The River Project: an Open-Ended Engineering Design Challenge from Bench-Scale to Pilot-Scale

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Dr. Courtney Pfluger received her Doctoral degree in Chemical Engineering from Northeastern University in 2011. In the fall of 2011, she took a position as an Assistant Teaching Professor at Northeastern University in the College of Engineering as a part of the First Year Engineering Faculty with a focus on chemical engineering. She has taught the first year courses, Engineering Design and Engineering Problem Solving, and Chemical Engineering Process Controls and Conservation Principles courses. In the summer of 2013, she developed and ran a faculty led Dialogue of Civilizations program to Brazil where she taught two courses that focused on Sustainable Energy Technologies and Brazilian Culture. This program has successfully ran for 5 years and continuing! She was instrumental in the development of the curriculum redesign of the first year program called the Cornerstones of Engineering. In the fall of 2014, she piloted a section of the Cornerstones of Engineering that was focused on sustainability as the theme. The pilot course of the redesign of the first year curriculum was successful and has now been implemented to all first year engineering students at Northeastern. Dr. Pfluger has also spent her time volunteering as Faculty Advisor for the American Institute of Chemical Engineers (AIChE) and ChemE Car student groups. The ChemE Car team competes annually at the AIChE regional conference. The NU-AIChE student group organizes many Chemical Engineering and College of Engineering community building activities throughout the year.

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Abstract:
Northeastern University has developed a two-semester approach to the Unit Operations Laboratory introducing different modes of learning through a Discovery, Development and Design approach. Students are introduced to broader concepts that allow them to develop skills in designing experiments and analyses (discovery), build upon those concepts while working on equipment to address specific problem statements (development), and then apply their knowledge and experience in designing an experiment, unit operation, or system (design). The first semester focuses on fluid mechanics, and the second semester, emphasizes heat and mass transfer and separations.

The culmination of these two semesters is a four-week design challenge on water remediation. For this project, students design and build a small circulating river system with multiple design characteristics, such as including stagnation, rapids, and an environmental setting (e.g. rural vs. urban). The student teams then select a pollution scenario (run-off or point-source, and sewage waste or industrial waste) which they will then have to design a treatment system for in order to meet the clean-water standards for rivers as determined by the Environmental Protection Agency. Simulated pollutants containing both chemical and particulate contaminants with unknown compositions are provided to the students for them to conduct bench scale testing as they design and construct their treatment system to address pH, dissolved oxygen concentration, conductivity, turbidity, and temperature. Using basic chemicals and novel filtration designs, students implement an integrated understanding of fluid mechanics, mass transfer, separations, thermodynamics, and kinetics in order to characterize their systems and execute their remediation systems over two trials within their river. The project concludes with a technical report written as from a company to a town council to propose their full-scale treatment system. The project also finishes with a novel presentation in which the student teams must give a town hall-style presentation and defend their proposed treatment system to an audience of upper classmen, faculty, and alumni, who act as local citizens and ask probing and demanding questions of the presenters.

Our presentation will describe the methods, details, and assessment of a unique and fulfilling laboratory module.

Background:
Northeastern University's approach to teaching Unit Operations to chemical students focuses on a two-semester, two-course series of instruction utilizing a Discovery, Development, and Design approach to learning. These courses are loosely affiliated with two Transport classroom courses

with respect to course topics, but are conducted separately and are addressed as separate overall courses.

The Discovery, Development, and Design (3-D) approach is a pedagogical style that structures experiential learning so that students draw connections between their introduction to new concepts, the application of those concepts in larger and more complex systems, and the opportunities to apply their gained knowledge and experience within an open-ended project. Discovery uses curiosity and imagination to build connections between fundamental phenomena and personal experience. Discovery can be simply encapsulated within the statement of "What happens when . . .", and allows for introduction to classroom concepts, experimental and analytical design. Development uses knowledge of these relationships discovered in the Discovery stage to develop an experimental plan. This plan allows students to test hypotheses of system behavior and quantify relationships among variables, usually within an industrial-scale system that operates based on the concepts previously introduced. Design then allows for the broadest application of experiential learning. This stage drives students to create an experiment answering a specific problem, or find a solution to a specific challenge dealing with fundamental properties; Design effectively incorporates inquiry, discovery, experimental methods, open-ended problem identification, and solution. Overall, the 3-D approach integrates hands-on experiences with lecture learning, laboratory courses and in-class demonstrations/projects to give students the knowledge and experience necessary to be strong problem solvers with a grasp on curiosity and the importance of life-long learning.[1-4]

At Northeastern, the two semesters of Unit Operations Laboratory are taken over the course of 18 months, with most students taking a co-op position for six to eight months between the laboratory courses. The overall structure of the two courses is to primarily focus on fluid mechanics, momentum transport, and experimental design within Lab I, while focusing on heat transfer, separations and mass transfer, and analytical design within Lab II. In corresponding with the 3-D approach, Lab I is broken into five modules (two Discovery, two Development, one Design) and Lab II is conducted through four modules (one Discovery, two Development, one Design).

Within Lab I, the two Discovery modules center on discussion and introduction of fluid properties, such as surface tension, viscosity, density, and cohesion, as well as fluid flow, including laminar and turbulent flows and introduction to fluid flow through pumps and mixing. The two Development modules build off of each other, with an initial group calibrating and investigating industrial-scale fluid flow modules, including pumps, mixers, blowers, piping and other parts that induce fluid friction. The second group would then evaluate the equipment performance through an experiment of their own design. The Design module that completes the course is an open-ended experimental proposal, in which groups attempt to design a theoretical experiment that addresses a concern raised by one of the National Academy of Engineering's Grand Challenges.

Lab II follows with a simple Discovery experiment that could include cooking potatoes or capturing carbon dioxide released from soda cans, in which groups are not allowed to apply theory but must instead develop their own analytical design, thus helping them to connect mathematical and experimental understanding to a further degree of application through data analysis. The two Development modules, similar to Lab I, focus on industrial-scale equipment. The first module allows students to conduct experimental and analytical design on a heat exchanger, ranging from shell-and-tube systems to air fins to helicoil devices. The second module introduces concepts of mass transfer and separations through equipment including a distillation column, liquid-liquid extraction column, and a reverse osmosis membrane.

