Lab-Scale Treatment Wetlands: A Model for Undergraduate Learning

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Abstract

Because of the efficient treatment processes of wetlands, engineered treatment wetlands are increasingly being used to treat stormwater and wastewater, and especially combined sewer overflows. Constructed treatment wetlands are low-cost, require minimal maintenance, can be implemented in a decentralized fashion, and contribute to ecosystem preservation. All of these reasons have brought treatment wetlands to the forefront for consideration by communities working to reduce combined sewer overflows and improve water quality, especially in small cities and towns with limited resources.

Many of these same reasons motivated us to bring constructed, treatment wetlands into the undergraduate civil and environmental engineering curriculum. Serving as a model for water quality and quantity management, students engaged in hands-on experiences using a small-scale wetlands setup in the Cook Laboratory for Bioscience Research at Rose-Hulman Institute of Technology. In independent research projects, undergraduate research students measured water quality parameters including TSS, BOD and nutrients (nitrogen and phosphorus) and optimized removal of various contaminants. In the classroom in Environmental Engineering Laboratory, students measured water quality parameters of various water bodies within a watershed and researched the impacts of excess nutrients on water quality and economies. Students toured the constructed treatment wetlands and were able to learn directly from a peer who had previously participated in research using the wetlands.

Interviews of the undergraduate researchers allowed assessment of improvements in students' abilities to perform the scientific method and their confidence in doing so. Post-surveys were conducted to determine the classroom students' learning related to the function of wetlands in improving water quality and stakeholders' quality of life. Results confirmed that constructed, wetlands can serve as a model for students to better understand water quality and the function of low impact design in the environmental engineering field.

Introduction

Natural wetlands are composed of diverse ecosystems that perform important functions such as improving water quality, absorbing rainwater for flood storage, cycling nutrients, and providing wildlife habitat [1, 2]. In a wetland system, sedimentation, filtration by soil media and plant interception, and microbial life adsorb, transform, or break down water pollutants including total suspended solids (TSS) or turbidity, biochemical oxygen demand (BOD) or the amount of organic carbon in the water, nitrogen and phosphorus, and non-neutral pH [2, 3]. For point-sources, these water pollutants are regulated through National Pollution Discharge Elimination System (NPDES) permits under the Clean Water Act [4]. Mimicking natural systems, constructed treatment wetlands are capable of removing stormwater pollutants, and in addition, they are low-cost, require minimal maintenance, can be implemented in a decentralized fashion, and contribute to ecosystem preservation. Because of the efficient treatment processes of wetlands, engineered treatment wetlands are increasingly being used to treat stormwater and wastewater, and especially combined sewer overflows (CSO). All of these reasons have brought treatment wetlands to the forefront for consideration by communities working to reduce CSOs and improve water quality, especially in small cities with limited resources.

Over 700 cities nationwide [5] rely on an outdated combined sewer system where stormwater and wastewater are conveyed in a single pipe network. In 1994, the US Environmental Protection Agency (EPA) issued a CSO control policy intended to bring CSOs into compliance with the Clean Water Act [4, 6]. Traditional approaches to reducing CSOs include expanding wastewater treatment facility capacities or adding tunnel or detention basin infrastructure to store wet-weather flow from a combined sewer system. A sustainable, biomimetic alternative is to divert the overflow to constructed, treatment wetlands that replicate the beneficial functions of natural wetlands.

Constructed treatment wetlands at Rose-Hulman

To help teach our students about the impact of eutrophication and tools that can be used to address these challenges, students built two lab-scale, constructed treatment wetland systems in 2014 [7]. These wetlands are composed of three basins each (Figures 1 and 2); the systems differ in the second basin as to the type of wetland: subsurface flow (SSF) or free-water surface (FWS). SSF wetlands consist of a subsurface bed of porous media that is planted with emergent plants and through which the water flows. Primary usage is secondary treatment of wastewater [8-10]. Conversely, FWS wetlands contain areas of open water of shallow depth and very low flow velocity with floating-type and emergent plants. FWS wetlands tend to be used primarily for the treatment of wastewater, and the treatment of mine and stormwater discharge [3].

