Int. J. Engng Ed. Vol. 25, No. 1, pp. 181–195, 2009
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Exploring the Effectiveness of an Interdisciplinary Water Resources Engineering Module in an Eighth Grade Science Course*

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Engineering education has historically been given little attention in the USK-12 classrooms even though engineering incorporates scientific and mathematical concepts into meaningful, everyday applications. Including engineering and design projects in K-12 science and mathematics classes may improve student interest and comprehension, while also reaching a broader range of students than traditional lecture-based classes. For this study, the authors implemented an engineering design project focusing on water resources in 8th grade science classes. Students were exposed to either an engineering project (treatment) or a more traditional format (control) and their knowledge of water resource issues was evaluated using a pre-post assessment tool. Overall, students in the treatment classes showed statistically significant improvement in two areas—they displayed higher levels of thinking on open-ended questions and greater content knowledge. This research indicates the effectiveness of engineering in enhancing student learning and supports its inclusion in the middle school science curriculum.

Keywords: K-12 engineering education; project-based learning; middle school education; water resources

INTRODUCTION

WATER QUALITY AND WATER ACCESSIBILITY are important areas of global concern and significance for many individuals and humanitarian agencies. Although 75 per cent of the earth's surface is water, only a small amount is potable (less than 0.7 per cent) [1, 2]. Consequently, safe drinking water is inaccessible to nearly 20 per cent of the world's population and, given current rates of population growth and urbanization, is becoming an increasingly limited resource [3]. Reflecting the critical importance of water resources, the Indiana 8th grade curriculum contains a unit focused on human impacts on water and water quality. However, due to the perceived lack of relevance to students' lives, they may not fully grasp what is needed to ensure safe drinking water. A key approach to resolving water quality issues in the US may reside in providing education that presents accurate information in a meaningful way.

The National Research Council (NRC) has a content standard of 'science in personal and social perspectives,' which focuses on populations, resources and environments as well as 'risk and benefit analysis' to encourage the development of the student's systematic and critical thinking skills [4]. As a component of these standards, the NRC also emphasizes the importance of local and global environmental health and scientific literacy in the US. While these are important guidelines that help educators to structure lessons that develop a greater understanding of water use and water quality, questions remain about how they are translated into classroom instruction and the subsequent impact on student learning, especially through the use of engineering and applied science modules.

Engineering education has experienced limited use as a vehicle for curriculum and instruction in K-12 classrooms, largely because science and math textbooks tend to focus on specific facts and concepts rather than the application of those concepts or ideas [5–7]. While students in science classes may participate in scientific experiments, these activities are typically not tied to real-world

* Accepted 30 September 2008.

experiences or problems and may leave students with little understanding of application, both of which may limit students' comprehension of scientific concepts. To address this issue, the American Academy for the Advancement of Science (AAAS) and NRC has emphasized student exploration of the everyday world to promote a deeper understanding and stronger conceptualization of science concepts, while deemphasizing rote memorization of scientific facts and theories. [5, 6, 8] Hence, the use of engineering design projects has been suggested as learning tools to help students investigate their surroundings and to make those important connections to their everyday lives. [8–15]

Studies have shown that engineering and design projects can be beneficial for students in terms of helping them to conceptualize ideas [16] and to develop a greater understanding of the material being presented [10]. Engineering modules can be effective in reaching a greater number of students, particularly minority students or those from disadvantaged backgrounds [17]. A major challenge for engineering as a discipline is to demystify the notion that engineering is only for high-performing students. Engineering education and engineering practices should be accessible and appealing to a range of students to encourage career exploration in this field. When engineering is targeted on high-performing students, many potential engineers are neglected. Restricting engineering only to a select group of high-achieving students greatly truncates the number of engineering students, and consequently hinders the progress of the discipline. In short, selecting only high performers precludes students who can pursue engineering, limiting the number of engineers available for research and industry—a detriment to society [18].

The purpose of our research was twofold:

1) to explore students' understanding of issues related to safe drinking water
2) to understand how the introduction of an engineering module into the curriculum shapes student learning and conceptualization.

To the authors' knowledge, there is no research explicitly exploring the effects of using an engineering module versus a traditional lecture format on conceptual understanding in middle school science, and there is no research on the effects of an engineering module on minority and typically disadvantaged (lower socio-economic status) students at the middle school level. Thus, the specific research questions for this study were:

1) How does participation in an engineering module influence 8th-grade students' conceptual understanding of human impacts on water resources and water quality?
2) How do 8th-grade students' conceptual understanding of water pollution and water purification differ by gender, race/ethnicity and socio-economic class following their participation in an engineering module?

Our hypothesis was that students who experience an engineering design project concerning water quality develop a greater breadth and depth of understanding of the human impacts on water and the US regulations for safe drinking water. We further hypothesized that typically disadvantaged students would achieve greater benefit from participating in the engineering module than the traditionally strong students.

THEORETICAL FRAMEWORK

This study draws from two areas of literature:

1) social constructivism
2) community of practice.

Social constructivism structures student learning as a dynamic, iterative process developed through social interaction with members of the community and culture [19]. From this perspective, students construct their knowledge independently, not in isolation, but through a socially-negotiated practice of understanding [19–21]. They develop understanding based on prior ideas and experiences [22, 23] and through physical and mental manipulation of objects [24]. Thus, one key to facilitating learning is to enable students to successfully accommodate new information and to interact effectively and discuss with their peers their view of the topic in hand [22]. This latter point drives the concept of a community of practice [25].

Within the community of practice members deepen their knowledge and expertise in their discipline by interacting with other community members [26]. Individuals learn from each other's successes and mistakes to develop solutions together that would be too difficult or complex to be developed individually [27]. Activities invite structure and produce real-life experience; knowledge is obtained through participation. Sharing and discourse on the practical is sharing understanding and knowledge [25].

The fundamental tenet in a community of practice is that knowledge is not an object, but an entity; key points on the nature of knowledge are that knowledge lives in the human act of knowing, is implicit and explicit, is communal and personal, and is dynamic [28]. Knowledge is the accumulation of experience and the reservoir of actions, thoughts and conversations, which facilitate learning from other community members vicariously [27]. Members in the community make advancing and progressing their understanding an integral part of the activities and interactions, serving as a living repository for experience and expertise. As such, storytelling, conversation, mentoring and apprenticeship between community members are required [29], and through the process of communal involvement knowledge is developed and acquired. Committed to exploring, developing, and sharing relevant knowledge, communities of practice believe 'Knowledge involves the head, the heart, and the hand; inquiry, interaction and craft' [28].