The culmination of both courses is the Design module in Lab II, the River Project. This module allows for students to apply their understanding momentum, heat, and mass transfer, as well as thermodynamics and kinetics; their curiosity and creativity towards unknown materials and novel engineered flow systems; and their confidence in experimental and analytical design.

The full 3-D approach for both courses is depicted in Figure 1.

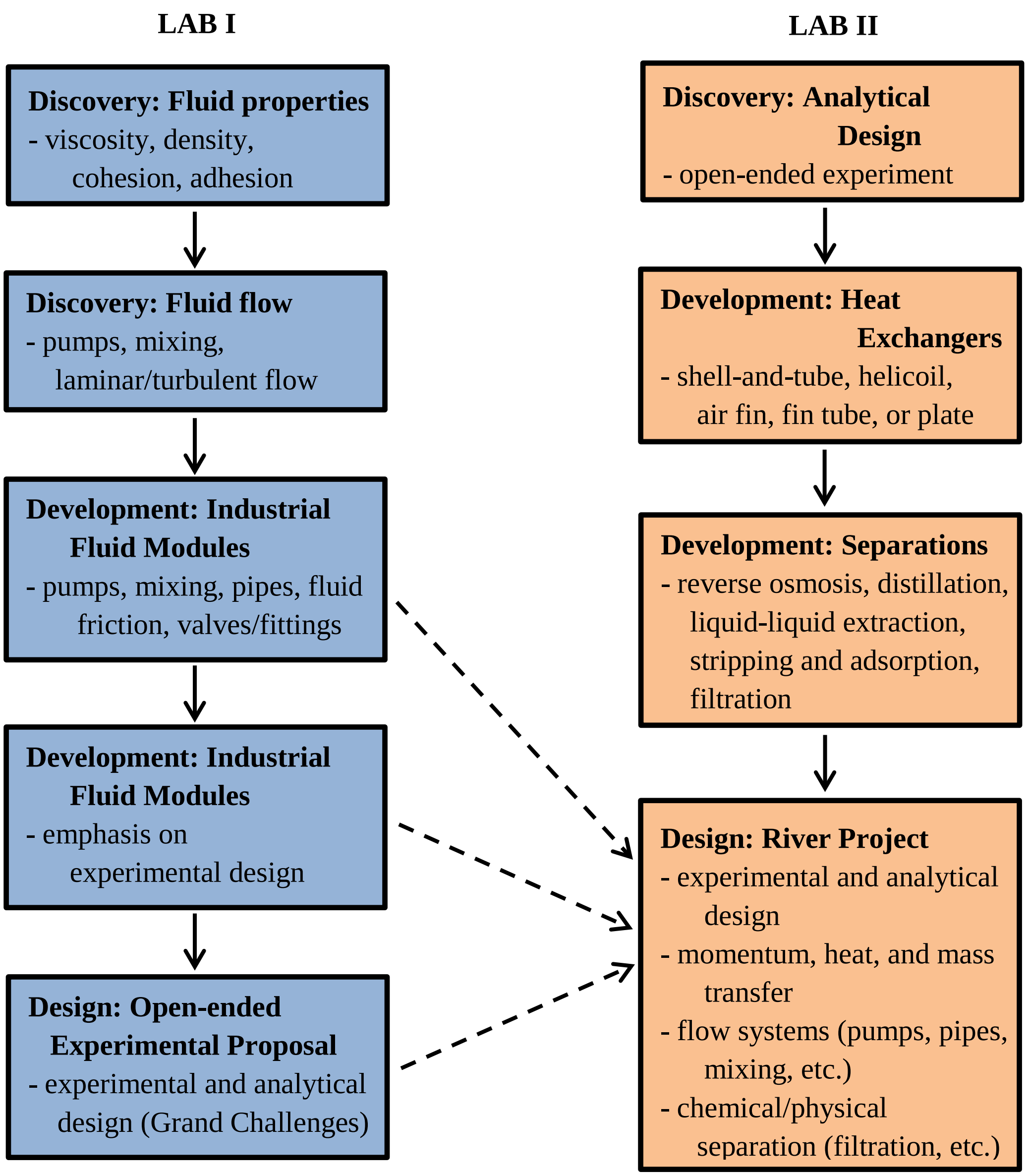

Figure 1. Flowsheet depicting the 3-D approach in both Lab I and Lab II. Solid arrow lines represent the progression in each course, while dotted arrow lines represent connections between courses to the River Project, the culmination of both lab courses.

The 3-D approach was first introduced and assessed in the laboratory courses over four semesters in two years from Fall 2008 to Spring 2010.[5] This transition coincided with transforming the laboratory courses from a single 2-credit hour course in students' fourth year to two separate 1-credit hour courses with Lab I offered in students second-to-third-year and Lab II offered in students third-to-fourth year. Informal student feedback indicated that students liked the hands-on activities (98 percent of 44 survey respondents), especially big equipment (over 80 percent). Students enjoyed the discovery experiments (more than 83 percent) but had mixed feedback on dealing with open-ended aspect of discovery experiments, with only half of students appreciating the open-ended structure. With respect to the open-ended design project, approximately 62 percent felt comfortable with open-ended design.

Shortly after 2010, in response to student feedback and instructor assessment of the courses, both Lab I and Lab II each became 2-credit hour courses to reflect the quantity and quality of work accomplished. In the sixteen semesters over eight academic years following the full transition, various instructors have attempted to further improve the content of the courses, including developing new modules and working to improve initial module designs. Approximately ten instructors have taught Lab II in those eight years, all contributing to course development in different forms. Of particular focus in this paper will be the River Project. The authors of this paper have been the instructors for 27 of the 41 sections of Lab II offered in the last six years, and will thus discuss the current form of the River Project.

Current Structure of Lab II:

Each Lab II class is 3.5 hours for 20 third-year and fourth-year students per section, and is held weekly. During class, a majority of the time is provided for students to be able to become familiar with equipment and interpret its operation, design and conduct experiments, analyze data, take additional measurements as necessary, and generally have opportunities for hands-on experience. Some time is occasionally taken for introductory presentations by the instructors as necessary, usually at the beginning of each module or to highlight certain measurements and observations that students might want to complete during the class period. The instructor may need to briefly make announcements or address other concerns during this time as well. Otherwise, students are given the freedom to fully immerse in experiential learning.

Multiple sections of both Lab I and Lab II are offered in both the fall and spring semesters to accommodate the number of students per class and the variations in student schedules. Sections have a maximum of 20 students, and three to four Lab II sections are offered each semester for a total of seven or eight per academic year.

