Evaluating the Development of Higher Order Thinking with an Environmental Engineering Build Project

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Introduction

The objective of engineering education is to equip students with the knowledge, skills, and attitudes needed to be able to produce engineering work at a high quality. One of the biggest challenges engineering educators face is introducing students to the complexities associated with conducting real engineering work and then equipping them with the ability to engage that work with competence and insight. Learning taxonomies are tools that can be used to categorize the cognitive levels at which learners are engaging with material as a means of providing structure and metrics to the educational process, with achievement at higher levels of a taxonomy generally corresponding to the desired intellectual abilities for practicing engineers [1, 2, 3].

The general consensus among engineering educators has long been that creative, practical, and active educational methods are needed in order to produce engineers who are well-prepared for the workplace. Presenting students with problems and projects, laboratory experiences, design challenges, group work, and other deviations from the typical textbook and lecture format may offer some of these more effective learning experiences if conducted well. However, they also have an associated cost, requiring a greater investment of physical infrastructure, instructor time and effort, a reduction in time spent covering material in more traditional ways, or all of the above. The question quickly arises: is the enhanced learning activity worth it? Building a better understanding of how these activities improve students' learning of the subject matter will allow instructors to make better-informed decisions about how to value and structure active educational efforts in future courses.

This study aims to evaluate the question of value gained as it relates to a water treatment design project implemented in a junior level environmental engineering course. Several forms of assessment are used to evaluate the hypothesis that the project is a more effective tool than typical classroom instruction for helping students achieve higher levels of cognitive abilities related to water treatment concepts.

Background

Many of the kinds of educational activities that involve providing students with activities and challenges outside of the typical textbook and lecture class experience can be classified as inductive learning methods. Inductive methods are all learner-centered as opposed to teacher-centered, requiring students to pursue the acquisition and application of knowledge on their own accompanied by structure and guidance provided by the instructor. Inductive methods are generally regarded as a better means than deductive methods (e.g., lecturing) for developing students' "deep" learning of a subject, intellectual growth, and professional preparation [4].

Problem-based learning, or PBL, is one of the more commonly adapted inductive methods in professional fields like medicine and engineering. In PBL, students are presented with an open-ended, ill-structured, and realistic problem and then work to obtain a solution, often in teams. PBL is a particularly relevant tool for implementation in the engineering classroom, as it has been shown to have a positive effect on “skill development, understanding interconnections among topics, deep conceptual understanding, ability to apply appropriate metacognitive and reasoning strategies, teamwork skills, and even class attendance” [4]. However, some of the tradeoffs include that PBL can be less effective at developing content knowledge, the wrong conclusions students reach may go uncorrected, the activities are often difficult for the instructor to implement, and students may be resistant to the new paradigm of being responsible for their own learning [4, 5]. Several of these concerns may be mitigated by implementing an approach involving “scaffolding” as a balance between challenge and support, with heavy instructor support at the beginning of an activity that is then gradually reduced throughout the activity [2, 4]. To make PBL even more effective, the problems to be solved may involve activity and collaboration. Active and constructive learning experiences engage the learner’s attention and require them to produce outputs containing new ideas [6], while collaborative learning experiences involve students working in groups to achieve a common goal [7].

Project-based learning is technically different from PBL, often requiring the solution of several problems and with a greater focus on the development of an end product instead of the knowledge acquired during the educational exercise [4]. However, the activity described in this study possesses features of both project- and problem-based learning, and so will continue to be referred to as PBL, hybridizing “project” and “problem” without further differentiating between the two methods.

One of the most common tools used to classify learning as lower-level or “shallow” versus higher-level or “deep” is Bloom’s Taxonomy [8]. Bloom’s Taxonomy proposes six levels of learning in increasing order of cognitive engagement: Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation. While many variations of and expansions upon Bloom’s Taxonomy have been produced since it was initially introduced in 1956, the original taxonomy still provides the best fit for civil engineering and similar applications, mostly due to its establishment of evaluation as the pinnacle of cognition for a particular subject [9].

The topic of water treatment seems to be a common target for implementing PBL or other creative educational experiences within environmental engineering courses [10, 11, 12, 13, 14]. While there has been some evidence of these activities improving students’ engagement and enthusiasm regarding water treatment topics [10, 13] or ability to better recognize social contexts [12], little evidence was found on the way these activities may actually influence students’ learning of water treatment concepts, particularly at higher levels on Bloom’s Taxonomy.

Project Development

A problem-based, active, constructive, and collaborative water treatment design project was developed at Cedarville University. This project has been structured to encapsulate many recommended features of PBL, as it is open-ended, realistic, teamwork based, and scaffolded.

