

## **Integrating Engineering, Innovation, and Research at All Levels: An Educational Model for Water Reuse Design**

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## Abstract

Growing urban populations, increasing water consumption, and decreasing predictability of climate all point to an ever-increasing need to improve water-use efficiency and watershed management around the world. Moreover, providing clean water and restoring the nitrogen cycle are two of the fourteen National Academy of Engineering Grand Challenges that future engineers will need to act upon. Therefore, treating once-used water on-site to safe effluent-reuse standards—rather than using the water just once and flushing it back to an expensive, high-maintenance centralized treatment plant—has the potential to help address these challenges by restoring the local water-nutrient cycle.

With these considerations, during the spring of 2016 a capstone project at Northeastern University was designed to task civil and environmental engineering students to provide solutions to those Engineering Grand Challenges. The project involved the selection of an on-site wastewater reclamation and reuse technology, followed by the design, construction, and operation of a pilot system to test the selected technology, as well as the creation of educational material including a website for educational and outreach purposes. The project was presented internally at the university-level and at a regional student design competition related to water, for which the students received first place, and had access to participate at the national level competition. The project was finally handed to the Civil and Environmental Engineering department, and it has been used for research both by high school students as part of the Young Scholar Program (YSP) over the summer of 2016 and by several undergraduate students since September 2016.

This paper will discuss the implementation of this hands-on capstone project that along with providing students with a high-quality curriculum, research opportunities, and exposing them to real world problems, this project-oriented capstone initiative helped equip the next generation of engineers to make a valuable contribution and put them at the forefront of education, engineering, and innovation.

## Introduction

Design is widely considered to be the central and the most distinguishing activity of civil engineering. It has long been understood that engineering institutions should graduate engineers who could design effectively to meet societal needs. Capstone programs vary widely from school to school and a single definition or format that applies to all programs does not exist [1]; however, a comprehensive culminating design experience is usually provided in a capstone program. For Durel (1993) “a capstone course should be a synthesis, reflection and integration, and a bridge or a real-world preparatory experience that focuses on the post-graduation future”

[2]. Dutson et al. (1997) [3] reviewed more than 100 papers describing capstone experiences in engineering education, presenting differences and similarities among institution and among different engineering departments. Capstone projects in civil engineering usually involve detailed analysis and design; however, the construction of prototypes with testing and analysis is not a common component, in contrast to other engineering disciplines (e.g., mechanical engineering).

Traditionally, the civil capstone at Northeastern University has been divided in 3 areas: structural, transportation, and environmental. Using teams of 4-5 students that are advised by a faculty member and engineering practitioners, students design a civil engineering project that primarily involves the selected sub discipline, and are tasked to propose a design solution to a specific issue (e.g. for environmental: wastewater treatment plant upgrade to meet specific limit, design stormwater management solution for new development, remediation design for contaminated site, etc.)

In the spring of 2016, a new approach to capstone was experimented for one environmental engineering capstone project. As five of the fourteen National Academy of Engineering (NAE) Grand Challenges for Engineering are directly related to civil/environmental engineering (solar energy, carbon sequestration, nitrogen cycle, clean water, and infrastructure), it seemed to be appropriate to use the NAE framework and topics to have a new approach to the civil engineering capstone projects that include hands-on project experience, innovation, and service-learning in addition to the traditional design-only scope.

Research scientists have pointed out at the International Geosphere Biosphere Program (IGBP), that big-pipe drainage and water-infrastructure projects are a potential driver of climate change due to the aggregate effects of man-made water withdrawals and discharges on the surface-energy budget of land-atmosphere interactions. This conclusion has been also supported by a report for the American Society of Civil Engineers (ASCE) Task Committee on “Infrastructure Impacts of Landscape-driven Weather Change,” in which the Committee “*argues for explicitly considering the well-established feedbacks triggered by infrastructure systems to the land-atmosphere system through landscape changes*” [4].