Each assignment in the course is graded based on technical content (40 percent), communication (30 percent), formatting (20 percent), and participation (10 percent). These overall categories are broken down into specific components, such as evaluating the quality and appropriateness of the designed experiment's objectives, quantitative analysis, the structural organization of the deliverable. In Lab II, students must produce five main deliverables: a memo-style individual report for their Discovery module; a group report for their heat exchangers Development module; an individual report for their separations Development module; and both a group presentation and a formal group report for the River Project for their Design module.

River Project Description:

The River Project is a multi-week open-ended laboratory module requiring students to apply their experiences, knowledge, and curiosity to an environmentally focused design project. Each group is presented with a scenario in which they represent an engineering team hired by a town council, tasked with developing a water remediation system that will return the quality of their nearby river to acceptable United States Geological Survey (USGS) limits for clean water. The group is tasked with building a pilot-scale model of the town's river that is 100 times smaller than the actual river, conduct bench-scale testing on potential chemical and physical separation systems, design and analyze their treatment system, and then propose a treatment system that will effectively treat the town's river.

USGS standards for clean water are used as guidelines for clean water within this project, specifically focusing on five parameters. The standards for actual rivers can vary depending on location, season, and weather, so more specific requirements are established as goals for the students' water treatment systems.[6] The five parameters are indicated in Table 1.

Table 1: USGS clean water standards that students strived to meet by the end of River Project.

Parameters	**Range**
Temperature	2 - 35°C
Dissolved oxygen	> 5.0 mg/L and < 110 % saturation
Conductivity	300 - 700 µS/cm
pH	6.5 - 8.0
Transmittance	> 85%

It should be noted that transmittance is used as an equivalent evaluation for turbidity, or the lack of clarity in the water.

While these parameter ranges are set as treated water targets for each group to aim for as achieved by their treatment systems, these ranges are not the final arbiter of students' grades on the project. Much like an engineering capstone course, the effort made into designing and constructing chemical and physical separation remediation systems, as well as the final proposed scaled-up system to remediate the fictional town's river, are better means of assessing student performance.

The individual rivers that each group develops, in addition to their water remediation system, can vary dramatically depending on the physical and chemical separation treatments used by the group, as well as the design of the river itself. Decisions made by each group during the building of the river will have larger impacts on the limitations of their permitted remediation systems later on. For example, each group is asked to select the location of their river in the first week of the project, such as an urban or rural setting. While this appears to be a basic set-the-scenario question at first, students are then presented with limitations for their system in the following weeks based on their design. A group that chooses an urban setting must face the reality that most urban property is already developed and being used, and so the group will be restricted in the amount of space around their river that their remediation system can be designed within; in comparison, a group choosing a rural setting may be given substantial space within the laboratory to build their remediation treatment, but may be limited in how aesthetically pleasing the system has to appear to thus blend in with the surrounding rural area. These student-selected locations are not limited to originating in the United States; however, the standards by which the river cleanliness will be evaluated is still based on the USGS standards.

Groups are asked to select one of two pollution types simulating types of waste, as depicted in Figure 2. An "industrial waste" mixture is made of a 2L ammonia : 13 L water solution with a small amount of magnesium sulfate mixed in to create flocculants; in addition, a very small amount of physical contaminant represented by large Styrofoam pieces may be added. A "sewage waste" mixture is made of a 2L vinegar : 13L water solution with 1/3 of a can of coffee grinds added to induce a dark color, along with 300-400 mL of ground-up Styrofoam particles pieces, beads, and other small debris to represent physical contamination. The contents of these solutions are never provided to the groups, nor is the objective to determine what the pollution precisely is. Instead, the different waste types require significantly different treatment systems, and students are directed to focus on treating the unknown pollutant they have chosen and are provided.

Figure 2. Images of the 'sewage' and 'industrial' waste pollution used in the river project.

The waste is introduced to their river systems as either a point-source or as run-off. Point-source pollution would be poured into a single location in the river basin, while run-off would be introduced by pouring along the length of the river basin.

The river water will recirculate through the system, meaning that introducing the pollution as a point source will not truly have the same impact that a real-world point source would, as the polluted water will eventually return to the location where the pollution was first introduced. The largest difference in introducing the pollution as a point-source or as run-off in the laboratory river beds is the scale of the physical separation to filter and collect large particulates as the pollution is poured into the flowing river. Point-source filtration can be more localized, while run-off filtration needs to be far more extensive throughout the system.

The pollution will not be continuously poured into the river, as would be more standard with a pollution source in a real-world river. Instead, a set amount of waste will be poured in based on the size of the full river system as it is designed. This restriction is necessary in part because of the limited volume of fluid that the river systems can hold, and also based on the modeling of a real-world river within a circulating system. A one-time pour of the pollution into the river is instead conducted during the actual module.

Equipment:

When the River Project was first designed and implemented in Lab II, class sizes at our institution were small, with 20 to 30 students in total taking the lab course each semester. These smaller class sizes allowed for small student groups to be assigned, with 6 or 7 students per group working on a small river bed. As class sizes have increased to nearly 80 students taking the course each semester, group sizes have changed to 9 or 10 students per group, each group working on either a large river bed or on a two-tiered small river bed system. This change is in part based on size and space restrictions in the laboratory, as well as limitations in supplies. However, the use of larger river beds has helped provide the same overall experience even with the adjustment in group size.

The large river beds are approximately 4.0 feet long, 2.5-3.0 feet wide, and 1.5 feet deep. These river beds have been pre-assembled from 0.5 inch thick clear PVC. Each of these large river beds is mobile on specifically designed 1.5 feet tall steel carts. All beds have been sealed at the edges to ensure no leaking can occur. Any student influence on the design is strictly limited to the amount of material put into the river bed, as opposed to the plastic base itself.

Smaller river beds are approximately 3.0 feet long, 1.5 feet wide, and 1.0 foot deep, constructed from 0.125 inch thick clear PVC. These were originally provided as single units to student groups when the groups and class sizes were smaller. With the growth of class sizes, a group would now use two of these smaller river beds in series if provided these beds as their equipment. These can be developed into two-tiered systems, with a wooden box of the same dimensions that can be placed under one of the small beds; the flow out of the elevated bed feeds into the other river bed. These beds are not mobile and must remain situated on laboratory tables for the duration of the entire module.