The setup of our wetland systems have changed over time to accommodate various research projects undertaken by undergraduate researchers. Currently, the wetlands are arranged to have a recycle line that can pump water through the wetlands more than one time (Figure 1). Each basin also has a sampling port that allows for water samples to be drawn after flow through each basin.

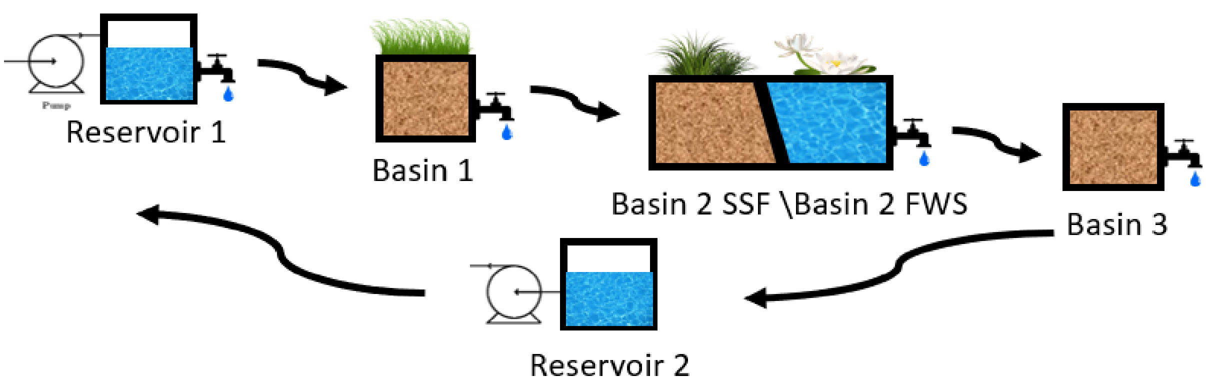

Figure 1. Schematic of wetland systems setup showing recycle line and sampling ports.

Figure 2. Photo of wetland systems setup in 2018 showing the FWS system in the front, and the SSF system in the back.

Each basin in the wetland system was designed to remove specific pollutants. While soil compositions in the basins have changed over time, the current compositions are designed to remove TSS, BOD and nitrate and phosphate (Table 1), and the recycle line was added to increase the retention time.

Table 1. Current soil composition of the wetlands

Basin	Contaminant removed	Size (in x in)	Soil components (%)			
			Organic	Soil	Gravel	Calcium carbonate
1	TSS	20 x 20	5	45	50	0
2	BOD & Nitrate	24 x 60	50	40	10	0
3	Phosphate	24 x 24	15	40	5	20 pebble-sized + 20 fines

Context-based learning

Literature has demonstrated that increasing project work and positioning problems in a broader context in engineering education can improve student learning and retention [11-13]. More specifically, these practices have been shown to help students better develop creative thinking, problem-solving, communication, and teamwork skills that are desired for students' future careers as engineers, researchers or entrepreneurs [12, 13]. One study shows that in addition to improving the relevancy of learning for all students, increasing contextual considerations may improve gender diversity in engineering [14]. In addition to project-based learning in the classroom, the context-relevant nature of undergraduate research not only can allow students to develop a deep understanding of a technical topic or process, but also improve their research and professional skills [15]. It should be noted, however that these gains are relative to mentor involvement and effectiveness, and the nature of the work involved in the research: analyzing and evaluating data yields more gains than the act of following protocols [16].

Approach

To develop rich learning environments that are contemporarily relevant and versatile, we developed two constructed, treatment wetland systems. These wetlands were designed to be used in independent, undergraduate research projects, as well as to supplement undergraduate coursework.

Utilization of wetlands for undergraduate research

For the research projects, one to two students worked to complete the project. Students either worked on a project full-time for 10 weeks in the summer, or part-time for 10 weeks during the academic spring term (Table 2).