Community or individual artifacts, such as tools, documents and products, are the embodiments of knowledge, but personal learning and knowing exists in the skill, understanding and relationship of community members [25]. The community takes pride and appreciates the collective nature of knowledge, which allows the individual to use communal knowledge to expand and develop his or her own personal breadth of understanding. In today's society, with ever-increasing challenges and complex problem solving, multiple perspectives within the community complement and advance members' expertise and understanding [26].

The shared nature of knowledge encourages debates and discussion, reasoning that controversy makes a community vital, effective and productive [25]. Latour and Cummings state that with no-one to discuss drafts of ideas, check proposals for strengths and weaknesses or debug prototypes, we cannot understand what is feasible or fruitless [30]. In the K-12 academic setting, the focus of community-centered environments is to transfuse community practices and to engage the learner in activities with well-defined goals and sub-goals [28]. To succeed, the learner is to become a contributing community member, able to discuss intelligently, critically analyze theories and advance understanding; the mentors are invested in both the development of learner and the quality of the outcome (product, project or design) [26]. In the K-12 system, this is seen through teachers and instructors carefully seeding learners within the classroom, making time and resources available for student work, encouraging participation from all students, providing authenticity for work and giving the students a voice in decisions [21]. From this standpoint, stewarding knowledge, fostering learning and cultivating understanding surpasses the production of factual, static information.

From the constructivist and community of practice framework, students generate the meaning from the experience and activities of the community and relate their understanding to prior experiences and existing concepts. For this study, the shared experience for the students was to create a safe drinking water system. The students, though attending a rural school, were from very diverse backgrounds and experiences. For example, in an opening discussion on water quality, 10–15 per cent of them had lived in or traveled to an area with poor quality drinking water and were restricted to bottled water only (i.e. Mexico and Central and South America). Many students already had preconceived ideas concerning safe drinking water; however, they lacked a scientific understanding of water quality and water resources.

Thus, the students' scientific understanding is embodied in their experience and discourse through the activity (practice). Consequently, student learning is a reflection of their unique social, educational and cultural experience. Utilizing the community of practice framework to evaluate and justify the inclusion of engineering design modules in middle school science classrooms, three concepts were promoted through the student activity.

1) Interaction: engagement and opportunity to build relationships and trust with community members through the shared repertoire of concepts, tools, language and stories, allowing the community a unique resource for learning [31]. In this project, students were provided with classroom time to design, build and test their drinking water apparatus. They worked in small groups, with the emphasis being on interacting with others. All students were to contribute to each part of building a safe drinking water device, placing the student interaction and participation as a paramount component of the activities.
2) Artifact Development: well-defined goals and sub-goals of creating a portable drinking water device (the community artifact) promoted students' focus and motivation. The project artifact was symbolic of the students' understanding of water quality concepts. Students were placed in cooperative-learning groups that would allow them to use their communal knowledge to develop their design and succeed in the task. Groups were created such that there multiple perspectives within the group that would complement the students' understanding and progress the group's product.
3) Critical Analysis: the concept of continuous learning as a response to participation in the learning environment was emphasized. Throughout the project, discourse between students and student groups concerning project development was expected. Students were to share their findings and work within their group and with the entire class. In the final assessment of the project, peers were encouraged to discuss and question others' designs, noting each design's advantages and disadvantages.

This approach centered on the understanding that all students were to interact and build relationships while fulfilling the project goal of designing a safe drinking water apparatus. Their success was a function of their connectedness, giving voice to all members, promoting understanding and learning from their peers.

ENGINEERING DESIGN MODULES IN MIDDLE SCHOOL EDUCATION

Placing engineering in the K-12 curriculum is an attempt to increase student awareness of engineering and to demonstrate the importance of learning science through application-based projects and inquiry. Increased attention to K-12 engineering in the US is due in part to the perceived failure of science and mathematics instruction relative to other industrialized countries [32]. According to the 1999 Third International Mathematics and Science Study Repeat Report, US scores in both science and mathematics dropped considerably between fourth and eighth grade, compared to the international average, indicating that US students' performance dropped as they progressed through the educational system [33]. Berryman suggests that the critical years for increasing student motivation and interest in the STEM (science, technology, engineering and mathematics) fields appears to be during the middle grades (fourth to eighth grade) [34]. To this end, adding engineering design projects to the middle grade curriculum may be an effective approach to improving the status and appeal of the more technical careers to a wide range of students.

Engineering design activities are not only an effective strategy for improving student motivation [35], but the integration of science, mathematics and technology can bring a deeper level of knowledge to the student [for review 36]. Design and engineering projects are able to fill the gap between factual content knowledge, abstract knowledge and application. Roth suggests that there are several key aspects relevant to teaching science effectively, all of which can be attained through engineering design projects [25]. Key aspects include developing and utilizing problems, projects or activities that:

- Connect classroom knowledge to authentic, compelling applications.
- Use cognitive modeling to create physical representations of science.
- Allow for change, either through multiple iterative projects or through cognitive iterations of projects.
- Combine different types of knowledge, including facts, concepts and skills, while exposing students to knowledge that is difficult to convey in formal training and education.

By creating and implementing a water resources unit at the eighth grade level, the attempt was to incorporate components of effective science teaching using an engineering module. In order to facilitate a deeper understanding of the scientific concepts of water quality, the students in the treatment group conducted an engineering design project where they designed, built and tested a water purification system, and then presented their findings to the class. The project provides students a new model for developing knowledge and provided a confluence of connected and complementary teaching avenues in an attempt to reach the multitude of science students in the class [14].

