Design-Based Science for STEM Student Recruitment and Teacher Professional Development

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We have developed a design-based project for outreach efforts to recruit students to STEM fields as well as science teacher professional development. The project challenged high school students in a one-week high school summer outreach academy and middle and high-school teachers in a two-week summer science institute to design and construct a system to remediate water impacted by acid mine drainage, a ubiquitous and locally-relevant issue, and involved them in field experiences with real remediation systems. The design and construction of the remediation systems also involved learning and application of science concepts from chemistry to environmental science, the engineering design process, mathematical problem solving, and the use of technology for data acquisition and analysis. In addition, the project involved students and teachers in 21st century thinking skills and the characteristics of scientific and technological literacy as they collected data, designed systems and subsystems, utilized data-driven decision making, solved problems, and communicated their results to their peers.

Introduction

Engineering design-based learning, a subset of project-based learning, has been suggested as a valuable pedagogical tool in STEM education to better engage students, provide a context and relevance to learning, and facilitate long-term meaningful learning of concepts. As Froyd and Ohland (2005) state, "To become experts, students must not only acquire facts, but also organize their knowledge to facilitate its application to diverse situations" (p. 148).[1] In addition, incorporating technological/engineering design, the "T" and "E" of STEM, into science and mathematics instruction can promote higher order thinking skills while capitalizing on the motivation students have for problem solving.

To facilitate the integration of design-based learning in schools, an educational model called Integrative STEM (ISTEM) provides a mechanism to work with currently established educational systems and content-area silos while providing the potential to effect systemic school changes. As engineering design projects are integrated, they become the unifier for content in science, math and other content areas while addressing and improving students' technological literacy. "ISTEM education refers to technological/engineering design-based learning approaches that intentionally integrate content and process of science and/or mathematics education with content and process of technology and/or engineering education" (M. Sanders & J. Wells, personal communication, 3/16/10).

Growing evidence suggests that student engagement and science and/or math learning are improved by using design approaches in the science classroom in elementary school,[2,3,4] middle school,[5,6,7] high school,[8-12] and at the undergraduate level[1]. Further, the Katehi, Pearson, and Feder, Eds. (2009) suggest that incorporating engineering into the K-12 curriculum can provide tremendous learning opportunities in five areas: "improved learning and achievement in science and mathematics, increased awareness of engineering and the work of engineers, understanding of and the ability to engage in engineering design, interest in pursuing engineering as a career, and increased technological literacy" (pp 49-50).[13] However, despite the critical need for students in 21st century society to possess problem solving skills and basic technological literacy to be informed decision makers, technology and engineering education has received little attention in K-12.[13]

The ISTEM approach is reinforced further in the *National Science Education Standards for Science and Technology*, *Benchmarks for Science Literacy*, and *Standards for Technological Literacy*, all of which suggest that science and technology instruction can be treated as complements to emphasize connections between the natural and designed worlds.[14,15,16] Aspects of scientific inquiry (the use of evidence, logic, and explanation) can be coupled with aspects of design (real world constraints, trade-offs, developing a solution to satisfy a purpose) so that students experience how knowledge is gained and problems are solved in real world STEM scenarios.[13] In addition, such ISTEM activities require that learners use skills that are characteristic of scientific literacy[17] and technological literacy[18] as they collect data, design systems and subsystems, utilize data-driven decision making, solve problems, and communicate their results to their peers.

ISTEM practices engage students in the design of solutions to real world problems, providing a context for and relevancy to science and/or math content. They also provide the opportunity to develop meaningful learning experiences that focus on relevant and engaging authentic problems. However, to enhance engagement, the content on which the project is based must connect to a topic that that is relevant in student's lives.[1] We have used a locally relevant problem, acid mine drainage, as a springboard for a design-based project for outreach efforts to recruit students to STEM fields as well as science teacher professional development.

Acid Mine Drainage

Acid mine drainage (AMD) negatively impacts water quality and aquatic ecology of receiving water bodies in coal and metal mining regions across the globe.[19,20,21] The oxidation of pyrite (FeS_2) and other sulfide minerals are the primary drivers of AMD formation, which often results in acidic pH and elevated ecotoxic metal concentrations in the effluent produced. AMD disrupts the productivity of the aquatic ecosystems via direct metal and hydrogen ion toxicity to all aquatic organisms as well as the accumulation of precipitated metal oxyhydroxide sludges that degrade streambed habitat.[22]

AMD is the leading cause of water pollution in Pennsylvania, degrading approximately 8,800 km of streams.[23,24] Many Pennsylvania streams have been rendered fishless due to AMD impacts.[22,25] This degradation of rivers and streams is estimated to account for $93 million of lost revenues, accounting for recreational fishing losses alone,[26] which may be overshadowed by losses incurred from restriction of other recreational activities and the degradation of irrigation, industrial and potable water resources.