Groups are frequently offered the choice between the larger river beds or the two-tiered systems. Students have found both systems to be desirable with no animosity expressed over the system they work with.

All river beds have small threaded ports on the sides that can be closed with plugs, or have pipes connected to them to allow for flow in or out, depending on the treatment systems that students design. All river bed systems hold between 100 and 150 liters of water, depending on whether the two-tiered system or the larger river bed systems are being used.

Figure 3 a-c. A river in progress of being constructed in a larger river bed. In (a), the students are seen using large bricks, plastic dividers, large stone and duct tape to create a path for the water to flow through. In (b) and (c), the bed has been filled in with sand, rocks, and bricks for the bottom of the river. In the bottom right corner of (b), the side of the river bed with a lower wall provides the location for water to flow out of the bed and into the white cylindrical tank that will catch water before recirculating it. The exit flow has been reinforced with a tin foil frame to help direct water into the tank. A large red hose can be seen in (b) and (c) as students prepare to use city tap water to fill the river and investigate the flow patterns they have created.

Each group is provided a tall 55L cylindrical plastic tank, into which the water leaving the river basin will flow. The tank is connected through plastic tubing to two 10 hp centrifugal pumps, which serve to recirculate water from the tank back to the top of the river. Thus, the entire river is self-contained within a circulating system.

Chemicals from the laboratory chemical storage include calcium carbonate, aluminum sulfate, magnesium sulfate, sodium carbonate, sodium bicarbonate, and activated carbon. Other chemicals have been made available at times based on student requests; however, given that students do not know what the pollution actually consists of, it is best to limit the chemical supply to a scope that the instructors are fully aware will not poorly react with the pollution or other elements within the system.

Materials made available to the students include fabric and metal mesh of varying pore size; tin foil, cotton filters, coffee filters, and steel wool; Plexiglas sheets and plastic buckets, which can be cut to size as necessary; tubing, plastic columns, fittings and valves; variacs, which can modify the voltage provided from a power source; pumps, beakers, pipettes, mixers, and more. These supplies and equipment are presented on several large rolling racks, thus leaving the decision to the students what to use and implement in the treatment system for their project.

Schedule:

The River Project is conducted over the course of four weeks, with two main deliverables of a townhall-style presentation and a formal report. Students work within their respective groups throughout this project, which are assigned by the instructor at the beginning of the module.

<u>Week One</u>

In the first week, students are introduced to the project through an instructor-led presentation on water pollution and the current state of water cleanliness throughout the world, including discussion of some of the rivers and lakes considered to be the most polluted worldwide as well as reports of pollution from recent events. This presentation also introduces students to USGS limits for the definition of clean water. The presentation can be rather sobering for the students, given the pictures used of chemical pollution inducing river water colored red or yellow as well as the massive amounts of physical pollution in some water streams; the importance of water remediation is emphasized, particularly with respect to an estimated 14,000 people dying every day as a result of water pollution.[7]

An expansion of this introductory presentation has included a case study of the Waves for Water filter system, in order to initiate student consideration of physical separations. Common water containments, their size, and the filter design are introduced, followed by highlighting the associated flow rate/head pressure relationship and how it changes over the lifespan of the filter. This case study was particularly powerful in the Fall 2017 semester with the connection to the water contamination after the 2017 hurricanes that affected Texas and Puerto Rico.

The description of the project itself and the expectations from the instructor are then presented, along with the timeline for the project. Highlighting pictures of rivers and water treatment systems from previous iterations of the course is crucial in helping students understand the scope and specificity of the project.

After students are separated into groups, and provided with materials to build their river bed, including sand, bricks, rocks, and other dividers, groups are encouraged to take a half hour to diagram and design their river bed. Each group then begins to construct their river, using approximately 100 to 150 pounds of sand, 50 pounds of gravel, and five to 10 bricks and cinder blocks per group. The river beds are filled to ensure the flow and circulation of the river develops appropriately, and to ensure that at least one area of rapid flow and one area of stagnant flow exists in. A topographical example of one group's assembled river is depicted in Figure 4, with an image of another group's filled river bed depicted in Figure 5.

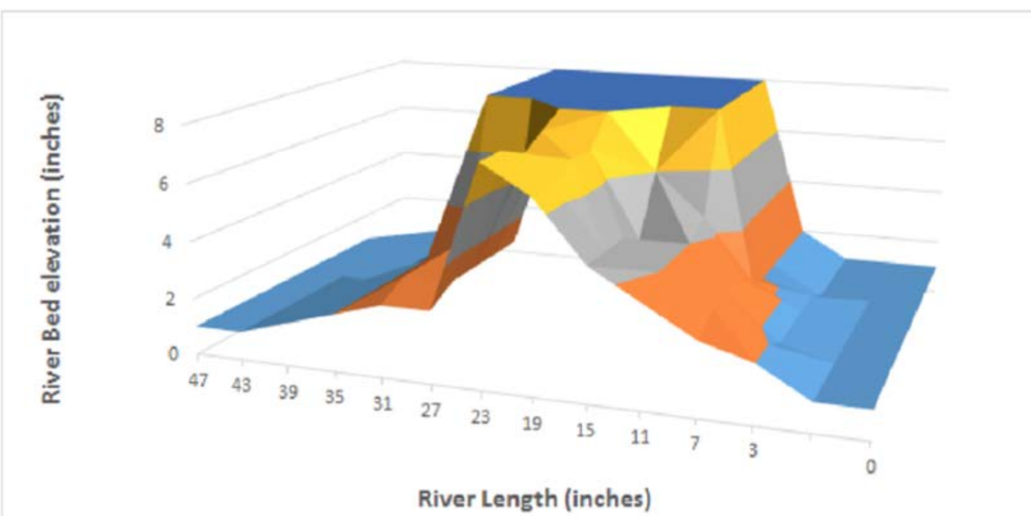

Figure 4. A student group's topographical depiction of their river, as illustrated by the students. In this depiction, a large island is illustrated in the center of the river, with the lower height on one

side for the water to flow around the island. The outer bounds of the plot represent the plastic walls of the river bed itself.

Figure 5. Image of a group's model river, filled with sand and rocks, prior to filling with water. The height of the sand and rocks in the image is similar to the topographic depiction of the island in Figure 4. Flow would likely be from left-to-right in the river bed, with water introduced through a port on the side of the plastic frame.