Table 2. Summary of wetland-related research projects

Term of project	# of students	Overall project goals
Summer 2016	2	Determine wetland hydraulics, and determine baseline TSS, BOD, nitrate and phosphate removal from various waters
Spring 2017	2	Determine baseline TSS, BOD, nitrate and phosphate removal, and build a water collection device
Summer 2017	2	Improve TSS removal by modifying wetland layout, and more fully characterize nitrogen removal
Spring 2018	1	Build recycle lines and create a synthetic stormwater recipe
Summer 2018	1	Investigate the impact of the recycle lines on TSS, nitrate and phosphate removal, and improve phosphate removal by adding limestone

Overall, since Rose-Hulman primarily offers undergraduate degrees, the principal outcome of a research project is the student's learning. To this end, the learning objectives for the summer research students were:

After completion of the research project, students should be able to

1. write testable hypotheses
2. design and carry-out experiments in a reproducible way
3. analyze data and identify key findings
4. communicate findings in written, visual and verbal form

The final deliverables of a research project included a research paper to be archived in the university's library system, a poster and/or oral presentation given to an internal audience and an external audience if feasible (depends on timing and funding), and records of physical lab notes and electronic versions of raw and analyzed data. As a result, all students have presented at least once at internal symposia, and six students have presented at five different external conferences.
In addition to achieving the learning objectives, students gained research skills including experimental design, collecting water samples, measuring water quality parameters, trouble-shooting issues that arise, and keeping experimental notes. By achieving these skills, it is also my utmost intent for them to gain confidence in their abilities to design and perform experiments, and to persist through challenges.

Utilization of wetlands for Environmental Engineering Laboratory

For use in a course, a lab module in Environmental Engineering Laboratory was modified to teach students about the sustainability challenges that arise from the presence of excess nutrients in US waterways and low impact design solutions to address these concerns. Students were also taught how to measure and analyze water quality parameters related to poor water protection practices. The Environmental Engineering Lab is a course taught to junior civil and environmental engineering students concurrently with an Introduction to Environmental Engineering lecture course. While the lecture and lab courses overlap in some content, they are separate courses, and due to time constraints, the content that does overlap, does not necessarily line up temporally. The other modules included in the Environmental Engineering Lab class include

- alkalinity
- coagulation and flocculation
- filtration hydraulics
- disinfection
- BOD_5
- specific oxygen uptake rate
- design of an experiment

The Environmental Engineering Lab is the final class in the sequence of water resources / environmental engineering required classes. The learning Objectives for the Water Quality Lab:

After completion of the water quality lab, students should be able to

1. describe how excess nutrients impact local and US ecosystems.
2. identify and analyze the impacts and benefits of improving water quality on local and national economies.
3. recommend solutions to surface water quality issues.
4. measure and analyze water quality parameters.
5. integrate information from many sources to gain insight.
6. describe the societal impacts of improving water quality.

Prior to the water quality lab module, students researched impacts of excess nutrients in Indiana by answering the following pre-lab questions:

1. Research nitrogen as a pollutant and trace its route from its source in Indiana to a major waterway, and out to the ocean. Provide a map and narrative explaining source, route, destination, and transformations that can happen along the way.
2. Identify three stakeholders involved in the journey of nitrogen as it travels to the ocean, and describe their relationships to nitrogen.
3. Estimate the economic consequences to local and national industries of excess nitrogen in the environment. Discuss the impacts of nutrient pollution on at least three industries.

During the lab, each team of four to five students collected water from two of eight locations, including from a wetland and a stream and its tributaries on campus. Collection locations included upstream and downstream of confluences of tributaries and the wetland to the stream to allow students to analyze changes in nutrient and TSS concentrations in the campus watershed. Students measured pH, temperature, specific conductance, total hardness, coliform counts and concentrations of TSS, DO, and nitrate. Follow up questions asked students to compare and explain pollutant concentrations across the data sampling points, recommend optimal placement of low impact development measures, and predict how such measures could improve water quality. Students who had previously participated in undergraduate research activities using the lab-scale constructed treatment wetlands provided a tour of the wetland systems and described their research for their peers.