This engineering design project allowed students to develop their own working knowledge of water systems, treatments and purification methods within a community of practice framework. The learning environment developed through engineering modules encourages students to discover and explain natural phenomena and science concepts (*phenomenaria* [37]). These modules and projects are collaborative and provide social skills for the students, as they involve students assigning group and individual tasks, negotiating and delegating responsibilities, and developing working relationships with their peers [38, 39]. As opposed to teacher-driven knowledge construction (e.g. lectures), engineering modules support student-driven learning and the interdisciplinary nature of science, engaging students in creating their own knowledge based on personal and meaningful experiences [40].

The research study was developed with two controlled learning environments: one was a traditional, lecture-based classroom and the second was an inquiry, participatory classroom that included the engineering module. It has been argued that learning environments concentrating solely on the memorization of knowledge promotes a superficial understanding of science concepts does little to dispel alternative concepts and tends to stifle creativity and enthusiasm [41, 42]. Additionally, student learning in this environment is a passive process in which the teacher conveys knowledge to receptive students. The teacher may be providing the student 'all the correct answers' and/or telling the students what to study and memorize; however, this instructional method may not reach students who are disinterested in the subject or who have limited background and understanding of the language spoken in the classroom.

Compared to lecture-based pedagogy, project-based learning requires students to be active participants in the construction of knowledge. Students construct mental models that support the advancement of their conceptual understanding about science and science concepts [43]. This teaching style places learning in the hands of the students, allowing them to proceed at their own pace and to forge their own conclusions. Within this framework, the middle school student is introduced to lateral thinking, which is designed to stimulate students to think in a broader perspective and promote creative problem solving [9]. With engineering modules, students can be exposed to unstructured problems that they would experience in the real world and can learn to develop solutions that are scientifically, economically and socially feasible [9].

Three research objectives initiated this study:

1) to determine if an engineering module would allow students to develop more complex understanding of water purification methods and higher levels of scientific knowledge, relative to a traditional lecture-based teaching approach.
2) to assess whether students would develop more complex reasoning for water purification methods through the engineering module.
3) to understand the effects of engineering mod-

ules on traditionally disadvantaged student populations.

Through these objectives, the fundamental base of the project was to assess student learning through an engineering module.

METHODS AND IMPLEMENTATION

Subject population

A sample of 126 students from 10 eighth grade science classes (total population of students = 220) from an Indiana state-defined rural middle school (non-MSA) participated in this study. With project approval from the teachers and school administrators, student selection criteria were:

1) signed assent and consent forms by the student and legal guardian
2) responses to both the pre- and post-evaluation.

All parties were informed of their rights as study participants, and consent and assent forms were approved by the Institutional Review Board.

This population of students was chosen as they were already taking part in a larger grant, and two of the co-investigators were regularly involved in classroom activities through the NSF GK-12 program. These particular classes were selected for the study because the teachers were implementing concurrent units on water resources and water quality using different pedagogical techniques. Five science classes were taught using instructional formats such as lectures, notes and videos (control) while the remaining classes adopted a more inquiry-based approach to teaching and learning (treatment).

The ethnic background of the total enrollment of the middle school was 71 per cent White, 27 per cent Hispanic, and two per cent Multiracial/Other, with 57 per cent of the total student population receiving free/reduced lunches [44]. Table 1 shows the gender, race/ethnicity, primary language, socio-economic class (free/reduced lunch status), and overall science grade for the students participating in the research study. The individual grades for the students in the control group science grades were not provided. However, the average student grade for the control classroom was a 2.9 based on a 4.0 scale (A = 4.0, B = 3.0, etc.), similar to the average student grade in the treatment classroom (3.1).

All subjects were informed that they would undergo a pre- and post-evaluation concerning their views of safe drinking water, water quality and methods of water treatment. The evaluations were conducted approximately one week before and after the unit on human impacts on water quality in each classroom. Since the two teachers operated on slightly different schedules, the two groups of students did not necessarily complete the evaluations on the same day.

Curriculum and instruction

As the use of engineering modules is a relatively new shift to provide collaborative and high challenge, low risk environments, the American Society of Engineering Education (ASEE) set forth six guidelines to promote and improve K-12 engineering education [45]:

1) Use of hands-on learning.
2) Use of an interdisciplinary approach by incorporating technology and writing in math and science courses.
3) Engineering benchmarks in standards.
4) Use of teachers in K-12 outreach and curriculum writing, and increase teacher salary.
5) Use of mentors to make engineering fun.
6) Creation of better incentives for universities and companies to engage in K-12 outreach.

These guidelines were used in developing, creating and implementing the engineering module used in this study. For the treatment classes, the design project was to construct a working water purification device. Students were to detail and present their work, explaining how they decided on their design and how their device purified water. Classroom mentors were utilized as two graduate fellows worked in the treatment classroom.

Table 1. Demographic information for participating students. Gender, ethnicity and primary language spoken at home were obtained directly from the students through a questionnaire. No overall science grades were provided from the control classrooms; however, the average student grade was provided. Differences between the control and treatment average student grade was negligible (3.1 for the treatment vs. 2.9 for the control on a 4.0 scale). There was no statistical difference ($p < 0.05$) between the treatment and control group subject population

Group	Gender	Race/Ethnicity	Primary language spoken at home	Socio-economic status (fre/reduced lunch)	Overall science grade
Control (n = 60)	58% Male 42% Female	77% White 13% Hispanic 2% African-American 2% Did not know, did not answer	92% English 8% Spanish	68% Ineligible 32% Free/reduced eligible	
Treatment (n = 66)	36% Male 64% Female	68% White 18% Hispanic 6% Multi-racial 6% Did not know, did not answer 2% African-American	83% Englgh 17% Spanish	62% Ineligible 38% Free-reduced eligible	39% A 38% B 15% C 8% D 0% F

Table 2. National [4] and Indiana state [47] science standards the control and treatment classes utilized in their respective curriculum unit

National Standards	
Control	Treatment
Integrate all aspects of science content.	Integrate all aspects of science content.
Communicate scientific arguments.	Communicate scienfitic arguments.
Learn subject matter disciplines in the context of inquiry, technology, and science in personal and social perspectives.	Learn subject matter disciplines in the context of inquiry, technology, and science in personal and social perspectives.
Use activities to investigate and analyze questions.	Use activities to investigate and analyze questions.
Science as argument and explanation.	Science as argument and explanation.
Management of ideas and information.	Management of ideas and information.
Public communication of student ideas and work to classmates.	Public communication of student ideas and work to classmates.