The Programs

The student summer academy program, titled the Environmental Engineering Design Academy (EEDA), provides an opportunity for students who have just completed their sophomore and junior years of high school to participate in a week-long college experience focused on environmental engineering. The summer academy is taught by faculty members in the Environmental Engineering program and supervised by student resident assistants in the School of Sciences. Goals for the student summer academy are to encourage students' interest in STEM careers, provide an opportunity for students to experience college life, and enhance students' understanding of the field of Environmental Engineering.

The design and construction of the acid mine drainage system is the main assignment associated with the summer academy, for which students earn two college credits, 1 credit each for Engineering 101 and 102. In addition to completing the acid main drainage project, multiple field activities are conducted to illustrate the relevance of the issue to students.

One such field activity, conducted in collaboration with a local river restoration project, includes a trip to a mine drainage borehole, which has resulted in a landscape covered with iron precipitate. In addition to experiencing the dramatic visual impact of the drainage on the area, the experience includes analyzing water samples taken along the flow of the water discharge and opportunities for the analysis of field data to inform decisions as the students design and develop the project (described further below). Other field trips conducted during the week include a trip to a local research and development firm, which is involved in developing products and processes that have environmental implications such as pressurized coating and electric vehicle technologies.

Goals for the MSP SEEDS (Math Science Partnership STEM Engaging Educators in Design-based Science) teacher professional development summer institute are to improve participants' understanding of physical science and environmental engineering concepts relating to water pollution and acid mine drainage remediation, model a STEM-integrative and design-based pedagogical approach, and facilitate the development of design-based science units to enhance science instruction within schools. In addition to conducting activities designed to improve content, design process, and pedagogical knowledge such as general chemistry and the engineering process, teacher participants worked on the acid mine drainage remediation project, adapted slightly for adult learners. Field trips to acid mine drainage remediation sites were also conducted with teachers to include authentic activities to make the project as locally relevant as possible and to provide ideas for potential resources that teachers can draw on during the school year for their own lessons.

Teachers are also responsible for developing a project plan during the two weeks, which is a precursor to the integrative curriculum unit plan that will ultimately be implemented in the classroom. The project plan template that was used comes from the Buck Institute for Education (www.bie.org). The project plan is the driver of the curriculum unit plan, which is designed to enhance and provide a context for existing content lessons rather than supplant existing lessons.

The Project

The project challenged high school students in a high school summer outreach academy and middle and high-school teachers in a two-week summer science institute to design and construct a system to remediate water impacted by acid mine drainage, a ubiquitous and locally-relevant issue, and involved them in field experiences with real remediation systems. The design and construction of the remediation systems also involved learning and application of science concepts from chemistry to environmental science, the engineering design process, mathematical problem solving, and the use of technology for data acquisition and analysis.

Teams of 3-4 students or teachers were tasked with the challenge of building a bench-scale AMD remediation system using common materials of the type available at a hardware store (see below). In addition to restrictions on system size – bench space available per team was approximately 12'x3' – and available materials, the design constraints included a treatment time of two hours and a volume of AMD to be treated of ca. 5 gallons. The AMD was presented to each team in a sealed plastic carboy with the treated water to be placed back into the carboy for physicochemical analyses. The water quantity and quality parameters measured are listed in Table 1 along with the treatment goals that were presented to the students. The treatment goals were drawn from TMDL standards that guide effluent quality targets for AMD treatment in western PA (which generally mirror EPA secondary drinking water standards).

EEDA students and MSP SEEDS teacher participants were prepared for the project by readings, short lectures, field trips, and both expert-guided and self-guided experimentation. Readings and short lectures covered the basic chemistry of AMD generation, environmental impacts of untreated AMD, and treatment strategies – especially passive techniques – for alleviating the problem. Students were assigned homework problems based on the readings and lectures. Field trips were conducted to both an untreated AMD discharge and a passive treatment system. Students collected spatially distributed water chemistry data on both trips which stimulated their thinking about the systems they were building in the lab. Initial experiments with AMD and potential treatment materials (see below) were heavily guided by the instructors. As the students developed an understanding of the chemistry involved as well as the over-all design process, time was allotted for teams to conduct independent experimentation which eventually culminated in the design/construction of full systems.