Methods

To assess the impact of using constructed, treatment wetlands on students' learning from independent research projects, one-on-one interviews of six of the research participants – at least one student from each project team – were conducted after research activities had concluded. Four of these students participated in research over the summer, and two of them participated during an academic term. Both students from the project in the summer of 2016 were interviewed. Students were asked questions about changes in their skills and ways to improve their research experiences [17] (Appendix I). The interviewer asked students specifically about their abilities and confidence in their abilities in the following list of skills [17] prior to and after their experiences:

- Understand contemporary concepts in your field
- Make use of the primary scientific research literature in your field (e.g. journal articles)
- Identify a specific question for investigation based on the research in your field
- Formulate a research hypothesis based on a specific question
- Design an experiment or theoretical test of the hypothesis
- Observe and collect data
- Statistically analyze data
- Interpret data by relating results to the original hypothesis
- Reformulate your original research hypothesis (as appropriate)
- Relate results to the "bigger picture" in your field
- Orally communicate the results of research projects
- Write a research paper for publication
- Think independently

To assess students' learning in the Environmental Engineering Lab course, in 2017, post-course surveys were conducted regarding students' perceptions of their abilities to describe the sustainability of excess nutrients and to analyze data in context (Appendix II). Following internal review board requirements, informed consent was obtained from each participant prior to being interviewed and/or participating in the survey.

Results

Student learning in undergraduate research

Given the fact that at small universities undergraduate research is limited in the number of students involved, six students were interviewed. While this is a small sample size, common themes surfaced regarding students' benefits and takeaways, frustrations, and suggested improvements for the project. Overall, students described that while their research amounted to more work than they expected, they also learned more than they expected. Specifically, students generally reported that they learned a lot about water quality and constructed wetlands, how to reformulate their research hypotheses in light of new data or situations, how to find and read primary literature, and perhaps most important for their future careers and surprising to them, how to write a research paper. Based upon their responses in the interviews and based on their deliverables, students met the four learning objectives during their research experiences. They also learned what research entailed, which was a motivating factor for several of the students in pursuing an undergraduate research experience. Other students noted that they wanted to pursue undergraduate research to help them obtain future internships, or to fulfill needed technical elective course credit.

While students reported that they were forewarned that there would be bumps in the road, they were still generally surprised by the need to reevaluate their direction often. While they were also forewarned of the need for physical work and the time required for reproducible measurements, some students expressed frustration about the amount physical labor required to collect enough water to pump through the wetland, as well as the time required to measure water quality tests in triplicate on top of operating a wetland with a six to twelve hour retention time. The students who were working solo on the project wished that they had a teammate to help with the physical labor and/or the measuring of the many water samples. They also reflected that a teammate would have been helpful when making decisions by acting as a sounding board. Students also wished for more documentation on procedures and practices.

The summer students suggested that the extra programs such as journal club or university-wide workshops for research students were helpful in terms of building students' research skills and confidence. Specifically, in our journal club over one summer, the two students and I switched off presenting relevant papers to each other and identifying constructed wetland installations or related water treatment facilities that we could visit. The students reported that presenting papers helped them gain confidence in their abilities to analyze data, and to know if their values were within acceptable ranges. Visiting real implementations of constructed wetlands also helped the students gain confidence in their research, as these visits allowed them to interact with operators or designers who could serve as role models in the field.

Most striking to me was how much students learned about themselves as a result of their research experiences. One student learned that they were more interested in creating and organizing electronic documents related to the wetland processes than the actual research itself, which they said was insightful as they moved immediately into their professional career and found themselves feeling similarly about their work there. Another student found that the experience helped them feel confident about entering graduate school. Finally, another student expressed that while they were a senior having specialized in structures, the research motivated them to pursue the water resources and environmental engineering subfields when coursework had not, and ultimately had a big impact on their career by steering them to find intersections between structures and water. This student is now engaged in DigIndy Tunnel System in Indianapolis, IN to reduce CSOs. This student described how beyond the experimental and professional skills gained as a result of their project, the exposure gave them technical language and topical knowledge, allowing him to pursue and excel in the field.

The overall nuggets gleaned from these interviews were that students

- learned a lot about water quality and constructed wetlands in a much deeper way than classwork had previously required. This knowledge investment left them well-versed in the topics.

- found the open-ended aspect of a research project daunting and unexpected. In nearly every project, students asked for the “right” procedure or process, and were sometimes frustrated that part of their project was discovering and documenting a process.
- found writing a research report difficult and different than they had previously experienced in classwork, with respect to format, quality and caliber. Students iterated many times to meet expectations.
- needed a substantial amount of my time since many of their research and professional skills required to complete a research project were not yet developed. This time investment on my part was especially important when students did not have a teammate.
- found the external presentations especially motivating. If funding remains available, I will continue to coach students to prepare and give presentations beyond Rose-Hulman to challenge them and expose them to other research students and topics.