The idea for this project originated from Dr. Darryl Low at LeTourneau University in the mid-2010s. That project provided junior-level environmental engineering students the opportunity to construct and operate pilot-scale water treatment plants. Water was retrieved from a local river and students were initially provided 55 gallons to treat. Groups of 3-4 students designed, built, and tested a system that produced a volume of 35 gallons of potable water within 48 hours and met water quality testing of alkalinity, pH, solids, conductivity, turbidity, and bacterial growth according to TAC 290. The plant operations were permitted to be a combination of batch and continuous flow.

Initial Implementation

The environmental engineering course in this study was first taught at Cedarville University in Fall 2020 as a third-year course with 3 lecture hours and one 2.5-hour lab each week. The course is required for all civil engineering students. This course includes learning outcomes connected to ABET's Program Outcomes 1-6. Several course learning outcomes focus on the application of analytical techniques used in environmental engineering, applying standards for drinking water experimentally, communicating in written and oral forms, and understanding the need for water in various communities. During the first year the course was offered an initial version of the project was planned and implemented in support of several of the course learning outcomes. To help communicate environmental engineering topics and prepare students for the project, lab activities for the first six weeks included (1) an introduction to lab equipment and practices, (2) turbidity and conductivity, (3) alkalinity, (4) chlorine residual, (5) jar testing, and (6) sand filtration. During the subsequent weeks, the structured lab times transitioned into team project work sessions.

At the commencement of the project, students were placed on five teams of 3-4 students each and tasked with using simple materials to build miniature water treatment plants capable of producing 15 gallons of water within 8 hours. Up to 30 gallons of non-potable source water were provided on test day to feed each individual system. In addition to the volume production requirement, the effluent quality was evaluated for turbidity < 1 NTU and a residual chlorine 0.2-4.0 mg/L Cl_2. All the built components and the effluent basin (a 55-gallon drum) were required to fit on a 4'x4' pallet, not exceeding 6' in height. Designs were required to implement the unit processes of coagulation, flocculation, sedimentation, media filtration, and disinfection in a continuous flow system. Teams were required to build plants that could work virtually independent of human interaction (except for plugging in or turning on components at the start).

One of the project goals was for students to learn how to repurpose rudimentary materials to make a complex system. Students were provided materials such as wood dimensional lumber and paneling material, small-diameter plastic tubing (¼"-1"), PVC (½" – 1"), mechanical fasteners, adhesives, and media for filtration. Teams were required to create their own basins from plexiglass sheets and lengths of PVC pipe. Teams had access to hydrated alum as a coagulant and concentrated sodium hypochlorite as a disinfectant. Small peristaltic pumps for chemical addition, a medium influent pump, small electric motors, plastic propellors, batteries, and a DC power supply were provided to each team. Students were informed at the beginning of the project timeline that the source water would be retrieved from an on-campus retention basin just before the test day and groups could perform water quality tests or experiments on it as desired.

Along with the requirements listed above, the guidelines handout included a roughly structured schedule for teams to track their progress. Five weekly lab sessions were dedicated to working on this project. Groups wrote informal weekly memos about their plans for the upcoming week.

The instructor also met with each team during the lab sessions for 15-30 minutes every week to confirm progress and offer technical advice.

On the test day, all five water treatment plants were operational. Water quality and quantity were evaluated, as well as component functionality and leaks. Turbidity and residual chlorine were tested three times throughout the test day. Four of five teams successfully met the water quality requirements, while only three plants produced at least 15 gallons due to significant leaks in the plexiglass basins. This session was followed up with a short (8-10 minutes) in-class presentation later in the week, and peer and self-evaluations by each student.

The original project scoring was significantly weighted toward the team's weekly memos as 60% of the project grade. This focus was intended to show students the value of making reasonable and timely progress toward project milestones. Test day performance (water quality of turbidity and chlorine, leaks, flow consistency, output volume, creativity) contributed 24% and the subsequent presentation was 16% of the project grade.

Further Development

Development has continued on this the project over the subsequent three years; these changes have been summarized in Table 1 below. After receiving student feedback in Fall 2020 that the timeline felt rushed, the project was extended from 5 weeks to 6-7 weeks.

In the second year, CAD designs were required prior to commencing construction to minimize errors and materials wasted. A more detailed guidelines document and materials cost sheet were provided in the second year, and cost was used as part of the overall evaluation on test day. A small discount was applied to the purchase cost for using recycled materials available in the civil engineering laboratory stockpiles (lumber or piping used for previous projects). Additionally, groups were allowed to remove a single unit process of their choice, if they believed their treatment plant could function adequately without it. A technical written report was developed to organize the teams' progress throughout the project and solidify student understanding of the project as a whole system. A bonus of +5% was awarded to the team that achieved the lowest [turbidity (NTU) × cost] score, to incentivize an effective and economic design.