Each group also constructs the recirculation system for their river using the provided tank, tubing, and pumps. After filling the tanks, pumps, and river basin, with the river design fully constructed, each group's river system contains between 100 and 140 L of water. Depending on the volume of fluid necessary for steady flow, each group is informed that they will need to remediate 30 or 45 L of the unknown pollutant in future weeks. An example of the full recirculation system as illustrated by one group is depicted in Figure 6.

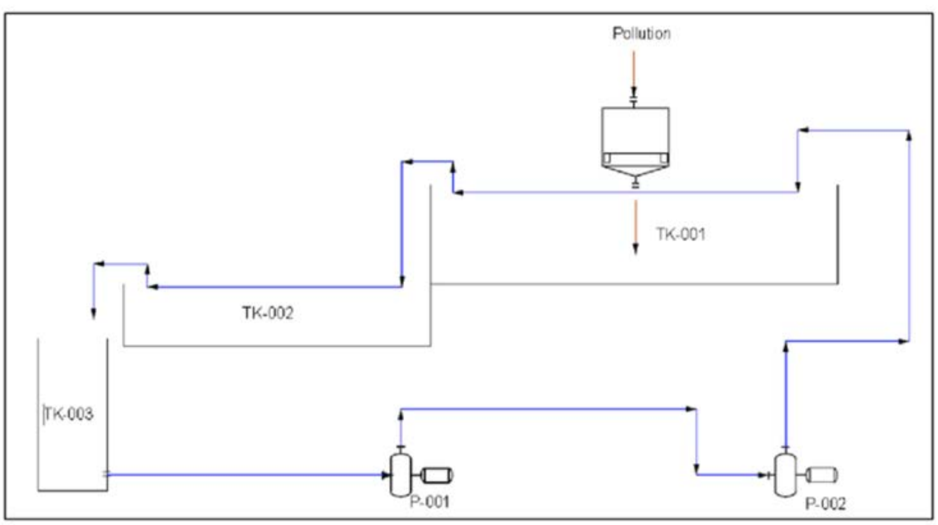

Figure 6. Side-view illustration constructed by students of their recirculation system, with a two-tiered river bed system (depicted by the two river bed 'tanks' TK-001 and TK-002), a tank to catch and hold river water at the base of the river (depicted by tank TK-003), and a series of pumps to recirculate the flow (depicted by pumps P-001 and P-002). The point-source pollution location is also depicted pouring into TK-001.

At the end of the class session in the first week of the module, each group must submit documentation addressing several points. The group must select a) the type of pollution (industrial or sewage), b) the pollution source type (run-off or point-source), c) the location of their river (urban, rural, mountain terrain, etc.), and d) the name of their river. In addition, the group must add to a safety check-in / check-out sheet listing the potential hazards and concerns that should be addressed at both the start and end of lab each week.

Week Two

In the second week, each group is provided a small 4L sample of their chosen pollutant, without being told of the contents. The students are shown a permitted list of chemicals in storage that they can use treat their pollutant, which as previously described include calcium carbonate, aluminum sulfate, magnesium sulfate, sodium carbonate, sodium bicarbonate, and activated carbon. Students can select from the materials described in the overall project equipment. Students can purchase further materials or chemicals on their own within a small permitted budget provided by the university (~$50), and are allowed to purchase further materials with their own expenses.

Groups frequently split into two components during the bench-scale testing. One component of the group focuses on determining an appropriate chemical treatment to remediate the pollutant, including both adding the appropriate chemicals as well as assessing what means of introducing the chemicals will be necessary. The other component focuses on building the treatment system to address physical separation of the pollutant, including filters, packed bed columns, settling tanks, and any additional pumping in and out of the main river bed that is necessary for these treatments. The differences between these components should not be understood as one team testing and one team building, which students can interpret as the purpose of their efforts without clarification from the instructor. Instead, these components are labeled the 'chemical team' and the 'separations team', with one component focusing on chemical treatment and separation of the waste, and the other component focusing on physical separation of the waste. Communication between the components is important to ensure that the overall remediation plan will effectively blend the approaches, particularly in making sure that the means by which the chemical treatment is added will be integrated into the physical separations treatment. With frequent communication between the different components, as well as frequent cross-over in later weeks of the module, students in each group usually develop the same overall understanding of their work and project, as exhibited in the final deliverables.

Other measurement supplies that are provided to the students include broad and precise pH paper, conductivity meters, thermocouples, turbidity meters and colorimeters. These measurement tools include monitors through Vernier software that allow for multiple measurements to be taken over a longer period of time, and thus evaluate any trends in a sample; these data are particularly useful when investigating systems with flocculants or particulates that may settle out over time, or samples that are reacting with a chemical treatment during measurement.

Students specifically take measurements of pH, conductivity (mS/cm), temperature (^{o}C), transmittance (%), and dissolved oxygen (mg/L). Bench-scale measurements of pH are frequently assessed with titration curves, to determine the optimal amount of a chemical treatment to add to the polluted river. Students usually take measurements of treated wasted over a period of time to evaluate the changes until a new equilibrium is achieved. Transmittance measurements taken with a colorimeter help assess clarity from particulates in the water.

All groups meet with the instructor individually during the laboratory session to address their current progress, needs, and concerns. This meeting allows for the instructor to help direct the group as necessary toward system designs with greater chances of success, or to encourage the students to continue pursuing their current directions of action. This meeting is also one of the earliest times that groups will be considering how to address the problem of improving conductivity within the treated river. While adding different chemicals is a means of readily improving the pH, the added chemicals also dramatically increase the ion concentration within the river and thus increase the conductivity as well. The instructor may make suggestions about different means of improving conductivity, such as ion exchange resins, like clay, or membrane-driven separation, which can be simulated through a simple medium like pig intestines, at which point the students begin researching low-cost means of ion reduction or ion capture.

Some of the suggestions made or some of the approaches taken to solve the conductivity problem may not be directly applicable on a larger-scale. For example, sugar can be used to help capture and reduce ions in the simulated pollution used, and students can discover it to be effective on a bench-scale approach. However, if students attempt to use sugar in their pilot-scale model river bed, the amount of sugar necessary to reduce conductivity to acceptable limits is nearly 120 kg for 140 L of water. This overwhelming amount is clearly unreasonable, even before considering scaling-up to an actual river. But sugar does help represent an inexpensive means of modeling ion capture, to at least help students begin to consider a more complete chemical separation approach as well as make stronger recommendations in their final report based on research for a more complete solution to solving conductivity. Similarly, while pig intestines are not truly scalable, they can simulate the effects of dialysis tubing and ion separation through an inexpensive means that students have access to. Through research and comparison to dialysis for larger flow rates and systems, students can again approximate a potential solution to conductivity on the bench- and pilot-scale. Other methods with more common use in real-world applications, like membrane-based separation, are also viable if students choose to pursue that approach within the permitted budget.

