<60%). For the most recent class (spring 2019) with 13 students enrolled, 4 students (31%) performed at the "Very High" level, 5 students (38%) at the "High", and 2 students (15%) at the "Average" and "Low" levels

Table 1

Scores on Questions 1-7 of the End of Semester Course Evaluation

Question	Rating Min	 Max	 Average
Rate how this course has advanced your understanding of the scientific method (i.e. observation, data collection, analyses, and interpretation).	8	10	9.0
To what extent has this course helped your ability to recognize and correctly interpret variables in a mathematical formula?	4	10	7.0
To what extent has this course helped your quantitative reasoning abilities?	5	10	7.5
To what extent has this course helped you to link classroom concepts to real world environmental issues?	8	10	9
How responsive was the professor to your questions and concerns?	9	10	9.5
How effective was the professor in teaching this course?	7	10	8.5
Overall, how satisfied were you with this course?	6	10	8

respectively. No student scored below 60% (i.e., < 12/20) on the quiz. The distribution is similar to the two prior semesters. This result suggests an overall high level of QR skills for students in a geography program.

An additional form of assessment takes the form of interactive questioning sessions in the field to gauge the ability of students to relate concepts learned in the classroom to field procedures. This is a formative assessment to identify gaps in student understanding and address them while they perform fieldwork. Example questions for ER are: (1) Why use a non-conductive rope to separate the receiver and the transmitter dipoles? (2) What advantage do you get by connecting more than one receiver in series? (3) What limitation(s) of this entire setup can you think of, on this specific site? To answer these questions, a student would need to draw upon basic theoretical background offered in the classroom. The students are similarly assessed on the GPR and EM methods.

The more standard form of assessment is an end of semester course evaluation adapted from the university's evaluation instrument. This instrument further adds student voices and or perceptions regarding their own learning, which is consistent with Mogk and Goodwin (2012) and Waldron, Locock, and Pujadas-Bootey (2016), who have emphasized the need for metacognitive-based assessment of student learning. Appendix C shows the survey questions administered and Table 1 summarizes the student responses to the scoring part of the survey (questions 1-7). The results shown are aggregated over the Spring 2018 and Spring 2019 semesters. Overall, the scores offer evidence to positive learning outcomes for students in the course. For example, when asked the extent to which the course has helped students to link classroom concepts to real world environmental issues, the minimum aggregate score is 8/10. This is significant because the ability to conceptualize and solve real world problems depends on a student's understanding of relevant theoretical frameworks. The results also show that the course has had a positive learning outcome with respect to students' quantitative reasoning abilities although, as expected, the overall average rating is lower in the quantitative categories. Altogether, students also expressed overall satisfaction with the course. Responses to the open-ended questions are consistent with ratings on the scoring part. On question 1, the most positive aspect(s) of the course, a majority of the students favor the field work component (>90%). Only a handful of students had the video/case study discussions aspect as their favorite. For question 2, most students don't see an aspect of the course they would change except a few that felt the CQ was too difficult. In all, written comments indicated students took ownership of their accomplishments and relished the opportunity to address real-life environmental issues of practical significance. Sample students' comments are presented below:

> It was a great feeling to be out there doing geophysics and solving the problems that professional people solve for big money. This class has given me possibilities after I graduate. I learned a lot in the class-resistivity, gravity, seismic, mathematics, simulation, etc and will definitely consider geophysical imaging as a career in the future.
>
> The time to set up equipments and run the surveys was a lot of hard work but I enjoyed it and gained a lot of new knowledge. Now I see that geophysics answers many important problems in the environment like identifying graves, sinkholes, pollution and more. These are important problems, and I am happy to have the chance to become an expert.