8th Grade Indiana Science Standards	
Control	Treatment
8.1.6 Identify the constraints that must be taken into account as a new design in developed, such as gravity and the properties of the materials to be used.	8.1.4 Explain why accurate record keeping, openness, and replication are essential for maintaining an investigator's credibility with other scientists and society.
8.1.7 Explain why technology issues are rarely simple and one-sided because contending groups may have different values and priorities.	8.1.6 Identify the constraints that must be taken into account as a new design in developed, such as gravity and the properties of the materials to be used.
8.1.8 Explain that humans help shape the future by generating knowledge, developing new technologies, and communicating ideas to others.	8.1.7 Explain why technology issues are rarely simple and one-sided because contending groups may have different values and priorities.
8.2.7 Participate in group discussions on scientific topics by restating or summarizing accurately what others have said, asking for clarification or elaboration, and expressing alternative positions.	8.1.8 Explain that humans help shape the future by generating knowledge, developing new technologies, and communicating ideas to others.
8.3.6 Understand and explain that the benefits of Earth's resources, such as fresh water, air, soil, and trees, are finite and can be reduced by using them wastefully or by deliberately or accidentally destroying them.	8.2.7 Participate in group discussions on scientific topics by restating or summarizing accurately what others have said, asking for clarification or elaboration, and expressing alternative positions.
8.7.1 Explain that a system usually has some properties that are different from those of its parts but appear because of the interaction of those parts.	8.2.8 Use tables, charts, and graphs in making arguments and claims in, for example, oral and written presentations about lab or fieldwork.
	8.3.6 Understand and explain that the benefits of Earth's resources, such as fresh water, air, soil, and trees, are finite and can be reduced by using them wastefully or by deliberately or accidentally destroying them.
	8.7.1 Explain that a system usually has some properties that are different from those of its parts but appear because of the interaction of those parts.

Table 3. Open-ended questions for the pre-post evaluation. These questions were not assessed for correctness, but more for an understanding of how students viewed water quality issues in the US

1. When someone says that your drinking water is safe, what does that mean or what does "safe" mean?
2. What would make water "unsafe" for drinking?
3. Do you think the U.S. is able to provide people with safe drinking water? Why or why not?
4. Do you believe there are placed in the U.S. with unsafe drinking water? If yes, list places in the U.S. where you believe the availability of safe drinking water is an issue.
5. What can be done to make water "safer" to drink?

Table 4. True/false statements and answers from pre- and post-evaluations. One point was given for a correct answer, and zero points for an incorrect answer. Thus, the highest score achieved would have been 5 out of 5

Statement	0 points	1 point
1. Clear water is safe water to drink.	True	False
2. The lower the pH of the water, the safer the water is to drink.	True	False
3. Warm water has more dissolved solutes than cold water.	False	True
4. Water will purify itself, so there is no need to worry about safe drinking water.	True	False
5. To a certain degree, water can still be safe if there are some chemicals or solutes dissolved in it.	False	True

Table 5. Grading rubric for design question from pre- and post-evaluation. The question was as follows: assume you do not have access to safe drinking water. Design an effective device that could be used to make the water safe to drink. IDENTIFY what makes the water unsafe to drink and EXPLAIN how your design ensures safe drinking water. Use any means necessary to explain your answer, such as drawings, maps, or sentences. Use space on the back if necessary

Coding category	Score	Sample response
No Response; Irrelevant Response	0	"I don't know." "Go somewhere else."
Student is aware there are contaminants, yet does not correctly identify them nor explain design.	1	"Take all the bad stuff (dirt, germs, etc) out."
Student identifies 1 or more contaminants and provides incomplete explanation of how to remove them.	2	"Use a filter to remove the dirt."
Student identifies at least 2 contaminants and provides incomplete explanation and justification of how to remove them.	3	"Get rid of the dirt by using a filter with a pore size small enough that it can remove the dirt, and if there is bacteria and germs in the water, boil it for 10 minutes to kill them."
Student identifies all 3 contaminants. Uses evidence to justify and explain design.	4	"Test the water to see what contaminants are in it. Though it is best to remove as much contaminants as possible, a small amount can be in water for it to be safe to drink. To remove dirt and sediment, use a filter with a pore size small enough to be able to remove dirt particles. Boiling the water for 10 minutes can help to breakdown bacteria and germs by rupturing their cell-membrane. A slow-sand filter can help remove chemicals by causing the chemicals to attach to the sand, letting the water pass."

In comparison, the control classroom structure used a more traditional model of teaching, relying heavily on lectures and notes. The teacher of the five control classrooms estimated that 60 per cent of classroom time was spent on lectures, 20 per cent on hand-outs and worksheets, and 20 per cent on the final project. The treatment classroom teacher, however, focused more on active learning, with less than 10 per cent of total classroom time devoted to lecturing.

Coverage of the unit on human impacts on water resources and water quality included group projects in both classrooms; however, these projects differed greatly. Both classrooms used the same textbook and were expected to reach the same level of understanding through their curricular units on water resources and water quality. For the final unit project in the control classes, students were to design and draw their ideas for future human habitation in light of environmental changes and population needs. Students were provided only with paper and pencils to design and create their 'future city'. Students were expected to diagram and report on how the future city would operate and provide for its citizens. Students were evaluated on thoroughness of project details.

The treatment class' project centered on understanding local water quality issues with a laboratory exercise that allowed the students to test tap surface water samples from various locations in Indiana. To incorporate the engineering module into the unit, students were asked to create a tabletop apparatus to purify and ensure safe drinking water from a water sample. Students in the treatment group were placed in cooperative learning groups and tasked with designing a practical water purification system, which implied that the students could build it themselves with readily available materials. The teacher assigned cooperative learning groups for the students in order to separate social cliques and provide a working environment representative of the class as a whole (e.g. minority students did not work together and highly-motivated students were separated).

For the final assessment in the treatment classrooms, each student group was responsible for creating an informative and professional three-minute presentation regarding the effectiveness and specifics of their design. Having the students present their ideas and understand their activities was a method to encourage the integration of the scientific concepts, ideas and theories [43] and allow a more interdisciplinary approach. Evaluation of the final design project was based on several factors, such as how well the device ensured safe drinking water, how fast the water was purified, presentation skills, innovation of design and explanation of why/how the apparatus worked or did not work. The final presentations helped reinforce the concepts presented in the larger water resources unit and encouraged student reflection.