These complex feedbacks—changes in precipitation patterns, surface-energy budgets and evapotranspiration, and so on—derive from loss of groundwater and surface water due to human development and water withdrawals, channeling of large volumes of water out of developed areas, and into undeveloped areas at rates greatly out of balance with natural flow regimes. Many of these issues arise from a centralized approach to water resource management in urban areas, and a decreased reliance on large centralized water infrastructure projects may help decrease the feedbacks which themselves may negatively impact our water supplies, or at least contribute to the uncertainty of regional and global climate.

Additionally, the Metropolitan Area Planning Commission has stated in its report on reuse in the Boston area that: “[A] *deliberate and sustainable approach to water resources [must be taken] if*

*we are to expand economic development and maintain our high quality of life... [One strategy is] reclamation and reuse of treated wastewater for non-potable uses such as landscaping, industrial processes, and toilet flushing... Public education is vital and pilot projects are needed to demonstrate the feasibility of water reuse” [5].*

In accordance with the above, this paper will discuss the implementation of a hands-on capstone project that along with providing students with a high-quality curriculum and research opportunities, this project-oriented capstone initiative that exposed them to real world problems, helped equip the next generation of engineers to make a valuable contribution and put them at the forefront of education, engineering, and innovation.

## Methods

### - Selection Process of Capstone Projects Topics

The topics of the projects usually originate from consultation with the senior class, which occurred in the fall semester. The formal request for proposal (RFP) for the different projects are created by the faculty in collaboration with external clients (industry and towns) who are contacted by the advisor prior the beginning of the semester. The capstone instructor prior to assign teams require the submission of qualification in which each student must highlight his/her experience and its relevance to a preferred project. The students prepare a cover letter, a resume, a summary slide, and a presentation to the class. Students with complementary skills and interests for a specific project are put together in a team and are required to prepare a project proposal to answer the RFP. After the formal proposal is received, each team is invited to make a formal presentation for each project.

During the presentation, the students are required to demonstrate understanding of the project, the needs, and the approach. If the instructor considers the proposal from a team as satisfactory, a project is awarded and the students can start working on the project. All capstone projects involve: (a) understanding the problem from a client’s perspective, (b) formulating, designing, and comparing alternatives, (c) applying engineering standards and modern computing tools, and (d) consideration of economics, aesthetics, sustainability, manufacturability, and impact to the natural environment, ethics, social impact, political context, and public health and safety.

- New Approach for Capstone Projects: The Grand Engineering Challenge Capstone Providing access to clean water and restoring nitrogen cycle were two of the 14 NAE Grand Challenges for engineering that were selected for the Grand Engineering Challenge Capstone in the Spring of 2016. Treating once-used water on-site to safe effluent-reuse standards, rather than using the water just once and flushing it back to an expensive, high-maintenance centralized treatment plant, has the potential to help reverse this trend by restoring the local water-nutrient cycle and to reduce the urban heat-island effect. Moreover, as a response to the need of pilot projects to demonstrate the feasibility of water reuse and help overcome the perception to see wastewater as waste and not as an opportunity, this new approach was also a call to include an educational/outreach component in the proposal.

Per the above, a RFP was created and presented to the environmental engineering capstone students. A team of four students from the department of Civil and Environmental Engineering, who prepare a proposal for that specific RFP, was challenged to answer this call for pilot projects demonstrating on-site wastewater reclamation and reuse. The students had to first analyze various technologies, and then propose, design, build, and operate a pilot of the selected technology. To cover construction costs, the College of Engineering allotted an approximate budget of \$2000.00 for the construction materials of the system, including components that the infrastructure lab could appropriate and make use of should the system cease to be a research project of interest.

#### - Capstone Project Execution

Given the timeline the design team faced to complete the project, the design of the pilot system was conducted on an aggressive schedule while construction of previously designed components was ongoing. The design and construction process followed this general time line: treatment cell construction, hardware selection and ordering, treatment-media sourcing and acquisition, electronics prototyping and design, inoculation and start-up, testing and fine-tuning. The construction materials cost came to just over \$2080.00, total. A video timeline of the construction is available on the created website (<http://www.northeastern.edu/waternotwaste>).