Some designs encountered unnecessary challenges because of the limitation that basins could only be made out of plexiglass sheets. On test day, several groups experienced leaking basins or failing adhesives. Beginning in the third year of the project, the instructor provided plastic bins in various sizes (0.25-10 gallons) to minimize that hurdle. While limited in quantity, groups could make any desired modifications to their basins. Additionally, the 8-hour test was decreased to 5 hours to both lessen the time commitment for students and staff and to better match with the available component functionality. Specifically, the small chemical addition peristaltic pumps were found to function more consistently at moderate pump rates (vs. very slow).

During the third and fourth years of the project, the progress reporting was formalized to ensure effective task management and individual engagement. This change also allowed the instructor to give more timely and organized feedback. Groups submitted weekly team reports and each student was responsible for an additional weekly individual report. Team reports continued to be planning tools: memos designed to share an overview of what the team had accomplished the previous week and what they planned to do the week ahead. Individual reports were kept confidential with the instructor and used a template that let individuals describe their personal contributions and allocate their time spent. In the individual report, students also self-assessed their personal learning, teamwork, and performance from the past week of the project.

Project Overview

The study conducted in Fall 2023 was heavily reliant on the previous years of project development. The 17 enrolled students were divided into 5 project teams in two lab sections. The class consisted of junior-level civil engineering students, 3 females and 14 males. No racial or ethnic minorities were represented, but several students had international backgrounds. Groups were given the guidelines document with timeline milestones, final deliverables, and rubrics for the memos, test day evaluation, report, and presentation. The objective of this project remained consistent with the first year to design a water treatment system capable of treating 15 gallons of non-potable water to a turbidity of <1 NTU with residual disinfectant of 0.2-4.0 mg/L for acceptable pathogen/virus inactivation. In this iteration, as with the previous year, groups were required to produce the volume within only 5 hours. An example of one team's constructed project and the corresponding CAD drawings are shown in Figure 1.

Scaffolding this project focused on weekly tasks and check-ins between groups and the instructor during the lab session. The instructor provided both general and specific guidance but allowed teams to make their own decisions about the design. Teams were provided with a 7-week schedule at the beginning of the project as a part of the guidelines document (shown in Appendix A). Groups turned in weekly team reports with a filled-out material cost sheet and corresponding CAD drawings on the online learning management system as early as week 3, enabling groups to begin building their structures or collecting materials. A complete list of the materials provided can be found in Appendix B. Weekly tasks were often divided between members such that reasonable progress was made on individual unit processes, experimentation, CAD development, materials checkoffs, and building. The instructor communicated that important decisions should be made by the whole team, as opposed to by individuals. Having learned various testing methods during the first 6 weeks of lab, students spent weeks 2-5 of the project experimenting with jar testing variations, sand filter configurations, and pump testing for the various applications (e.g., influent, chemical addition).

Table 1 – Development of the water treatment plant build project from Fall 2020 to Fall 2023.

Semester	**2020**	**2021**	**2022**	**2023**
Class periods (hours) devoted to water treatment	5	5	5	4
Lab activities in preparation for water treatment	6			
Class size	20	13	16	17
Group size	3 to 4 students			
Project length (weeks)	5	6	7	7
Weekly scaffolding & deliverables	Weekly team memos Meetings with instructor	*All previous support, adding:* CAD drawings & material cost sheet for building approval	*All previous support, adding:* Weekly individual memos	
Building requirements	4'x4' pallet, 6' tall			
Treatment Goals	Volume: 15 gallons in 8 hours Quality: Chlorine & turbidity		Volume: 15 gallons in 5 hours Quality: Chlorine & turbidity	
Basin Construction	Plexiglass & caulk/adhesive		Variable sizes of plastic storage bins Plexiglass & caulk/adhesive	
Final Evaluation	Treatment goals Presentation Peer Evaluation	*All previous evaluation, adding:* Cost of Materials CAD Report		