Week Three and Four

During the third and fourth week of laboratory experimentation, each group is expected to conduct a trial run with their model river and designed treatment system. In the trial, an appropriate amount of pollution (depending on the size of their river basin and contents) is poured in at the pre-selected location(s) into the river, at which point the remediation system is allowed to start operating. Similar to an engineering firm, the burden of proof is placed on the students. Students are expected to not only design the remediation, but experimentation and analysis for efficacy of their trials. Analyses usually take the form of sample measurements from multiple locations within their model river every five minutes until either some level of steady-state values are achieved or enough data have been collected to capture the entire treatment operation.

The full river treatment systems can include many different features, including filtration, activated carbon columns, settling tanks, and mixers. One example of a complete river treatment is illustrated in Figure 7.

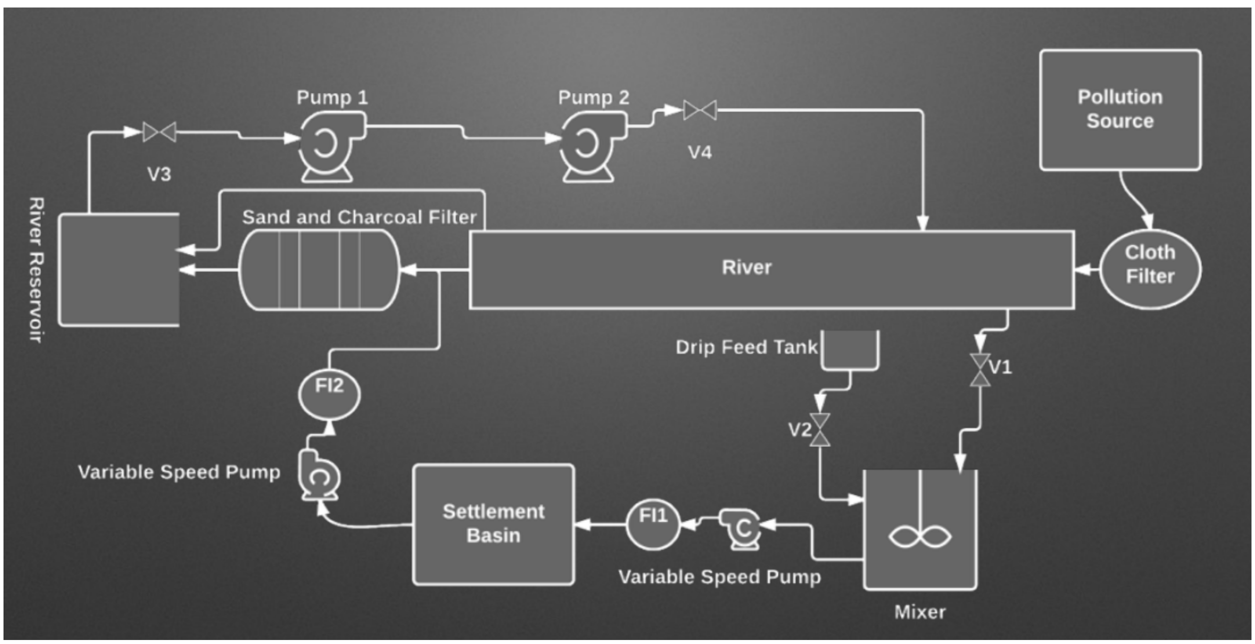

Figure 7. An illustration of one group's river and treatment system. A point-source is depicted on the right, with a filter being used for physical separation as the pollution enters the river. The river flows from right-to-left, exiting the river bed into a river reservoir at the left, then is recirculated back to the top of the river through Pump 1 and Pump 2. Treatment of the river water occurs through both a sand-and-charcoal filter at the end of the river bed, as well as through a chemical

feed from the 'Drip Feed Tank' which is mixed, passed through a settling tank, and then reintroduced to the main river.

The most common cause for failure to fully remediate the water is failing to reduce the conductivity within acceptable limits. Previous student groups have exhibited a range of creativity in developing conductivity treatments, including clay membranes, soil beds, pig intestine tubing, dialysis tubing, sugar, and sawdust, among others. The most successful attempts have resulted in needing either an unreasonable amount of chemical treatment, such as nearly 200kg of sugar for ion capture of 140L of river water, or more time to conduct bench scale experiments to more correctly scale up the treatment system. With this understanding, many groups will be able to meet three or four of the USGS standards.

At the end of the fourth week of laboratory experimentation, all groups properly dispose of their materials, rinse out the sand and rocks in their river, and clean out their riverbed. All sand and rocks are poured onto the floor of the laboratory to fully dry and prevent mold or other contamination from setting in before the next semester of the course begins to use the sand several months later.

Additional Time

A semester at Northeastern traditionally allows for 13 weeks of Lab II class time, which is divided into two weeks for the Discovery module, three weeks for the heat exchanger Development module, three weeks for the separations Development module, and four weeks for the River Project Design module, with one additional open week. Because of the potential for the extra week, and given that students groups always fail to meet the acceptable range for at least one USGS parameter, it would be advantageous to use that extra week for an additional trial run. However, these weeks are frequently lost as a result of university closings for holidays and snowstorms, meaning that class is frequently limited to the necessary 12 weeks for experimentation. At times, the instructors have allowed students access to their equipment outside of class for further development and experimentation, but given the growth of the student body and significantly more lab sections being offered (from four total Lab I and Lab II sections in Fall 2012 to eight total sections in Spring 2017), the Unit Operations Laboratory is too often being used by other classes to be able to handle the space needed by the additional students. Thus, the module is limited to the scheduled four weeks in most semesters.

Final Deliverables:

A week after the final laboratory session, each group is required to give a final presentation to the instructor and any TAs, as well as any invited faculty and students. The presentation is unique in that the audience is designed to be a town hall of citizens from the community where the river is supposedly located. This style of presentation is unusual for most students, who are used to experiencing technical presentations in which the audience has at least the same level of understanding as they do. In addition, the students are used to directing their presentation primarily towards the instructor of the course, which leads to a standard level of professionalism in their presentation style.