To conclude, the overarching goal of the unit in both classrooms was to understand the current state of water quality in the US and how individuals' actions impact the environment. While the unit goal between both treatment and control classrooms was similar (Table 2), the approach was not, which underscores the importance of this study.

Analysis

Students were asked to respond to eleven questions on a pre-post evaluation designed to elicit their conceptual understanding of water purification processes, as well as their thoughts regarding issues of water quality. Five open-ended questions focused on the human impact of the availability of safe drinking water (Table 3). Five true/false questions taken directly from the textbook common to both groups were included to assess factual knowledge of water quality (Table 4). The final question was a design question requiring students to describe and explain what was needed to ensure safe drinking water and how their purification design addressed the water quality issues they identified (Table 5).

To answer the design question, students were able to use drawings, words or phrases to explain their understanding of how water is treated and made safe for consumption (referred to as the engineering conceptual understanding). Students create images or drawings in order to make sense of their everyday experiences and understanding of the world [48]; it was believed that the design question would enable students to draw on their experiences and knowledge of clean drinking water. All responses to the design question were initially reviewed to develop codes associated with recurring themes, which were scored for use with statistical analysis.

The coding analyses in the open-ended questions and the design problem followed a content-driven systematic iterative process of text interpretation and categorization to establish patterns of importance [49]. First, the authors independently reviewed the data to identify meaningful descriptions or noteworthy statements related to the research questions. After meeting to compare preliminary findings and debate interpretations, they developed coding strategies through consensus; themes were subsequently derived from the series of coded statements to establish the main findings. The reliability of the analysis was strengthened by the diversity of perspectives that functioned as checks and balances in the analytical process and through a post-analysis examination for conflicting or disconfirming evidence. [50]

Student pre-post evaluations for the science and engineering scores were calculated into POMP scores, and the subsequent statistical results between control and treatment groups utilized these values [51]. General linear model was used to understand the effects of the teaching style (control or treatment) for the different student populations (e.g. minority and free/reduced lunch status), with a Tukey post-hoc analysis. The threshold for statistical significance was set at $p = 0.05$ (actual p-values are reported below). Evaluations that were left blank or that scored a zero were not included in the statistical comparison. Statistical analysis software used included SPSS 15.0 (SPSS Inc, Chicago, IL, USA) and NVivo 7.0 (QRS International, Melbourne, Australia).

RESULTS

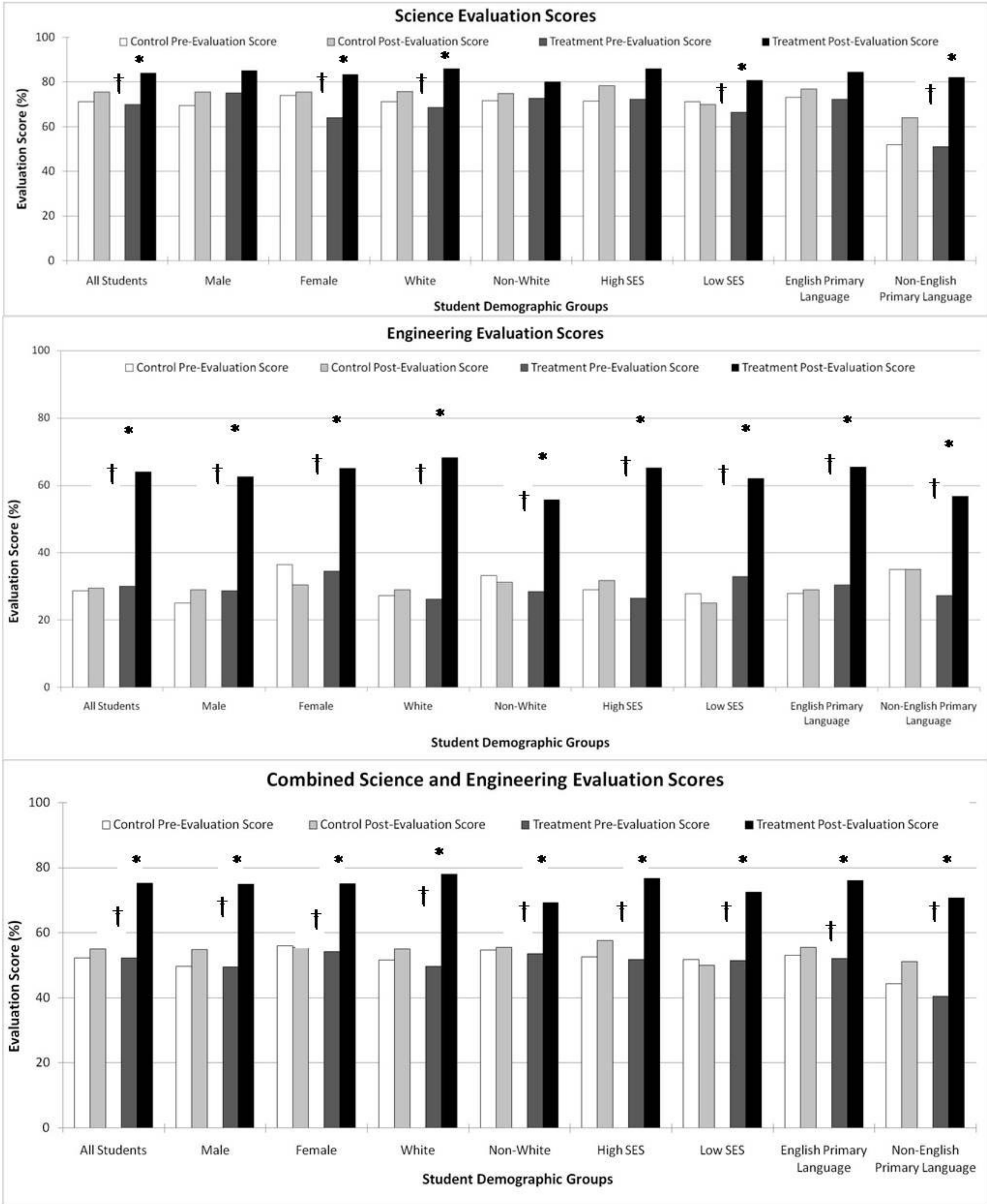
Overall, student learning was affected by the teaching strategy used, with the treatment group gaining a higher degree of improvement with the engineering module versus the control group's traditional teaching style of lecturing in both the science factual knowledge and engineering assessment (Figure 1).