> This was a fantastic course for me. Though I must admit that I am not a math person, this course has cleared most of my fears for numbers. I now can see equations as "coded words" and just a different way of communicating once you understand the variables.
>
> I feel fortunate to have geophysics knowledge! Without the early videos though I would of still been scared of what was to come in the class despite the professor's assurances that the class would be fine. The videos helped me to see firsthand how geophysics works and that made me more interested.
>
> The coolest thing for me was that we solved real problems close to home. Using resistivity and gpr to identify groundwater and soil polluted areas was a new discovery. I never would of thought that the trash we send to the landfill is actually polluting groundwater. Geophysics helped me to make this connection and it was obvious.
>
> Many other written comments echoed similar voices of satisfaction with the course. These, together with my assessment of final project reports and classroom presentations, led me to the conclusion that the course as delivered produces positive learning outcomes for students.

Potential for Broader Cross-Disciplinary Application

The curriculum adaptation presented here, though of geophysics content and localized, provides a model for cross-disciplinary application. For environmental scientists in general, the range of environmental problems that can be addressed by geophysics, geochemistry, or tools of environmental engineering are global in scope. For example, issues of groundwater and soil contamination, sinkholes/caves, dam leakages, unexploded ordnances (UXO), unmarked tombs at historical cemeteries, etc., are common global problems that can be addressed with environmental geophysical methods. Beyond environmental sciences, other global issues exist that require interdisciplinary solutions. In the health sciences, for example, several factors including social, environmental, biological, and climatic among others, influence disease prevalence and propagation. Currently, mathematical models that integrate social, environmental, biological, and economic variables to model and predict impacts of infectious diseases on human systems, are used to reduce human fatalities and other losses at the local, regional, or even the global scale. In this mix of problems and existing technologies lie ample opportunities for cross-disciplinary curriculum innovations to engage undergraduate students in interdisciplinary learning. Hence, similar to the approach described in this paper, a broadly trained sociology faculty member, for example, could adapt a course where sociology undergraduate students learn the application of mathematical models (or some other tool) to patterns of human response to crises over different spatial scales. The success of the approach presented in this paper is proof that students are highly adaptable to different learning modules if given the right tools. Thus, this curriculum adaptation model could similarly be implemented by other educators irrespective of discipline.

Conclusion

This paper describes a curriculum integration approach whereby the concepts and techniques of environmental geophysics are taught in an environmental geography program to enhance both interdisciplinary learning and quantitative reasoning skills for students. To adapt geophysics content to geography students, three major strategies are used: (1) the course begins with a review of case studies before introducing geophysics theory, to lessen intimidation and student phobias regarding the term "physics"; (2) applied learning is emphasized over theoretical rigor; and (3) the high-impact educational practices (HEPs) of field research and service learning are integrated to maximize experiential learning opportunities for students. For environmental sciences, courses employing HEPs have been reported to improve learning outcomes including critical thinking, interdisciplinary knowledge, and environmental problem-solving skills (Brownell & Swaner, 2009; Wawrzynski & Baldwin, 2014). Likewise, both formative and summative assessments in this course indicate that students learned environmental geophysics concepts and gained useful interdisciplinary, as well quantitative, reasoning skills. Additionally, students' written comments indicated that they took ownership of their accomplishments and relished the opportunity to address real-life environmental issues of practical significance in the local community. Although this curriculum adaptation is localized, the range of environmental problems addressed by the students is global. The issues of groundwater and soil contamination, sinkholes and solution cavities, and unmarked tombs at historical cemeteries are common problems addressed with environmental geophysics and are common at many locations. Thus, in a similar tune as Cantor, DeLauer, Martin, and Rogan (2015), I note that human–environment geographic issues are widespread, as are other global issues beyond the environment. These hold excellent potential for student learning via interdisciplinary, inquiry-driven, learner-centered research projects, and provide a platform for students to learn and acquire essential skills for solving real-world problems. Hence, the curriculum adaptation presented here could be implemented by other educators. Broadly, the student testimonies above and the overall success of this implementation should be encouraging to other faculty contemplating similar curriculum integrations. The success of this course suggests that, with the right approach and tools, students are capable of adapting to any curricular adaptions that provide them with practical learning opportunities.