The preliminary design included site location selection, sizing of the different components and selection of material and equipment, as well as a cost analysis. The full-scale system was proposed to treat the wastewater flow from 3 residential halls in the university campus and a site was selected based on factors such as available open space, surrounding residential density to ensure adequate flow, utilization of existing infrastructure (sewage and drain pipes), potential impact on campus community activities, and potential visibility for off-campus visitors, staff and internal and external students for educational/recruiting and aesthetic purposes. The decentralized plant was designed to achieve the highest water-reuse treatment tier, allowing for a variety of reuse opportunities including toilet flushing in the adjacent buildings and surficial irrigation of the surrounding lawn.

In addition to the hands-on component (the pilot plant), the students had to produce a preliminary design for a full-scale system implementation within the campus, as well as develop an outreach/educational program, and on top of that, to address the educational component of this project, the students developed lab handouts for undergraduate students, and research questions that could be pursued at different educational levels (high school through graduate level).

## Results

The technology selected was a living machine, known as Tidal flow wetland patented by Austin and Lohan [5]. The built system, shown in Figure 1, exemplifies a sustainable approach to water resources management, and it was selected for its ability to blend well into the campus environment, and because the academic review undertaken by the design engineers revealed that

this type of system is purported to have the ability to treat wastewater to the same effluent standards as more industrial-type systems (such as a membrane bioreactor) with a much lower energy and chemical footprint and higher educational value. Similar systems have been installed at several educational institutions throughout North America (examples at <http://www.livingmachines.com/Home.aspx>).

The hands-on element of this capstone helped the students develop additional skills to the ones typically developed during a design-only capstone. The core outcomes of this design-and-build project, in addition to the ones already presented were:

- Design and construct to design specifications.
- Engineer a solution to a real problem.
- Computational programming skills – C++, Matlab, using programmable microcontrollers.
- Numerical analysis and calibration of sensors
- Create and execute operation and maintenance plans.

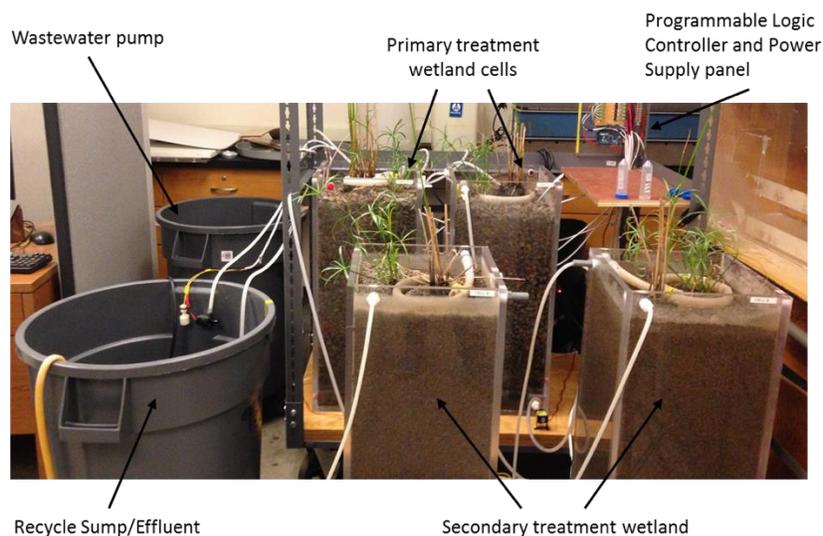


Figure 1 Tidal flow wetland: A sustainable approach to water resources management

Additionally, the students created a website that highlights the wastewater reclamation system designed and addresses the stigma against reusing wastewater. The main goals of the website “Water Not Waste” (<http://www.northeastern.edu/waternotwaste>) were to (a) educate the public about the importance of responsible water use, (b) demonstrate the benefits presented by greywater and black water reuse systems, and (c) help destigmatize wastewater reuse.