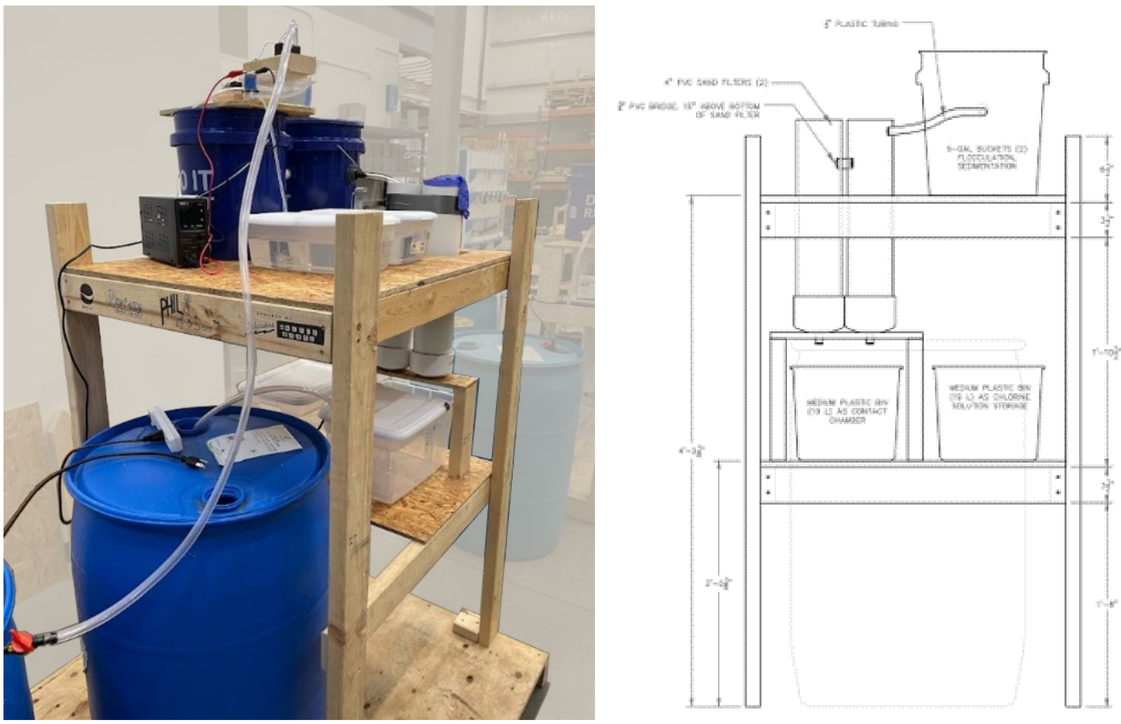


Figure 1 – Example constructed water treatment project (left) with corresponding CAD (right).

Project Challenges

While students identify that this is one of the most engaging and enriching projects they have participated in, it comes with a significant time commitment for both student and instructor. When asked to approximate their weekly tasks for the first two weeks of the project, students self-reported an average of about 3 hours. During weeks 3 and 4, students reported dedicating 5-6 hours on average to project tasks. This range is not reflected equally across each team, and some individuals listed up to 18 hours of project activities during the final two weeks. The current project timeline also required the instructor to review and provide timely feedback while managing the activity during the 2.5-hour lab. Individual and team reports were due by 5 PM the day preceding the lab period so the instructor could review the progress before the midafternoon lab. Students have also provided feedback that the presentation and report are valuable, but they requested a longer period of time between test day and the due date for presentation and report.

The other major challenge associated with this project is the facility space. While it is helpful to confine the water treatment plants to the size constraint of a 4’x4’ pallet, the actual construction space required is generally much larger. Including construction space, conducting the project with five teams required about 400 ft^2 of lab space. This lab space does not include additional space required for conducting experimentation and storing project materials.

Assessment Plan

Assessment was conducted on the students involved in the project in Fall 2023 with the objective of determining whether the project was able to produce evidence of students gaining greater abilities at the levels of analysis, synthesis, and evaluation on Bloom's Taxonomy. This assessment plan constitutes an experimental study [15]; however, as no control group was available, there exists the admittedly challenging objective of differentiating students' learning between what was gained through classroom instruction versus what was gained through their work on the project. A baseline data approach was implemented through the collection of pre- and post-activity quizzes, with quiz questions constructed to target students' abilities to analyze, synthesize, and evaluate water treatment concepts. Given the limitations of baseline data design [15], triangulation was also attempted through the implementation of post-activity interviews. The resulting mixed-methods study allows for the integration of data collected through both quantitative and qualitative methods [16]. Mixed-methods studies are often good fits for engineering educational research due to their ability to collect detailed information concerning a few individuals and generalized information about a broader population [17]. The overall structure of this assessment plan was based on a previous study evaluating the implementation of an active learning exercise in a civil engineering course [18].

Description of Quiz Instruments

Two quizzes were developed to be distributed at different stages of the project: (1) pre-activity and (2) post-activity. The pre-activity quizzes were administered after students had been introduced to principles in the classroom setting but before any significant engagement with the PBL activity had taken place, while the post-activity quizzes were administered after the conclusion of the PBL activity. Both quizzes consisted of questions selected to target assessment of students' skills of analysis, synthesis, and evaluation related to water treatment topics. All 17 students participating in the study took both quizzes. Analysis ability was assessed on the pre-activity quiz with a situation relating to increasing turbidity and a reasonable diagnosis of the cause. The post-activity quiz asked students to demonstrate their analysis ability by identifying relevant considerations in choosing a coagulant and the dosage. Evaluation ability was assessed on questions relating to coagulation and jar tests. Students interpreted graphs of jar testing to choose an appropriate dosage on the pre-activity quiz, and as a follow-up on the post-activity quiz they ordered the relevant considerations in choosing a coagulant and dosage in order of importance. Finally, synthesis ability was assessed as students were asked to design a skeleton water treatment plant. On the pre-activity quiz, they chose which unit processes and chemicals should be included, given a variety of water quality parameters and values. On the post-activity quiz, students further supported their answers with an explanation and by drawing lines connecting the unit processes with specific parameters that informed their decisions (i.e., presence of viruses, pathogens, bacteria, and NOM informed their choice of disinfectant). The questions for each quiz instrument are included in Appendix C.