The town hall style presentation, however, creates an audience that does not (or acts as if they do not) understand the science and engineering being presented. The questions that the audience asks are more in line with their own personal concerns, as opposed to questions about the scientific theory presented. Questions often address concerns of:

- "Who is paying for this? Will it come out of my taxes?"
- "Your system is too noisy, and it upsets the animals on my farm. What will you do about it?"
- "Who are you hiring to do this work? Is this going to create jobs for the town?"
- "Your system is big and ugly and it's going to hurt tourism. How will you fix that?"

All of these questions are based off of similar concerns that the instructors have heard at various town halls they have been to, with a list of potential questions provided to the audience to ask. While these questions are founded in reality, the presenting students have not experienced questions of this style previously, and the informal nature of the questions is often at odds with their attempts to project professionalism. The presenting students have to make sure they do not talk down to or patronize the audience, which can be difficult given the unique tone and content of the questions being asked. The roles of town hall citizens are filled by upperclassmen who will attempt to purposely throw off the presenting students either through their questions or their unprofessional approach, which does help create learning experiences for the presenting students in how to better communicate engineering to different audiences.

Besides the town hall presentation, all groups need to submit a formal report describing their bench-scale work, the results and analysis of their trial runs, their proposed scaled-up treatment system, and the economic analysis of their system. This group report is limited to 25 pages, with additional space permitted in the appendices.

Grading

Evaluation of the student work is entirely based on the final report and the final presentation that students complete. Each of these are evaluated on the previously described technical content, communication, formatting and participation factors. Students must demonstrate a clear understanding of the necessary river treatment parameters, conduct a quantitative analysis on the measured parameters, and develop a complete plan for a scaled-up treatment system with economic analysis. The work must be communicated clearly in the report, with well-structured transitions and appropriate level for the intended audience; the presentation must also be clearly communicated on the appropriate level for a non-scientific audience, including being able to answer questions of technical and non-technical content. Proper formatting and all expected sections within the report, including a complete executive summary and a thorough safety analysis, are all to be included. All evaluation is conducted by the instructors, with input from the TAs accounted for as appropriate.

Within this evaluation, the quality of the final treatment system that students develop is not the primary focus. If the treatment system fails, which happens on many occasions, students are not penalized for not having met the USGS standards. Students are made aware of this criterion as well during the first week of the module. The instructor will recommend to each group that they analyze their collected data on the bench-scale and pilot-scale river bed, while acknowledging failure, to produce more thorough recommendations for a scaled-up system for the theoretical real river. The failure can thus be used to better understand the necessary features and structure of the recommended scaled-up treatment for the theoretical river. The instructor evaluation focuses on how the group's module experiences and data, for good or bad, are communicated in the report and presentation to support the technical understanding and recommendations.

The varying size of the student groups operating with each river has not had a significant impact on the performance of the team. It may be expected that much larger groups had difficulty with all students engaging in the work, and with organization of the team being more difficult to achieve. However, the amount of bench-scale experimentation, treatment system construction, and analysis to be conducted allows for enough work for all students in the team, whether the group is six or ten students, to have work that they can contribute and be invested in. The largest difference in the work produced by the different group sizes is the overall complexity of the treatment system designed. Groups of ten students are more likely to add additional filtration or introduce a series of residence tanks as opposed to singular systems; groups of six students develop more straightforward systems that can often be just as effective in treating the pollution.

Student Group Performance

Because the groups all execute a wide range of treatment approaches, it is difficult to take an average of different groups' performance and then describe how well the students are able to meet the desired USGS parameters. Different chemical treatments and physical separation treatments will result in different final outcomes. As such, a better sense of groups' performance can be gained by considering the final results of several different student groups over the past few semesters. Six groups' data are presented in Table 2, with three groups having worked to treat the 'industrial' waste and three groups having worked to treat the 'sewage' waste.

Most groups are able to meet the acceptable range for several parameters to some degree of reliability, specifically temperature and dissolved oxygen. If each group's designed treatment system is functioning appropriately and bench-scale testing was conducted accurately, the groups are also able to meet the desired range for pH. Performance in transmittance is less consistent and depends on the designed treatment system; some groups have actually induced a chemical reaction with their treatment system that has degraded their activated carbon and turned the water black, or have caused large coagulation of the pollutant which then collected in the river bed.

Table 2. Initial pH and final parameter result data for several River Project groups. All data are taken from the respective groups' final reports.

Semester	Pollution Type	Initial pH	Final pH	Final DO (mg/L)	Transmittance (%)	Conductivity (mS/cm)	Temperature (°C)
Spring 2015	Sewage	~ 4.0	6.9 ± 0.1	6.13 ± 0.15	70.3 ± 0.1	3.41 ± 0.01	18.2 ± 0.05
Spring 2015	Sewage	~ 3.5	6.8 ± 0.2	5.80 ± 0.10	86.0 ± 0.1	3.00 ± 0.01	18.0 ± 0.05
Spring 2017	Sewage	~ 4.0	8.0 ± 0.2	6.30 ± 0.30	44.8 ± 0.5	3.46 ± 0.00	18.6 ± 0.05
Fall 2014	Industrial	~ 11.0	7.6 ± 0.1	5.60 ± 0.05	99.8 ± 0.1	5.56 ± 0.05	24.5 ± 0.05
Spring 2015	Industrial	~ 11.5	7.2 ± 0.1	6.10 ± 0.10	92.5 ± 0.5	38.0 ± 0.4	12.2 ± 0.05
Fall 2015	Industrial	~ 10.0	9.0 ± 0.2	9.40 ± 0.10	92.2 ± 0.5	2.10 ± 0.01	21.0 ± 0.05

No student group has yet managed to properly address conductivity, although some groups have met the USGS standards on the bench-scale and then been unable to scale-up the treatment to the pilot-scale. In some cases, the desired treatment plan was simply implemented poorly, such as one group which was actually able to secure a donation of ion-exchange resin from a military submarine, but then placed that resin within a filter bag which was simply tossed into the river bed without any flow specifically driven through it. Some groups have tried to use ion capture materials, like sugar, but then introduced the material in such a form that the material coagulated and was unable to let any flow pass through. Recently, groups have begun attempting to use sawdust and wood shavings based on their research into its ion capture properties, and made substantial improvements to the conductivity that could reach the desired range with more preliminary experimentation.