Materials and Methods

Abandoned mine drainage is typically high in dissolved metals and low in dissolved oxygen, alkalinity, and pH. Strategies for remediating AMD involve raising the Eh and pH of the water to control precipitation of metal (oxy)hydroxides so that the precipitates can be removed from the water stream. AMD for the EEDA project was collected from a flooded mine ventilation shaft near St. Michael, PA in five gallon carboys which were sealed to limit O_2 introduction. Collection was performed less than 24 hours prior to use of AMD for experiments or project work. Measurements of pH at the AMD source and in samples returned to the lab indicated a stable pH of 3.5. Iron concentrations were measured by flame atomic absorption and were found to be 62.1 mg/L in the starting AMD. Initial turbidity was negligible.

Materials supplied for the bench-top treatment project included limestone gravel (ca. 30 lbs. per team), spent mushroom compost (ca. 10 lbs. per team), silica sand, five c2gallon buckets (6 per team), eight foot sections of rain gutter (1 per team), empty milk containers, fiberglass screen, coffee filters, funnels, furring strips, glue, and tape. All materials were readily available at area hardware stores. Common tools such as drills, hammers, hand-saws, etc. were provided for system construction. A multi-meter (PASCO GLX) was provided to each team with probes for pH, oxidation/reduction potential, dissolved oxygen, and turbidity. Teams also had access to flame AA iron analyses.

Project results

The five EEDA teams produced a wide variety of systems. All teams introduced the full quantity of limestone available and, as a result, achieved circum neutral pH levels. All of the systems also introduced ample oxygen whether by sheet flow in gutters, flow over small ledges, or aeration in buckets. Major differences in system performance (see Table 1) arose primarily from strategies for water control and filtration. In particular, teams that utilized a large amount of organic materials (coffee filters, compost) achieved lower levels of Fe and turbidity, probably due to sorption of iron to the organic matter.

None of the teams was able to meet the treatment goals laid out for the project during the final test. In experiments during system construction, however, several teams were able to achieve less than 1 mg/L iron. The primary difference between the initial experiments and final tests was the quantity of water treated. As with real treatment systems, scaling the results from lab and pilot tests up to full system performance represents a challenge that environmental engineers work hard to overcome. In this way, the students and teachers learned a valuable lesson about real-world engineering. Given time for further experimentation and construction, it seems likely that all of the projects could have been modified to meet the treatment goals. Project treatment goal parameters and results from both the student and teacher projects' are provided in the following table.

Table 1. Treatment goals and outcomes for the bench-scale AMD remediation design exercise.

	[Fe] (mg/L)	Turbidity (NTU)	% Water Recovered
Treatment Goals	1.0	100	90
Student Team A	8.0	785	88
Student Team B	11.0	218	88
Student Team C	12.0	555	31
Student Team D	1.6	164	86
Student Team E	11.5	308	54
Avg. Student Results	8.8	406	69
Teacher Team 1	13.2	83	90
Teacher Team 2	19.4	148	86
Teacher Team 3	19.8	137	88
Teacher Team 4	17.4	57	80
Teacher Team 5	19.5	48	88
Teacher Team 6	16.1	112	82
Teacher Team 7	17.7	105	84
Teacher Team 8	0.2	6	80
Avg. Teacher Results	15.4	87.0	85

Program Assessment

Seventeen students attended the Environmental Engineering Design Academy, 10 male and 7 female. Eight of the attendees (47%) came from the county in which the University is located or the four surrounding counties, eight attendees (47%) came from Pennsylvania outside the local region, and 1 attendee (6%) came from Maryland. Three of the attendees (18%) would be among the first generation of college graduates in their families.

The Environmental Engineering Design Academy is assessed with information about the number of participants matriculating to the University by major as well as with a pre and post survey. Matriculation will be assessed in the fall of 2011 and 2012. Pre and post survey results are listed in the table below.