There was no statistical difference in pre-evaluation scores on the five true/false questions between the treatment and control groups of students (t-test, $p = 0.71$). Post-evaluation scores, however, were significantly different between the control and treatment classes for the true/false questions (t-test, $p = 0.017$), with the treatment classes outscoring the control classes. Treatment students with a primary language other than English made the greatest gains (63.3%). In the open-ended questions, students in the treatment group noted that water quality and safe drinking water was a more complex enterprise, and their responses showed a much more developed response as a result (Figure 2).

Using the pre-evaluation helped indicate areas of confusion or misconception by students on a given topic and allows for directed instruction to clarify these topics. For the treatment group, the pre-evaluation indicated uncertainty regarding effects of impurities and definition of clean water. Although the pre-evaluations were only examined after the unit and post-evaluation were completed, the students in the treatment classes still made marked gains in the areas where they scored lower on the pre-evaluation; overall post-evaluation scores were significantly better than pre-evaluation scores (t-test, $p = 5.6 \times 10^{-6}$) .

A within group comparison showed students in the treatment groups made statistically significant improvement (t-test, $p = 3.17 \times 10^{-6}$) in the water purification design question, with their average number of procedural steps (complexity) in the design increasing, together with the depth of their understanding of the water purification process (Figure 2). There was no significant change in the control group's average engineering score and complexity from pre- to post-evaluation.

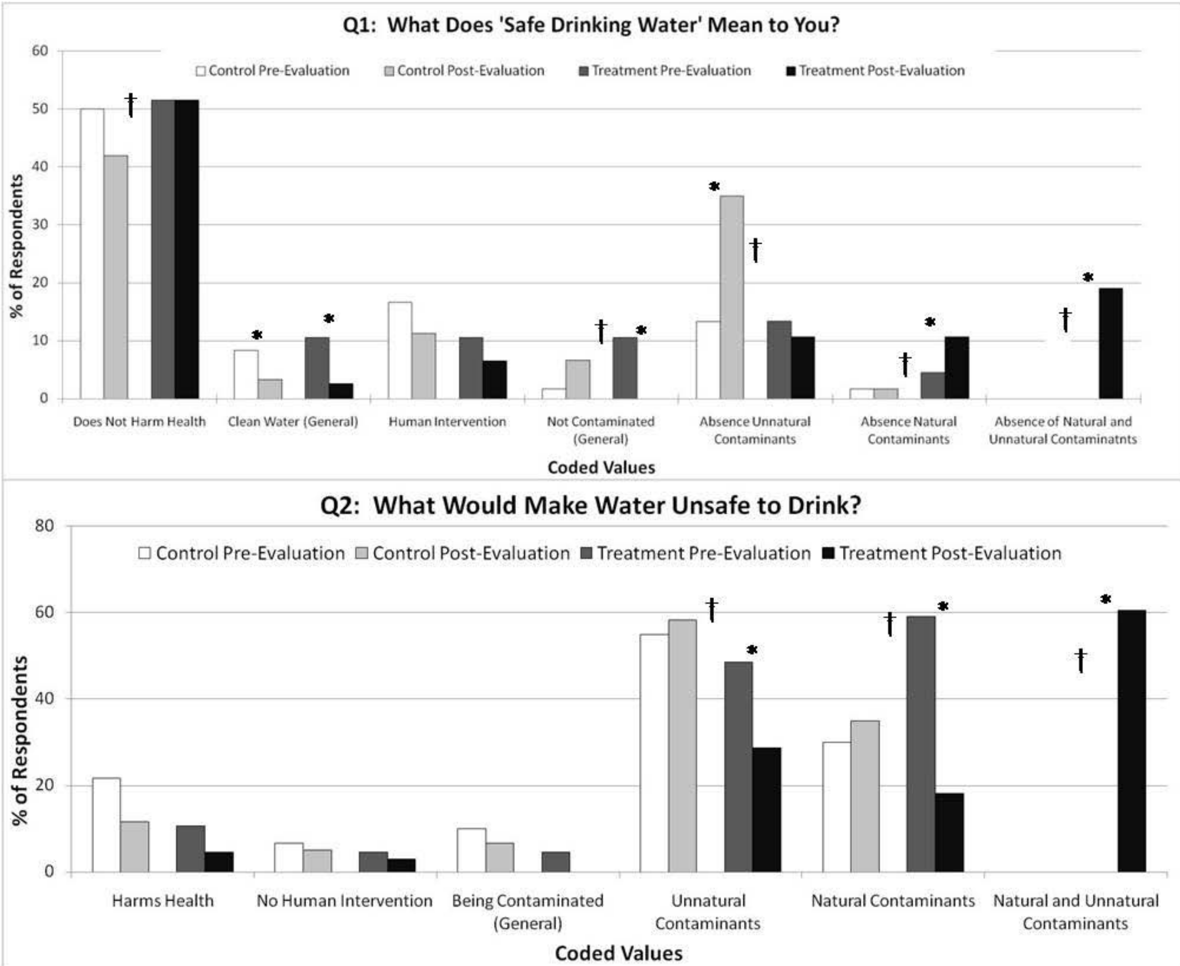
For the open-ended questions, treatment students were able to see water quality issues as more complex as a result of the activity as most students in the treatment class (60.6 per cent) recognized that 'unsafe drinking water' consisting of both natural (bacteria, germs, sediment, etc) and unnatural (pesticides, herbicides, various chemicals) contaminants. No students in either class held this view before the unit, and no students in the control room made this connection in the post-evaluation. Asking this question in reverse as what is 'safe drinking water?' showed a similar response, with only post-evaluation treatment students noting that an absence or minimal amount of natural and unnatural contaminants would yield safe drinking