Student learning in Environmental Engineering Laboratory

Based on post-module perception surveys, student learning in the Environmental Engineering Lab module was mixed (Table 3). Students reported most strongly that the lab module improved their topical understanding of non-point source pollution (85% agree or strongly agree) and its economic affects (>80% agree or strongly agree). These findings indicate that students perceive that they excelled at achieving learning objectives 1 and 2 which focus on the presence of nutrients and their economic impacts. Secondarily, as a result of this lab module, students reported above the neutral level (≥55% agree or strongly agree) in their abilities to consider context when performing data analysis. Thus, students perceived that they moderately achieved learning objectives 3-5 which include recommending solutions, analyzing data and making connections for specific purposes.

Table 3. Student responses led to knowledge acquisition as a result of the lab module

Question: This lab helped me to improve my… Responses options: 1=Strongly disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly agree	M	SD	% respondents reporting agree or strongly agree
Understanding of how nutrients enter, migrate and/or transform in the environment	3.9	0.6	85
Understanding of how non-point source pollution affects local economies	3.9	0.7	85
Understanding of how non-point source pollution affects national economies	3.9	0.7	81
Ability to analyze data in context of regulations	3.7	0.8	67
Ability to analyze data in context of developing innovative solutions	3.5	0.8	55

Notes: N=27, M is mean value, SD is standard deviation

Considering students’ abilities to use professional skills in this module, students reported most strongly having engaged in empathy to understand motivations and perspectives of others and a stakeholder’s needs (≥74% some, quite a bit, or very much) (Table 4). Additionally, students reported using good data analysis skills including integrating information from many sources and substantiating claims with data and facts (≥74% some, quite a bit, or very much). Interestingly, students reported using economic terms and drivers to a lesser degree (≥60% some, quite a bit, or very much) although they reported having achieved understanding as a result of this module (Table 4). In terms of generating novel solutions to the eutrophication problems, students did not perceive that they engaged in thinking about innovative solutions.

Table 4. Student responses related to use of professional and creative analysis skills as a result of the lab module

Question: During the course of this project, to what extent did you…? Responses options: 1=Not at all, 2=Not very much, 3=Some, 4=Quite a bit, 5=Very much	M	SD	% respondents reporting some, quite a bit, or very much
Understand the motivations and perspectives of others	3.2	1.1	78
Substantiate claims with data and facts	3.1	1.0	78
Integrate information from many sources to gain insight	3.0	0.9	74
Examine a stakeholder’s needs	3.0	1.1	74
Create value for a stakeholder	2.8	1.2	66
Evaluate economic drivers	2.7	1.1	60
Convey engineering solutions in economic terms	2.6	1.0	63
Explore a contrarian view of accepted (i.e., typical) solutions to eutrophication problems	2.6	0.7	67
Identify an unexpected opportunity for design	2.3	0.9	56

Notes: N=27, M is mean value, SD is standard deviation

Discussion and Reflection

Combining important student outcomes from the research projects and lab module, students reported that they learned about water quality (especially non-point source pollution) related to the constructed wetland project. Students also reported that they learned the importance of performing good research to substantiate their claims, whether experiment-based or theoretical. These two points indicate to me that constructed treatment wetlands are a good model for teaching water quality concepts. Using this model allows students to learn not only about and how to measure water quality parameters that should be considered in evaluating waters, but contemporary concerns and practices that are threatening our water resources, and also potential solutions to non-point runoff and CSOs.

In addition, I recently became aware of the impact that this project had on several students with respect to their writing. In the past year, three previous students communicated to me that they learned an inordinate amount about writing from their research experiences. These students thanked me at least one year after their research experiences: these correspondences occurred when meeting in person at conferences in the case of two students who had graduated, and in the senior capstone course, for a current student. Given the amount of time I have invested in mentoring my research students’ writing and critical thinking related to their data, this feedback was validating.