The website met these objectives by including the following:

- Graphical representations/images of the construction and operation of the pilot-scale system.
- The embedded concept of harnessing natural processes to sustainably manage wastewater as a renewable resource.

- Organized resources and links to help K-12 educators find funding for lessons/programs in STEM and sustainability topics.
- Downloadable lesson plan, student handout, and classroom presentation for a middle school lesson related to reusing wastewater.
- Interactive landing page graphics including a virtual house with water usage facts and a wastewater “fact or myth?” Quizlet.
- Descriptions of the different overarching engineering disciplines for secondary students.
- An interactive questionnaire for individuals to determine their daily water usage in gallons and suggestions to improve.

A schematic of the website components is presented in Figure 2.

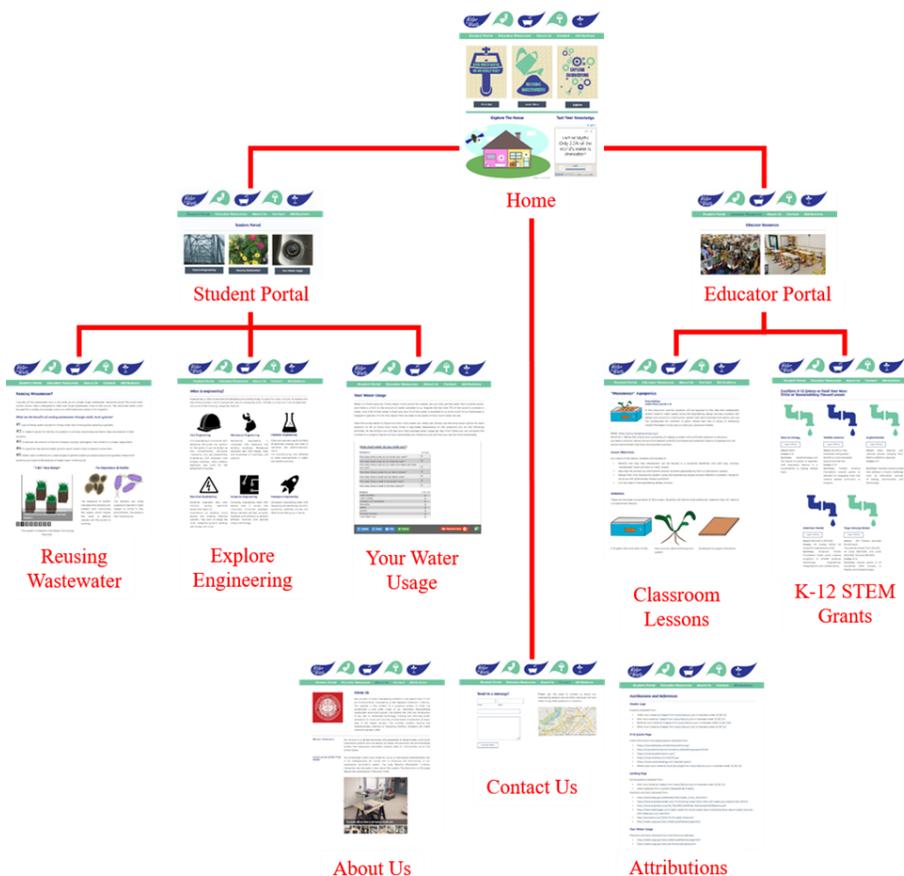


Figure 2. Website organization to meet goals for students, educators, and public in general

## Discussion

Once built, the pilot system serves two purposes, as a research tool and as an educational tool. First, as a research tool for undergraduate and graduate students, this system can be used to build data to show the reliability of tidal flow treatment as a decentralized wastewater treatment

approach for residential wastewater, or to research optimization of constituent removal by assessing the impacts of adjusting various treatment parameters (recycle ratio, treatment cycles per day, etc.), or to comprehend the physical, chemical and biological processes occurring in the system and their complex interaction. And second, the pilot could also serve as an educational tool because the system can be used to teach undergraduate students about alternative wastewater treatment, fluid dynamics and hydraulics, material properties, and even programming using Arduino and C++.