Assessment and student Response:

The River Project was first introduced to the lab courses as part of a significant revamping of the laboratory curriculum nearly eight years ago. The emphasis of the revamp was to implement the 3-D approach, with the River Project introduced as the culmination of the laboratory courses under the new approach. Given the changes, which include turning the courses from 1-credit hour to 2, as well as accommodations to address the undergraduate student body in chemical engineering at Northeastern nearly tripling in size, it is difficult to make direct comparisons to assess the impact of the River Project compared to experiments before the revamp. This evaluation would be further complicated as none of the instructors who instigated the revamp in the curriculum are either still involved in the lab courses or a part of the university. Further, since the time of the revamp, the River Project has undergone a steady series of improvements to become the open-ended experiment that it currently is, and so it is more viable to consider the project and its impact as it currently exists.

Given the condensed schedule in each semester, students are usually completing their separations Development module report after they have started the River Project. This timeline makes it difficult to precisely assess student understanding of all the course connections between the different modules before and after the River Project. Most of the assessment of the River Project itself has thus been obtained within context of student evaluation of the entire Lab II course.

Assessment has been primarily carried out through course assessment at the end of the semester, as based on the standard form conducted by the university with student responses provided anonymously to the instructors. The simple question requesting overall feedback from students is "Please comment on the strengths of this course and/or ways to improve this course." However, instructors discuss with the students the scope of the feedback, including requesting specific feedback on each of the modules, the structure of the course with the multiple modules, and the different deliverables for each module, as well as how each of these factors relate specifically to the River Project.

Based on end-of-the-year course assessment completed by students, as well as anecdotal responses directly to instructors and the undergraduate town halls held by the department, most of the student feedback with respect to the project has been positive. Students specifically appreciate the real-world nature of the project and how the open-ended nature of the project serves as a good culmination of both Lab I and Lab II. Students with environmental engineering interests have directly expressed their appreciation for the project, although most students do not acknowledge the connection to other engineering fields. Student comments reflecting a positive response have included:

- "I really enjoyed the river module! It was a ton of fun and I feel like we learned a lot of good problem-solving strategies. The town hall style presentation was interesting and a nice change of pace from a technical presentation."
- "I really liked the river project because I felt like it involved a lot of critical thinking and creativity from the group and I felt like I was working on a real-world problem versus a problem that was created for the sake of the lab."
- "The river project was really fun and was probably the best experiment I've ever been a part of. The large team setting ended up working well and I have no complaints with it."
- "The river project was awesome!"
- "The river project was a great experience."

One of the largest complaints is with respect to the time permitted, in that many students would prefer to have an additional week to work on the module if permitted (as previously discussed, this is not completely feasible), thus having a better chance at achieving complete success with their remediation system.:

- "I like the way the semester is set up with the lab schedule, but it would have been nice to have more time on the river project."
- "Another week on the river project would be nice since after the two trials we were getting better results, but did not clean the river completely."

When students recognize the 3-D connection and the development from module to module, the overall feedback on the course is positive as well:

- "I enjoyed each of the lab modules performed this semester (discovery, heat exchangers, separations, and the river project). I felt that each of these experiments were beneficial to our learning, and these modules should be continued."
- "Course is great for giving students hands on experience with experimental design."

However, students will occasionally comment that they did not understand the connection of the river project module to the rest of their laboratory experiences; when taken in full consideration, these comments have been highly dependent on whether or not the instructor discussed the connections with the students during the introductory presentation and helped them to realize how much flexibility they were provided within the project itself. The amount of clarification that students received also impacted their opinion of the different deliverables.

- "I also feel that the river project that was a majority of our grade was completely unrelated to Heat and Mass transfer."
- "While I enjoyed the River Project by the end, I personally learned much more about my topic in Transport 1 … This is because we were able to choose a topic we wanted to learn more about. I understand that this would be more difficult to implement in the Transport 2 lab but should definitely be a consideration for the future if the River Project is no longer used."
- "The expectations for the river project were not clearly laid out. The professor seemed to want excessive details for the cost analysis which is knowledge which we are not fully capable of answering as we are not professionals in the field. The town hall conducted was also confusing as our presentation was given in scientific format one which would not be presented in a town hall. The town hall asked questions which we were not prepared for not told we should have to answer."

These comments appear to be highly dependent on the instructor's explanations and discussions in the class. When the instructor has given a minimal introduction, as has happened with a temporary adjunct professor and with instructors in their first semester teaching the course, students did not understand the full scope of the deliverables or even the purpose of the project. However, when the instructor has articulated the connections between the fluid mechanics, heat transfer, and separations experiments and theory that students previously experienced in both laboratory courses, as well as reiterated the progression students made through the courses, these comments are not expressed in end-of-the-semester course evaluations. Essentially, despite the project being an open-ended activity, some guidance in terms of understanding the scope and purpose of the project is still necessary to provide a starting point for students to work from.

Other negative comments have specifically focused on conductivity, particularly with respect to their having had success on the other USGS parameters but none with maintaining the conductance close to the acceptable range.

- "I feel like it is not possible to actually succeed at the river project with the given materials in the lab, so it makes that lab even more useless."

With respect to general student feedback for the entire course, most student-requested changes to Lab II have focused on the course being equivalent in scope and difficulty to a standard classroom-based course. As such, a majority of students every semester request that the course be converted into a full 4-credit hour course, essentially having more credit-hours for the course but with the same current content. Students explain that they understand and appreciate the full scope of the work and study they put in to be successful in the course, and simply feel they should be rewarded for the comparative effort they provide in comparison to their other courses.

Overall, the majority of students exhibit and express enjoyment with the module both from the course assessment and anecdotally, and appreciate the creativity that the open-ended nature of the module allows them to pursue.

Conclusions:

The River Project is an effective final project to serve as a culmination of a two-semester two-course Unit Operations laboratory curriculum at Northeastern University. Students are able to apply their knowledge and experiences from previous modules focusing on fluid mechanics, heat transfer, and separations, and are provided the opportunity to combine creativity and ingenuity to design and build an actual system addressing a problem inspired by real-world necessities. In addition, the students develop skills in communicating engineering concepts and theory to broader audiences. Given the proper preparation and presentation, this module could be successfully adopted at other institutions.

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