Despite the successes achieved, educators looking to adapt geophysics in a similar manner should be aware of the following challenges: (1) Motivating geography students, who often have limited exposure to physics and mathematics coursework, requires a higher level of effort; (2) Geophysics equipment are expensive to acquire and maintain. Long-term maintenance can be expensive as well, depending on the level of usage. This means that careful planning, including internal arrangements for sustained support in equipment, must be in place; (3) Scheduling field times for adequate student exposure to the applied aspects can be a challenge. This challenge led to the first offering of this course to be in a summer session. However, students' ability to enroll in summer classes is limited by several factors; therefore, the course had to go on a regular semester schedule. Despite the above challenges, the overall value added to the educational experiences of students makes these sorts of curricular integrations worthwhile.

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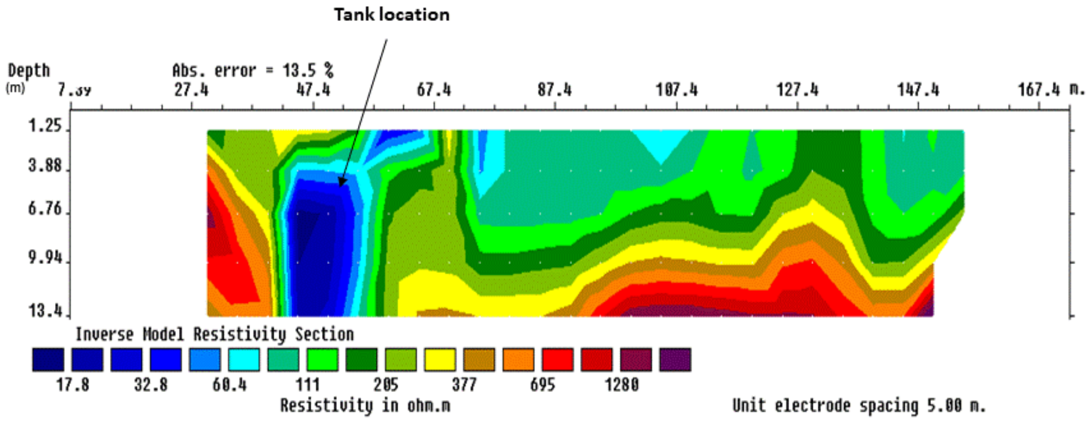
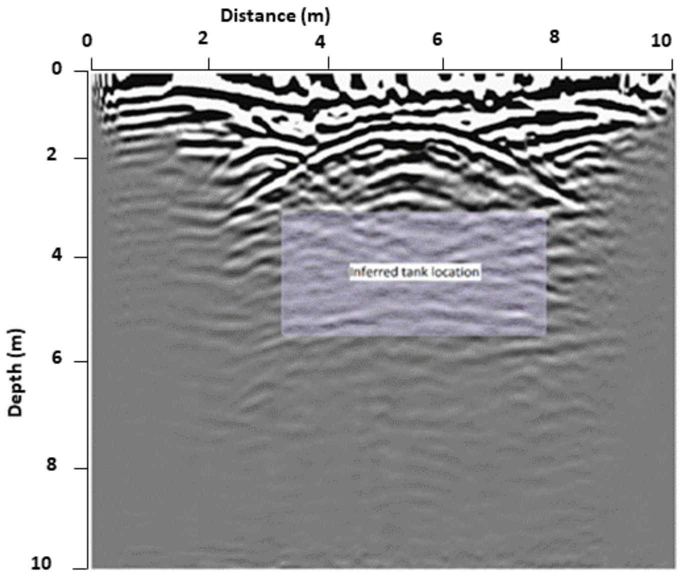
Appendix A