Description of Interview Instrument

Five students were selected from the 17 students in the study and invited to participate in a one-on-one interview with the project's co-investigator. Selection was semi-random, with criteria requiring at least one each of high, medium, and low performers in the course and one student from each of the five groups in order to ensure a reasonable variety of student perspectives. The students selected for interview included three male students and two female students, which reasonably reflects the demographics of the class.

The interviews were conducted in a semi-structured manner: specific questions were asked of each student, but the interviewer had the opportunity to ask for clarification or explanation if desired. Six questions were intended to serve as a direct assessment of students' understanding of water treatment topics and four questions were intended to serve as an indirect assessment of students' perceptions of their own conceptual gains due to their respective activity. Results were evaluated for evidence of thinking that occurred at the Bloom's taxonomic levels that supported and were associated with the question. For high-level questions seeking to show analysis, synthesis, or evaluation, students' lower-level understanding and application skills were also incorporated in the rubric. The structured questions can be seen in Table 5 in the Results sections below.

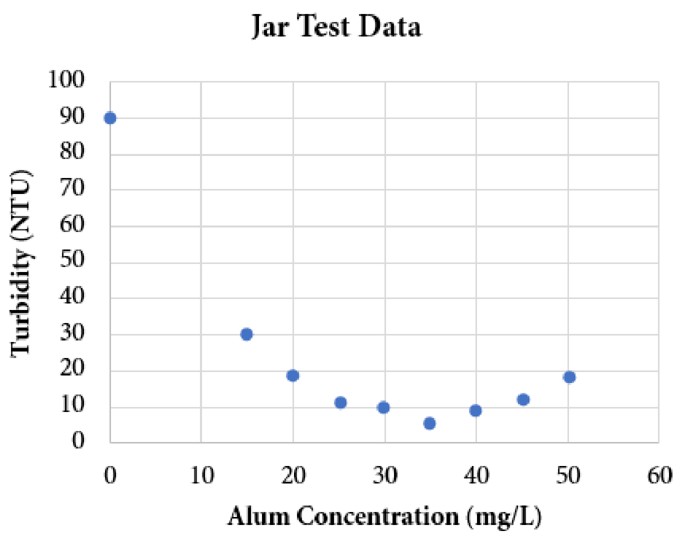
The numerical results collected through the quantitative evaluation were considered alongside the narrative results collected through the qualitative evaluation, with the intent of applying a mixed-methods approach to produce better confidence in the conclusions related to students' demonstration of higher-level cognition.

Quantitative Results

All students in the course (enrollment = 17) voluntarily participated in the pre- and post-activity quizzes. The quizzes were evaluated using rubrics on the basis of: Incomplete Data (ID), Incorrect Understanding (IU), evidence of Lower-Level Cognition (LLC), and evidence of Higher-Level Cognition (HLC). Results of the quizzes were not provided to the students during the course of the study.

An example quiz question and assessment rubric are shown below to demonstrate the varying achievement levels (Figure 2). Several of the questions allowed a short free response from students, and such answers could be categorized under multiple headings (e.g., both HLC and IU for distinct portions of an answer that separately indicated some higher-level cognition but also some incorrect understanding). Student identifiers collected with the quizzes allowed direct performance to be tracked from pre- to post-quiz, resulting in achievement levels and indicators of understanding listed as percentages in the following tables. Table 2 summarizes the results of both quizzes as a function of the number of students in the course. Table 3 shows the achievement level differences or "indicators" between the pre- and post-activity quizzes, noted as improvement, remaining consistent, or regressing. Specific data stemming from those changes are summarized in Table 4 as opportunities that led to improvements and the number of students who showed IU on the post-activity quiz.

1. As a water treatment plant operator, you perform jar tests weekly to inform the plant staff about adjusting coagulant dosage within the clarifier. You plot the data from your latest test with concentrations of 15-50 mg/L, in increments of 5 mg/L. Determine the coagulant dosage you would recommend and defend your choice with at least 1 sentence.



Achievement Level	Answer & assessment
Evidence of higher-level cognition (HLC)	Chose 25 mg/L due to its low turbidity (very close final turbidity to the optimum) and cost or storage savings.
Evidence of lower-level cognition (LLC)	Chose the minimum listed of 35 mg/L at ~7 NTU because it has the lowest turbidity **OR** chose 20, 25, or 30 mg/L without explanation.
Incorrect Understanding (IU)	Chose the sample blank (0 mg/L, 90 NTU **OR** chose a dosage of 15, 40, 45, or 50 mg/L.
Insufficient Data (ID)	No attempt at solution.