The outreach/educational component, was also deemed necessary for this capstone project. Indeed, literature suggests that the major obstacles in the widespread application of water reuse projects are the public perception and the institutional barriers [7, 8]. Therefore, addressing the stigma of water reuse through education and outreach was vital, together with the pilot, to demonstrate the feasibility of water reuse technologies.

The different portions of the website were aimed toward three main audiences: students, educators, and general audience. These audiences overlap but certain pages are directed toward one of these specific groups. The pages under the student portal of the website are geared toward secondary students. However, the student page “reusing wastewater” could be used to introduce undergraduate students to the function and operation of the pilot model. The target audience of the educator resources tab is primarily middle school educators. Although much like the student portal, this section will also eventually include information for the undergraduate level, including potential labs for the pilot model to be used in the undergraduate classroom. Table 1 explains the audience and the corresponding webpage and shows the skeleton of the website as illustrated in the results section. The audience is either explicitly stated on each page or implicit by inspection.

Table 1. Website components and audience.

<b>Home/Landing Page</b>		
Interactive House		Students/General Audience
Wastewater Quizlet		Students/General Audience
<b>Student Portal</b>		
Reusing Wastewater		Secondary/Undergraduate
Explore Engineering		Secondary
Your Water Usage		Secondary/Undergraduate
<b>Educator Resources</b>		
Classroom Lesson		Middle School Educator
K-12 Grants		K-12 Educators
Undergraduate Labs		Undergraduate Instructor
<b>Other</b>		
About Us		All Website Visitors
Contact		All Website Visitors
Attributions		All Website Visitors

In addition to the website and its content, the students developed three outlines for lab sessions for the civil and environmental students at Northeastern University that utilize the pilot system. These lab sessions were classified as physical, biological, and ecological, based on the topic (see example in Figure 3). The first laboratory exercise on the hydraulic characterization of media was fully developed and the experiments were based on the experience/knowledge gained during the building and testing of the pilot. Finally, in the final recommendation section of the capstone report, the students proposed several research themes/projects for undergraduate and graduate to undertake, as well as STEM related activities at Northeastern University.

Physical: Media choice is paramount when it comes to designing the most efficient system possible. In this lab we will analyze the relationship between media size, permeability, and porosity.

- Objectives:
  - Conduct porosity and permeability tests
  - Conduct sieve analysis
  - Understand physical properties of the media
  - Correlate to how media size can affect a wastewater treatment system (in the form of a question set at the end of the lab)
- Methodology:
  - Three different soil samples with different particle sizes will be used to conduct the tests
  - Utilize standard methods in existence for porosity and permeability tests, as well as sieve analysis

Figure 3. Exemplary undergraduate lab abstract

During this first trial of the Grand Engineering Challenge hands-on capstone, the team had the same requirements and expectations in terms of report preparation and presentation, as other capstone teams without the hands-on component. The report, in comparison to previous and concurrent capstone reports reviewed by the instructors, was of the same quality and received a high grade (A). It is important to highlight that as all capstone projects, this one was presented internally at the University level; and then it was presented at a regional student design competition related to water, for which the students received first place, and had access to participate to the national level competition.

We recognize that the hands-on component requires extra work and time, and the success of the project was in large part due to the dedication of the team members, who worked tirelessly for the completion of the project (the educational and the design/construction components). A suggestion which was put forward after receiving the students' feedback was to have the "Grand Engineering Challenge Capstone" to be part of a Grand Engineering Challenge Scholar Program (GCSP) which is a College-wide initiative and the department of Civil and Environmental Engineering is planning on institute soon. Therefore, in future applications of this hands-on capstone model, the team (or at least some team members) will be part of the NAE Grand Challenge Scholars Program, and additional credits will be granted to the students completing this capstone for the extra time and effort involved and the contribution made.