* p value < 0.05 between pre- and post-evaluation scores
† p value < 0.05 between post-evaluations scores in the control and treatment classes

Fig. 1. Graphs representing the changes in student evaluation scores based on classroom (control vs. treatment) showing the differences in gains by the student demographic groups. Students in the demographic groups could belong to multiple groups (i.e. Hispanic males that did not speak English at home would have scores counted in the Male, Non-White, and Non-English Primary Language groups). SES = Socioeconomic Status, based on free/reduced lunch status.

water. With the last question, which asked how we could improve water quality in the US, treatment students were more likely than control students to state both human intervention (i.e. better treatment facilities, testing, or filtering at home) and increased societal awareness (i.e. deter people from polluting). Students in the treatment class were over five-times more likely to have this answer than control students. The dual response of human intervention and societal awareness shows student understand-



* p value < 0.05 between pre- and post-evaluation scores
† p value < 0.05 between post-evaluations scores in the control and treatment classes

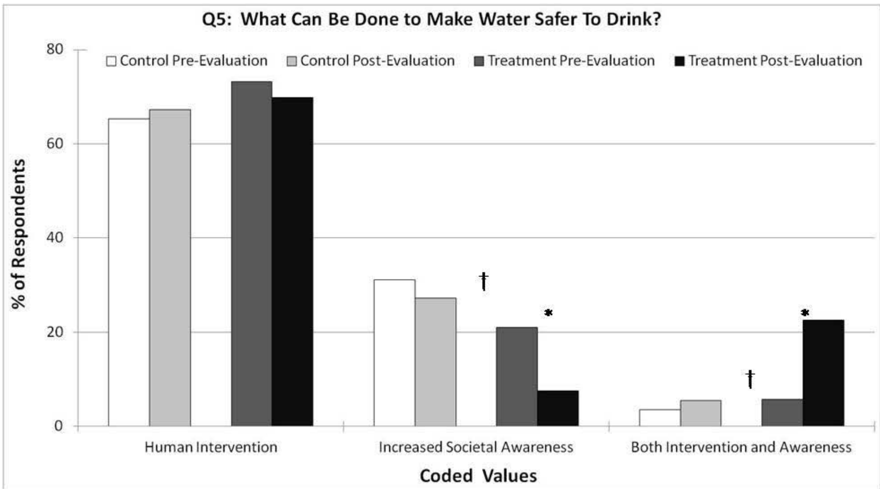
Fig. 2. Responses to open-ended questions regarding student thoughts on what makes what safe and unsafe to drink. The responses could have involved multiple codes and, as a result, the overall percentage is greater than 100 per cent. The only responses that were limited to one category were 'Absence of Unnatural Contaminants', 'Absence of Natural Contaminants' and 'Absence of Natural and Unnatural Contaminants' in question 1. In question 2, the responses 'Unnatural Contaminants', 'Natural Contaminants' and 'Natural and Unnatural Contaminants' were exclusive categories.

ing that water quality issues and resolutions are a result of multiple avenues of circumstance, action and intervention.

DISCUSSION

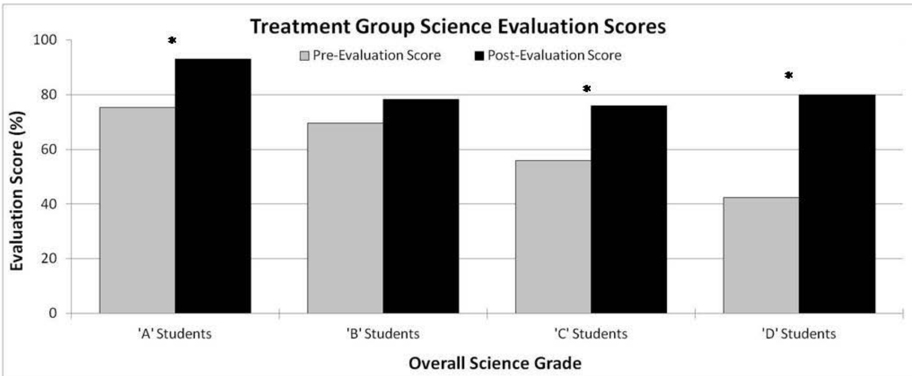
Our aim was to investigate how a community-centered approach to teaching and learning through an engineering module would influence student understanding of water and water quality, relative to a lecture-based style of instruction. Most notably, we found that students exposed to the engineering module improved their scientific understanding about water resources and management even though they were not 'taught' the material in a traditional sense.

In addition, students from traditionally disadvantaged backgrounds (ethnic minority students and students in the free/reduced lunch programs (low socioeconomic status)) reached similar end points as their counterparts in terms of science and conceptual understanding gains resulting from the engineering design unit. Differences in the treatment class post-evaluation scores as a function of students' overall science grades were statistically significant and noteworthy, especially in light of the 'No Child Left Behind' provision. Treatment class pre-evaluation scores for 'D' students were significantly lower ($p = 0.002$) than the 'A' students in the combined engineering and science score (28.7% vs. 59.0%). However, significant gains by both the 'D' students (53.3%) and 'A' students (57.3%) provided a similar ending point for both groups of students. This suggests that the engineering module was equally effective in reaching a wide spectrum of students, thus no children were left behind by this particular activity. The data suggest that engineering modules can positively enhance student learning, which in turn could



* p value < 0.05 between pre- and post-evaluation scores
† p value < 0.05 between post-evaluations scores in the control and treatment classes

Fig. 3: Student responses to the question, "What can be done to make water "safer" to drink?" The responses were exclusive to each category, meaning student responses were coded as human intervention, such as filter the water or build better treatment facilities, increased societal awareness, such as "tell people not to pollute" or deter people from contaminating the water, or both intervention and awareness to tackle water pollution with a multifaceted approach.



* p value < 0.05 between pre- and post-evaluation scores

Fig. 4: Graphs representing the changes in student evaluation scores based on final science grade in the treatment classes only. Significant increases were seen in the student evaluation scores pre to post in the 'A' students and 'D' students with all students reaching a similar end point.

encourage students to pursue more science and engineering classes and degrees as they continue in their education.