Finally, two students directly credited their abilities to obtain jobs in or align their careers with water resources and environmental engineering based on their research on constructed wetlands. Having the exposure to and opportunity to gain a deep knowledge of water quality parameters and processes in wetland systems allowed these students to gain footing in these areas of interest. It appears that treatment wetlands are not only a good model from which to teach issues affecting surface water quality and best management practices to alleviate these ills, but the topic seems to be motivating and exciting to students and hiring personnel alike.

Conclusions and Future Directions

Overall, students found the constructed treatment wetlands to be a helpful research and course module platform. In both instances, students gained field-specific technical knowledge, as well as exposure to larger, more open-ended problems in the environmental engineering field which provided creative and sustainable-thinking opportunities for all students, research experiences for some students, and career shifts for a couple of students.

In terms of research students, it seems clear that the research opportunities had a large impact on students personally and professionally. To improve their experiences, I would like to try to ensure that all students get to work with a partner. To grow as a mentor, I plan to create an “expectations” memorandum of understanding to help students know what is involved in research and lay bare expectations for both my students and myself. I also want to be sure to continue exposing my students to other applications related to their work via field trips, journal club, and conference presentations.

In terms of bringing the wetlands to more students in required courses, in future years, I would like to incorporate using the wetlands in my Environmental Engineering Lab course more fully by having students take samples using the constructed wetlands. Additionally, I plan to work with my colleagues to identify other opportunities to use the wetlands as examples in other required undergraduate courses such as Hydraulic Engineering, Water Resources Engineering and Introduction to Environmental Engineering.

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Appendix I

Interview questions for ***students***, to investigate student learning as a result of undergraduate summer research experiences:

Considering this list of skills and other you may identify,

- Understand contemporary concepts in your field
- Make use of the primary scientific research literature in your field (e.g. journal articles)
- Identify a specific question for investigation based on the research in your field
- Formulate a research hypothesis based on a specific question
- Design an experiment or theoretical test of the hypothesis
- Observe and collect data
- Statistically analyze data
- Interpret data by relating results to the original hypothesis
- Reformulate your original research hypothesis (as appropriate)
- Relate results to the “bigger picture” in your field
- Orally communicate the results of research projects
- Write a research paper for publication
- Think independently

(1) Which skill(s) did you feel particularly confident in prior to the summer research experience? Why or why not?
(2) In pursuing a summer research experience, which skill(s) did you especially want to develop? Why or why not?
(3) Which skill(s) did you develop through the summer research experience?
(4) Which skill(s) did you gain confidence in through the summer research experience?
(5) Which skill(s) did you wish you could have developed more through the summer research experience?

Appendix II

Lab 5 Module Assessment

The following survey is used for assessment. The goal of this survey is to assess the project activities. It will remain confidential and your responses will not contribute to your grade. Please answer the statements below as honestly and fairly as you can. There are no right or wrong answers, only honest ones.

1. The real-world application of the lab motivated me to do my best work. (Answer choices likert scale: Not at all – Throughout the project)

During the course of this project, to what extent did you… (Answer choices likert scale: None at all – Throughout the project)

2. Explore a contrarian view of accepted (i.e., typical) solutions to eutrophication problems.
3. Identify an unexpected opportunity for design.
4. Create value for a stakeholder?
5. Integrate information from many sources to gain insight.
6. Evaluate economic drivers.
7. Examine a stakeholder's needs.
8. Understand the motivations and perspectives of others.
9. Convey engineering solutions in economic terms.
10. Substantiate claims with data and facts.

To what extent did you work with your team? (Answer choice likert scale: almost never-almost always)

11. How many total hours did you spend on your project outside of class time? (Answer choices: 0-2 hours, 2-4 hours, 4-6 hours, 6-8 hours, more than 8 hours)
12. Of the time you spent outside of class, how much of it was spent working with your team? (Answer choices ~0%, ~25%, ~50%, ~75%, ~100%)

This lab helped me improve… (Answer choices likert scale from strongly disagree – strongly agree)

13. My understanding of how nutrients enter, migrate and/or transform in the environment?
14. My understanding of how non-point source pollution affects local economies?
15. My understanding of how non-point source pollution affects national economies?
16. My ability to analyze data in context of regulations?
17. My ability to analyze data in context of developing innovative solutions?