Table 2. 2010 Pre and Post Survey Results Environmental Engineering Design Academy (Ratings are out of 5)

Item		Pre-Survey	Post-Survey
Goals after Graduation	Complete Two-Yr. Degree	5.9% (1)	5.9% (1)
	Complete Four-Yr. Degree	53.9% (9)	64.7% (11)
	Complete Master's or Doctoral Degree	29.4% (5)	23.5% (4)
	Complete Advanced Professional Degree	5.9% (1)	5.9% (1)
	Other (undecided)	5.9% (1)	0
Intended Academic Field(s) of	Biology	7 respondents	9 respondents
	Chemistry	7 respondents	7 respondents
	Computer Science	4 respondents	4 respondents

Study after Graduation	Engineering	13 respondents	12 respondents
	Health Sciences	3 respondents	3 respondents
	Other	2 respondents (Physics/Astronomy, Fashion Design)	2 respondents (PreMed/Anesthesiology, Fashion Design)
Avg. Rating of Activities in Terms of Academic Value	Lake Challenge	NA	3.53
	Hughes Borehole	NA	3.12
	Research and Development Firm Tour	NA	4.06
	Cogeneration Plant Tour	NA	3.41
	Acid Mine Drainage Remediation Project	NA	3.59
Avg. Rating of Activities in Terms of Interest	Lake Challenge	NA	4.18
	Hughes Borehole	NA	2.53
	Research and Development Firm Tour	NA	2.53
	Cogeneration Plant Tour	NA	3.47
	Acid Mine Drainage Project	NA	3.06
Avg. Rating of Consideration of SFU in Future Plans/ Likelihood of Applying		3.06	3.12
Avg. Rating of Interest in Engineering		3.29	3.24

Future plans for assessment of the Environmental Engineering Design Academy include incorporating a pre and post assessment of content knowledge as well as student response journals and exit interviews to collect qualitative data about the program and design project on the students' interest in engineering and SFU. In addition, a survey of students' self-efficacy (adapted from the LAESE - Longitudinal Assessment of Engineering Self-Efficacy tool from Assessing Women and Men in Engineering, the Pennsylvania State University and University of Missouri, available at: http://www.engr.psu.edu/AWE/secured/director/diversity/efficacy.aspx#desc) will be administered for the summer academy. The survey results will be analyzed to compare pre and post results as well as administered to incoming freshmen engineering students (both matriculating academy participants and non-participants) to compare survey results from summer academy results with the incoming freshmen control group.

Thirty teachers and four mentor teachers attended the MSP Summer Science Institute. The target grade range for the program is grades 5-9, determined primarily because of the need for improvement of state assessment scores in math and science at that level, the fact that many of the teachers teaching at that level are only elementary certified, and the importance of preparing students in science and math at those grade levels as a basis for more rigorous high school coursework. Although most of the program participants were from the target grade range for the program, the size of the school district partners and the number of available teachers at that level necessitated that some districts also sent attendees who teach at the high school level.

The program includes an external evaluator who will assess classroom instruction through observations and student learning through a quasi-experimental, pre- and post-test assessment. The primary mechanism for assessing the summer institute is a pre- and post-test of teacher content knowledge. The test is compiled from questions from multiple validated test sources as well as questions developed by the University instructional team. Results from the pre- and post-test are provided in the below.

Table 3. MSP SEEDS Pre and Post Test Results

Test Parameter	Pre	Post
Highest Score	48	53
Lowest Score	23	27
Mean Score	33.21	37.29
Mean Percent Score	60.37	67.81
Standard Deviation	5.76	6.11
Median Score	32.00	38.00
Cronbach's Alpha	.76	.81

Conclusion

Utilizing the acid mine drainage remediation project was extremely rewarding in that it provided opportunities to make the material locally relevant and to connect with multiple outside organizations involved in the field. Although the student assessment did not provide the results that we had anticipated in terms of pre and post measures of student interest in engineering, the decrease was small and students involved were relatively young and might be expected to be undecided about areas of interest and career aspirations. Matriculation data about summer academy participants to the University will be collected for the next two years. In addition, the added assessment measures to be implemented next year will be helpful for more thoroughly assessing the outcomes of the summer academy.

Teacher content knowledge, not surprisingly, significantly ($p<0.01$) increased on the post-test. The teacher-developed project and design-based curriculum unit plans will be further developed at the curriculum planning event to be held during the fall semester. The ultimate test of the program will be how instructional practices change and student science achievement increases as the program evaluator assesses the program during the school year.

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