The success of students in the treatment class illustrates the benefits of incorporating elements of engineering into an eighth grade science classroom. Students who participated in the design activities showed a greater increase in factual knowledge of water quality and resources, as well as a deeper and more complex understanding of the water purification process. Although both teachers (treatment and control) structured class projects that allowed for freedom and creativity in design, the control group structure, with more lecturing and limited reality-based activity did not allow the development of conceptual understanding of the issues involved in water quality. This is shown in the student responses to open-ended questions as treatment students noted the complicated and multifaceted natures of drinking water issues. These results concur with other studies that marked gains can be seen through engineering modules and design projects [8, 15, 17, 52].

The engineering project also helped reduce the number of misconceptions that students held about water quality. A common misconception prevalent in the pre-evaluation for both classes was that chemicals could be killed—as one student stated, 'The chemicals in the water system would have to be killed for it to be safe' or killed as a result of boiling the water. However, in post-evaluation, there was a marked reduction in reference to 'killing chemicals', in the treatment group from pre- to post-evaluation (11 vs. 3), but not in the control classroom (11 vs. 12).

An important characteristic of engineering modules is allowing students to construct their own knowledge while also increasing their level of confidence in the material [21, 27]. Both control and treatment groups relied on team work for their final projects; it is likely that this also influenced students' knowledge gains. The use of cooperative learning and teaming activities enhances students' understanding by allowing them to build knowledge synergistically as well as promoting problem-solving abilities for all students [46, 53]. Implementing cooperative groups encouraged students as they proceeded in the project, yielding the conceptual goals of interaction, discussion and artifact development. It also demonstrates the importance of the collaborative nature of engineering, science and technical fields that facilitate the social construction of knowledge and cultivate generative and reflective thinking [53].

A high level of achievement by traditionally lower-performing students in the engineering activity also demonstrates the accessibility of engineering to a wide range of students. Many teachers are apprehensive about including engineering, thinking (incorrectly) that only motivated and intellectually-gifted students will succeed with engineering units. Our results contradict this assumption because all students performed well on the engineering unit; no one demographic achieved a greater or lesser degree than their peers, indicating low cultural or gender bias in the engineering module.

While there are some limitations to the present study, the insights gained are useful in promoting engineering modules at the middle school level. One limitation is that the pre-post evaluation was 11 questions, which is not sufficient to fully understand student knowledge and conceptual understanding gained through either teaching style. Though each section was geared toward assessing a particular type of knowledge, conceptual (open-ended), factual (true/false questions) or abstract (design question), it is difficult to delineate the type of knowledge integrated by the student most successfully through the project. Lectures and traditional teaching formats are geared towards understanding facts, so it was believed that students in the control classroom would outperform students in the treatment classroom on the true/false question. However, this was not the case as the students in the treatment classroom developed a greater understanding of the material presented as shown by their improved scores.

In the design question, students in the treatment group were at an advantage, having built, tested, and assessed the effects of the water purification process, but to ensure equal learning opportunity, the students in the control classroom were lectured on different wastewater purification methods, from the use of plants to clean water to the design of traditional wastewater treatment centers. Though it is understood that the designed evaluation does not truly assess student learning, the work presented does show that students can effectively learn conceptual and factual information from engineering modules. The use of a triangulated assessment, with interviews and observations, in addition to the written evaluation could provide insight into the level of learning achieved by students in project-based activities.

Another concern, especially for teachers, in using engineering units is that they might require increased work and effort than other types of approach. The implementation of a multi-week unit on water resources in the treatment classrooms was aided by the presence of GK-12 graduate fellows. The fellows were responsible for creating the activities and providing any extra assistance required by the students and primary teacher. This does not mean that engineering activities require additional instructors in the classroom; it is an ASEE guideline in utilizing engineering modules in the K-12 classroom [45]. While we do not know the long-term effects of the presence of GK-12 fellows, their sustained involvement with the middle school curriculum and instruction suggests a positive influence on student learning and participation in STEM disciplines. An interdisciplinary perspective was also evident in the water resources unit as it combined elements of earth and environmental sciences, language arts, engineering and geography.

This project and study followed the guidelines proposed for the inclusion of engineering modules in the curriculum and shows the positive learning effects for students. It also leads to more questions for future studies. The project work used cooperative learning groups within the classroom setting. Students were placed in groups based on science grade; the effects of using engineering modules when students work individually or in another style of group placement are unknown. Though engineering, in practice, is often performed in a team, the ideal method for grouping students within this education framework is unknown and warrants future investigation. Further, the long-term effects and learning utilizing engineering modules is unknown. Short-term gains were seen with this curriculum design versus a traditional lecture-based curriculum, but how students retain knowledge through this framework is unknown. Future studies to address the long-term benefits of engineering education should be initiated; with it, the effects on career choice and aspiration can also be explored. With the historically limited number of students pursuing engineering and graduating, this is an important aspect to study to better meet the needs of today's (and tomorrow's) society.

CONCLUSIONS

The results of the analysis of the impact of an engineering design module in middle school science learning provides additional support for those who advocate the inclusion of engineering modules and engineering education as an integral part of the middle school science curriculum. This work showed that students involved in an engineering module outperformed those in a more traditional, lecture-based format. It was also found that all students achieved high levels of improvement; there was no difference based on grades, race and ethnicity, socio-economic status and gender. From this data, it was concluded that the use of engineering modules enhances understanding of science for a wide range of students.

Middle school lays the foundation for high school coursework, setting up students for success in higher education studies in STEM disciplines. Therefore, exposing students to engineering modules and nurturing student creativity in such activities facilitates a deepening of their knowledge as well as providing meaningful experiences that promote the field of engineering. Additional studies are needed, however, to evaluate the lasting effects of exposure and participation in engineering modules, as well as the optimal timing and frequency of such activities and curricular units to increase student interest in and attraction to the STEM fields. Nonetheless, the goal of increased engineering education in the K-12 curriculum is not only to create more engineers, but to enhance students' critical thinking skills and their ability to construct their own knowledge, and this research shows engineering modules support these objectives.

Acknowledgements—This material is based upon work supported by the National Science Foundation under Grant No. 0538643. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The authors would also like to acknowledge Brenda Capobianco from Purdue University for her assistance, guidance and critical review of the manuscript.

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