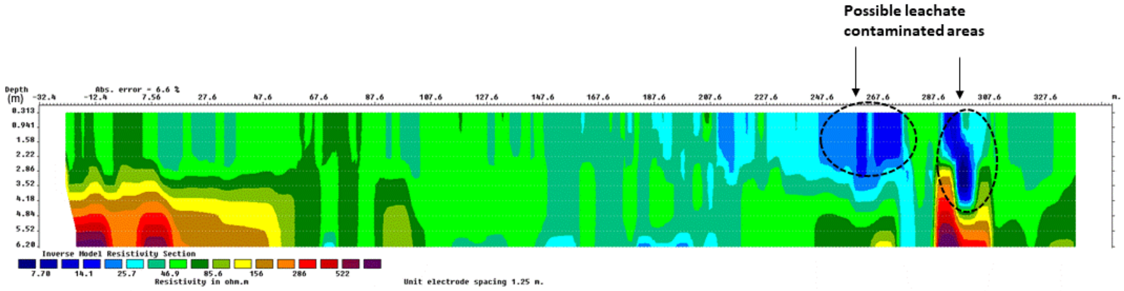
i. Final ER model showing anomalies for the buried gas tank at the old Shippensburg travel plaza



ii.

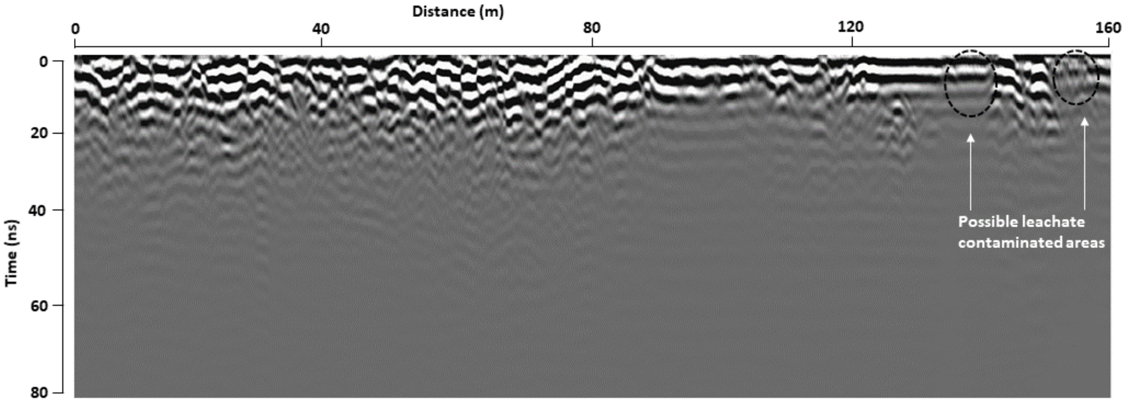
ii. GPR radargram showing anomalies for the buried gas tank.

Appendix B



i.

Final ER model produced on transect 1 at the Letterkenny closed landfill site.



ii. **GPR radargram, produced on the last 160 m of transect 1 at the Letterkenny closed landfill site.**

Appendix C

End of course survey (adapted from university course evaluation)

A: For this section (questions 1-7), rate each question on a scale of 1 – 10 (1 being minimum impact and 10 being highest impact).

1. To what extent has this course helped your understanding of the scientific method (i.e. observation, data collection, analyses, and interpretation).
2. To what extent has this course helped your ability to recognize and correctly interpret variables in a mathematical formula?
3. To what extent has this course helped your quantitative reasoning abilities?
4. To what extent has this course helped you to link classroom concepts to real world environmental issues?
5. How responsive was the professor to your questions and concerns throughout the semester?
6. How effective was the professor in teaching this course?
7. Overall, how satisfied were you with this course?

B: Open-ended questions:

1. Please describe the most positive aspect(s) of this course.
2. Please describe the aspects of this course you would change.
3. Please provide any other comments that you may have.

Appendix D

Field scenes of students at work with ER, GPR, and EM equipment.