## Current and Future Use: Research and Outreach

After the conclusion of the capstone, the first opportunity to use the system in outreach/research was within the Young Scholar Program (YSP), a very successful program lead by the Center for STEM Education at Northeastern University. The YSP is a 6-week summer program that offers future scientists and engineers a unique opportunity for a hands-on research experience while still in high school. The program is open to local applicants who have completed their junior year of high school (i.e. rising seniors). Over the summer of 2016, two rising seniors were assigned to work under the guidance of the PI(s) on a research project related to water reuse. The students were also asked to review the content of the website and create additional material, such as a glossary, to be added to the website. Finally, as part of the program, the students prepared a poster and gave an oral presentation about their project.

After the YSP program finalized, the pilot system has been and is currently being used for two research projects performed by a group of undergraduate students. A total of 5 students have worked on these two projects over the last six months. Both projects were sponsored by the Provost Office through the Undergraduate Research and Creative Endeavors Award program.

## Program Assessment

The assessment of the students' experience has become an important goal for higher education institutions. A full assessment of the experience is still in progress, but a preliminary evaluation of the program has been carried out. As part of this study, two different questionnaires (post-program interviews) were designed to solicit feedback concerning the students' satisfaction and expectations during their capstone or YSP experiences, as well as specific learning skills related to communication skills, research skills, and technical competence. Likert scale was used in all questions. 100% of the participants of the capstone project voluntarily participated in the survey (n=4), as well as 100% of the participants of the YSP program (n=2). The undergraduate research project is still ongoing, but a mid-program questionnaire and comments were solicited. Some of the extracts of the assessment are presented below.

### - Capstone Project Assessment

A set of 3 questions was formulated to understand the satisfaction level of the sample with the experience. To the question 'Q1: *The additional hands-on component of your project scope enhanced your capstone experience?*' 100% of students strongly agreed. To the question 'Q2: *The additional educational component of your project scope enhanced your capstone experience?*' 50% of the students strongly agreed, 25% agreed, and 25% reported neutral. Finally, to the question 'Q3: *Knowing the end use of your built project component enhanced your capstone experience?*' 75% of the sample reported that they strongly agree, and the other 25% reported that they agree.

Comment from question 1:

*“The hands-on component enhanced the capstone experience in a number of ways, first by enforcing a much more pragmatic awareness of budgeting and sizing issues than perhaps may have been realized if we were dealing solely with a theoretical design basis. Second, the hands-on component created the very real necessity of including lead-time for ordering and constructing necessary components. Third, the opportunity and necessity of trouble-shooting the initial design concepts in prototype helped not only to reinforce the constraints of theoretical equations and the need to adapt to reality after initial design, it also dramatically enhanced our understanding of the minutiae behind the design concepts, including everything from logic errors in programming functions, accidental siphons created during excessive pumping stages, to analyzing actual data to assess performance against expectations.”*

*“I truly feel that engaging in this hands-on capstone project created a synthesis of theoretical and practical application of knowledge that engineers need on a regular basis. It is easy after four-to-five years in primarily theoretical course-work to be a bit one-legged in our design efforts, and the opportunity to mix informed design theory with hands-on production practice strengthened the other leg, so to speak. Finally, working with the lab technicians was without a doubt the most rewarding experience I will remember at the University - the level of interest and participation they provided was wholly unexpected. I learned as much from them as I did from any professors in other coursework. Thanks again for a great experience!”*

*“As an engineering capstone, I felt the educational portion, while interesting, took too much focus away from the objective of the capstone course. However, the hands-on aspect of the project elevated my learning well beyond what the typical capstone project would have. I would do it again for sure, perhaps without the education portion”*

*“The weekly meetings with our advisor definitely helped us keep on track and stay responsible for completing what we said we'd complete each week and was a good outlet for questions and getting suggestions. Also, would highly recommend having a hands-on portion of capstones – hands-on experience reinforced the concepts of what we were learning about.*

Comment from question 2:

*“Working with the education team in an effort to inform non-technical users of the practical effects of the project helped the technical group to periodically pull back to a broader perspective, thus strengthening our communication skills after sharpening our technical skills.”*

Comment from question 3:

*“Not only did knowing the end use motivate our efforts because we were happy to be serving that end, but also we were able to incorporate thoughts about end-user convenience into our design.”*

*“The opportunity to leave behind a project that created additional learning opportunities for future students in a field of study that interested us and did not explicitly exist at the undergraduate level prior to our work was a great reward for our efforts.”*

- Young Scholar Program Assessment

For this program, a set of 5 questions was developed to understand the level of satisfaction as well as the expectations the participants had before and after participating in the program. The questions asked and the results obtained are shown below:

Q1: *How familiar were you with the tidal flow wetland system chosen and tested before the program?*

Q2: *How familiar were you with the tidal flow wetland system chosen and tested after the program?*

Q3: *The research experience by using a model built by an engineering capstone project allowed me to:*

(a) *Learn about a technical engineering topic (water reuse) that I did not know much about.*

(b) *Develop and apply new skill sets on*

(1) *Research (perform experiments)*

(2) *Communication (oral presentation, poster preparation, website material creation)*

(3) *Address sustainability issues (water reuse)*

Q4: *How useful did you find the experience for making the decision of which degree you would like to pursue?*

Q5: *After participating in the project, did the experience meet, exceed, or not meet your expectations*

100% of the students said that they were not at all familiar with the wetland system before the program (Q1); and 100% answered that they were somewhat familiar with the wetland system after the program (Q2). To questions Q3a, Q3b1, and Q3b3, 100% of students strongly agreed, while to question Q3b2, 50% of students strongly agreed and the other 50% agreed. Finally, to question Q4, 100% of the sample said that it was very useful, and to question Q5, 100% of the students said that the experience greatly exceeded their expectations.

- Undergraduate Research Project Participants

A full assessment of the research program is still underway, however some of the comments received in the mid-program evaluation are reported here.

*"I've enjoyed working with the system because of how clearly it demonstrates nitrogen removal."*

*"It's been a really awesome to experience a lab setting and see how research works. I'm so glad I got to work with some graduate student through this because he's taught me so much about water treatment, different research methods, and lab protocol, which has really enhanced my experience. As for the TFW project in particular, learning about the testing and analysis of water has been really interesting. Also, this project has made me consider doing something with water treatment in the future, which I hadn't really considered before. I really*

*like the idea of the biological process and trying alternatives that are more sustainable. And it's really beneficial to have what I'm learning in class, reinforced by what we do in the lab. Overall, it has definitely enhanced my college experience!"*

## Conclusions

Results of this study suggest that the integration of engineering, innovation, research, and outreach/education are key to create challenging capstone engineering projects with a purpose. Further research is clearly needed regarding this topic to elucidate additional and new ways to train engineers and to engage the future generation of engineers to work on emerging solutions and to be aware of the threats to quality of life and the depletion of nonrenewable resources that are problems of growing concern.

This study has one important limitation that should be considered. The size of the sample is limited due to the novelty of the application of the hands-on capstone design with an outreach/educational component. Therefore, we do not claim that our satisfactory experience constitutes a proven effective integration of engineering, innovation, and research at all levels. We also do not claim that implementing hands-on capstone projects with education and outreach as the end of the built project will guarantee that all students participating in future versions of the YSP or any other type of activity involving high school students will perform at a high level or exceed their expectations as it was obtained during this first experience. However, it is important to remark that the performance of an individual student depends on several factors, many of which are out of the instructor's control. The well-structured program and different approaches designed and deployed in the Department of Civil and Environmental Engineering at Northeastern University, as well as the commitment of the participants and the instructors, were all key factors to obtain a first successful experience that will be replicated and documented as part of new teaching methods for the redevelopment and modernization of engineering education and engagement of high school students to be part of the new generations of engineers that will face growing challenges in a very complex world.

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