Figure 2 - Pre-activity quiz question, assessing students' evaluation skills (above) and example rubric (below).

The analysis questions indicated the smallest change between the quizzes, and it appears that the project contributed little to the students' analysis skills (Table 2). The analysis questions showed achievement levels both improved and regressed, with great variation throughout the class. Students with initially IU were able to correct themselves to HLC or LLC (18%); however, other students who demonstrated HLC on the pre-activity quiz declined to LLC or IU (24%) (Table 3).

Table 2 – Results of pre- and post-activity quizzes for each higher-level achievement. Results are listed as a percentage of the total students in the course (n = 17).

	Analysis		Synthesis		Evaluation	
	Pre-Activity	Post-Activity	Pre-Activity	Post-Activity	Pre-Activity	Post-Activity
HLC	35%	26%	6%	33%	6%	24%
LLC	47%	65%	88%	49%	94%	47%
IU	18%	9%	6%	10%	0%	29%
ID	0%	0%	0%	8%	0%	0%

More significant changes were seen in both synthesis and evaluation categories. Most students initially achieved LLC on the pre-activity quiz in synthesis and evaluation (88% and 94%, respectively), while few showed signs of HLC (6% each). By the post-activity quiz, up to 33% and 24% of student answers reflected HLC in synthesis and evaluation, respectively (Table 2). Many of the students who achieved LLC of evaluation and synthesis on the pre-activity quiz progressed to HLC of evaluation and synthesis by the post-activity quiz. The synthesis questions produced the most notable increase in cognitive achievement as 36% of students indicated elevated LLC to HLC (Table 3). Still, some who achieved an LLC on pre-activity quiz evaluation or synthesis performed lower, regressing to IU or ID on the second quiz (Table 2). Interestingly, the evaluation questions prompted an even split between LLC improving to HLC and LLC regressing to IU (24%) (Table 3).

Table 3 – Indicators of understanding between pre- and post-activity quizzes, broadly categorized by improvement, consistent, and regression.

		Analysis		Synthesis		Evaluation	
		% of Responses	Overall	% of Responses	Overall	% of Responses	Overall
Improvement	IU→HLC	9%	24%	0%	40%	0%	24%
	LLC→HLC	6%		36%		24%	
	IU→LLC	9%		4%		0%	
Consistent	HLC→HLC	12%	47%	0%	45%	0%	47%
	LLC→LLC	35%		43%		47%	
	IU→IU	0%		2%		0%	
Regression	LLC→IU	6%	29%	9%	15%	24%	29%
	HLC→LLC	21%		6%		0%	
	HLC→IU	3%		0%		6%	

When comparing the two quizzes across all three areas, 45-47% of students demonstrated a consistent level of cognitive achievement. The LLC→LLC category was the largest single category for any of the taxonomic levels. In support of the established research concerning PBL, there were also several cases of regression from HLC to IU in areas of analysis and evaluation, indicating that through the activity students may have developed wrong understandings of water treatment principles that went uncorrected.

To further compare the impact of the project on achieving the higher level of Bloom's taxonomy, the quiz instruments were also evaluated for improvement. "Opportunities" were identified as present when students indicated incorrect or only lower-level understanding on the pre-activity quiz, creating an opportunity to demonstrate improvement on the post-activity quiz. (A similar approach was adapted in a previous study [18].) "Improvements" indicates the number of students who took advantage of their "opportunity" to increase their understanding to the target of higher-level cognition (i.e., IU or LLC → HLC). "Exited at IU" indicates students whose final achievement level on the post-activity quiz was IU and is represented as a percentage of the entire class (n = 17).

Table 4 – Comparison of pre- and post-activity achievement.

Assessment	Analysis	Synthesis	Evaluation
Opportunities (ID, IU, LLC)	11	16	16
Improvements to HLC	3	11	5
% Students	27%	69%	31%
Exited at IU	3	4	7
% Students	18%	24%	41%

With the methodology displayed in Table 4, it can be seen that an appreciable number of students took advantage of the "opportunity" for learning improvement offered by the PBL activity and "improved" to HLC in each of the three levels of Bloom's Taxonomy. The most significant improvement was in the area of synthesis, as a majority of students with "opportunities" to improve achieved HLC (11/16, 69%). This observation is especially significant when compared to analysis and evaluation, where less than half of the "opportunities" led to improvements to HLC. Several students also demonstrated some struggles with evaluation, either maintaining or regressing to IU in the post-activity quiz (7/16; 41%). This trend further corroborates the observation that PBL can be problematic by leading some students to reach incorrect conclusions or allowing their misunderstandings to continue uncorrected.

Qualitative Results

The interviews were recorded and transcribed by the project's co-investigator to maintain anonymity with the course instructor. Student responses were grouped by common themes, as well as their achievement of lower-level (understanding, application) and higher-level (analyze, synthesize, evaluate) cognition. The same terminology of IU, LLC, and HLC established in the quantitative assessment were applied to the qualitative results. As with the short-answer quantitative assessments, students' responses could be categorized in multiple ways as portions of their responses might indicate different levels of understanding.

Direct Assessment

The questions and responses to the direct assessment are summarized in Table 5. Questions 1 and 2 were directed at establishing a baseline of understanding (LLC) of water treatment concepts learned in the classroom or from the project experience, while questions 3-6 targeted higher-level achievement of analysis, evaluation, or synthesis (HLC).

All 5 interviewed students exhibited a correct LLC of the purpose of water treatment (Question 1). Answers followed a pattern similar to "provide potable water, both water for everyone to drink or use for general purposes." On Question 2 relating to determining basin sizing, each student also demonstrated LLC (100%). They understood and applied a key project idea of calculating basin sizes to a new context of large-scale water treatment plants.

Four of the five students (80%) were able to formulate the correct steps to quantify how much of a concentrated chemical solution to add to a dilute stream, achieving HLC in the form of analysis (Question 3). When asked to gather a list of evaluation criteria for full-size water treatment plants, most of the students required additional prompting through clarification question(s) (Question 4). While four students did present an HLC-indicating evaluation that included cost and efficiency (80%), three of the students also mis-evaluated and/or mis-applied concepts (60% IU), displaying mixed outcomes. Several answers alluded to concepts related to the build project but less relevant to the broader context of large-scale water treatment operations (i.e. "overflow, running out of chemicals, or not adding in things at the correct time"). This disconnected response may be indicative of students thinking that all project concepts correlate with real life, a potential issue of PBL. It is unclear if these answers show an incorrect or merely an incomplete understanding of full-scale water treatment operations.

Question 5 was aimed at students evaluating their team's chosen design after it had been tested. All students demonstrated HLC and were able to critique their designs for specific improvements like recommending "less fines in sand filter to increase flow" or "increased sedimentation retention time." Two students failed to establish a lower-level understanding (40% IU). For example, one student proposed a configuration change that would not have had a positive impact on the system, while another struggled to identify any room for improvement on his team's structure because the team met the minimum water quality and volume production requirements.

Students were tested on their ability to synthesize information from the context of the project into a real-world application with Question 6. Individuals were prompted to ideate what challenges water treatment plant designers may experience regularly. All five students demonstrated correct understanding and application of their knowledge (100% LLC). Two students made connections to specific unit processes or chemicals that were designed in the project (e.g., sand filters, alum as a coagulant). From this, it was determined that four of the participants were able to synthesize information clearly and correctly, achieving HLC (80%). Within their responses, three students demonstrated incorrect understanding, with answers related to basin materials cracking or managing relationships with contractors.

Table 5 – Categorization of direct assessment interview questions, resulting achievement level (# = students, out of 5).

Interview Questions	Achievement Level	Taxonomic Level	#	Representative Statement
1. Describe the purpose of water treatment.	LLC	Understanding	5	"To provide potable water"
	IU	N/A	1	"Enable safe, inhabitable infrastructure"
2. How do water treatment plant designers size basins?	LLC	Understanding/ Application	5	"Q equals V over t"
	IU	N/A	2	"Based on… the size of incoming water"
3. If you were working at a conventional water treatment plant, what steps would you need to take to determine the flow rate at which you'd add a concentrated disinfectant solution into a basin, if you were trying to achieve a certain concentration? (Given water quality parameters like temperature, pH)	HLC	Analysis	4	"Using QC equals QC"
	IU	N/A	3	"Figure out like the deactivation and log deactivations for certain things"
4. What makes one water treatment plant design better than another?	HLC	Evaluation	4	"Cost and efficiency…, different type of a filtering system"
	LLC	Understanding/ Application	5	"Satisfy requirements at lowest cost"
	IU	N/A	3	"Gauging human error a little bit better"
5. How would you have changed your system configuration based on the results your team was able to achieve?	HLC	Evaluation	5	"Adjusting the sand filter entrances; sealing issues; not enough coagulant mixture"
	IU	N/A	1	"The whole system seemed to fit together well. It was individual parts that did not perform"
6. What do you imagine are some of the bigger challenges in designing a full-scale water treatment plant?	HLC	Synthesis	4	"To try to produce a constant amount of water, but demand for water is not constant"
	LLC	Understanding/ Application	5	[see above]
	IU	N/A	2	"Because it's larger… possibly more introduction of mistakes and cracking"

Some lack of understanding (IU) and/or lower-level achievement (LLC) may be attributed to the nature of the project tasks being easily split between teammates. A few comments like "I did not do this part" surfaced when asked to provide the correct analysis method for chemical addition into a basin (Question 3). This was further reflected in another student's descriptions of their team management style (Question 10, discussed more thoroughly below) that was efficient through task delegation, but "we all didn't get to understand parts of the process."

Indirect Assessment

The indirect assessment began with the interviewer asking, "If I had asked you in September (after you'd seen the material in class, but before you started the Build Project) how well you felt that you understood water treatment concepts, what would you have said?" (Question 7). All five participants indicated that they achieved a basic understanding of water treatment concepts from in-class lectures and homework assignments, and this understanding was greatly improved with the project. One student commented that, "After the treatment project, I understand how the different processes work. And I can explain to a family member who asks me about the water treatment project that I did." Students were asked, "Do you think designing, constructing, and testing the water treatment plant helped you to better understand some environmental engineering (specifically water treatment) principles?" and followed up with an opportunity to clarify, "How did it help you?" (Question 8). All students clearly stated the activity helped with understanding, and three addressed specific aspects of synthesis that were improved, including how "everything functioned together."

In addition to discovering the impact of the water treatment project on achieving higher order cognitive levels, the investigators were interested in hearing student feedback about how different project tasks and deliverables could be improved for future years. Further, students were asked "Do you see value in all the parts of this activity (teamwork, modeling with CAD, experimenting, calculating, building, testing, reporting & presenting)?" and to rank them for their value in gaining understanding of water treatment principles (Question 9). Scores of 1-8 were used to gauge project facets from least (1) to most (8) helpful. In an open-ended response time, two students indicated that specific aspects of the project contributed to higher-order thinking. "Testing" (referring to running the system on test day) and "experimenting" (including any lab experiments performed during the project timeline; excluding the supporting course lab experiences) were rated as the most helpful parts of the activity, scoring 7.2 and 6.8, respectively. One student specified that his role on the project did not include CAD work; therefore, he acknowledged that it had value, but scored it as the least helpful component for his own learning. Most students identified "presenting" as the least helpful facet of the entire project for developing their understanding of water treatment concepts.

The interview concluded with students reflecting on their team management styles, "How could you and your teammates have managed this project better?" (Question 10). Two main ideas arose: (1) the division of labor vs. team unity and (2) the acknowledgement that they should have worked to make progress earlier. One identified that her team was unified in their decision-making, but they struggled to divide the work. Conversely, another student's team had a particularly organized teammate who assigned tasks efficiently. This led to a disconnect within the team since a few individuals did not know about the others' design decisions.

Table 6 – Ranking of project tasks in helping to understand water treatment topics (8 = most helpful; 1 = least helpful).

Project Task	Scoring	Score Range
Testing	7.2	5-8
Experimenting	6.8	4-8
Calculating	6.0	5-7
Teamwork	4.4	3-6
Modeling	3.6	1-6
Reporting	3.4	2-4
Building	3.2	1-6
Presenting	1.4	1-2

Overall, students appeared to greatly appreciate the hands-on experience this project provided for them to learn about water treatment concepts. As one student commented, "This is probably my favorite thing we did so far in the civil program though. This is a super fun project."

Conclusions and Recommendations

A PBL exercise with hands-on activities related to water treatment was implemented in a third-year environmental engineering course to supplement the theoretical content presented in lectures. It was hypothesized that this 7-week project would contribute to students' ability to demonstrate proficiency at higher levels of cognition – analysis, synthesis, and evaluation.

The data collected from this study supports the idea that this project reinforced both higher and lower Bloom's taxonomic levels. The data suggests the project was especially influential in developing student ability to synthesize, which seems fitting given the project's central emphasis on creating a functioning water treatment plant by integrating several unit processes. After completing the project, a majority of students demonstrated that their synthesis abilities had at least partially improved to a higher-level cognition on the post-activity quiz (69%; 11/16). On the whole, 80% of the interviewed students were capable of orally communicating an ability to synthesize, analyze and evaluate information about water treatment topics. Changes in students' analysis and evaluation skills were less consistent when measured from the quantitative assessment. Analysis levels both improved and regressed, with great variation throughout the class. Only 3 of 11 students with opportunities to improve achieved HLC on the post-activity quiz (27%). The evaluation questions prompted a close split between improving to and regressing from HLC, and 41% of students exited the post-activity quiz with some incorrect understanding (7/17). Building a better understanding of how these activities improve students' learning of the subject matter will allow instructors to make better-informed decisions about how to value and structure active educational efforts in future courses. The methods developed in this study may be useful for other instructors who wish to evaluate learning increases for similar projects.

Even so, several adjustments to the project timeline and deliverables could remove cumbersome or unnecessary project challenges that limit learning. It was confirmed that some team dynamics limit understanding in a few areas when tasks are divided evenly or efficiently between members. This partitioning of the project may be at least partially responsible for the observations that some students complete the project while still possessing incorrect understandings of certain elements. In the future, the instructor may opt to enforce a check-off system where the entire team must have written or verbal consensus before advancing the design, encouraging group discussion around each major design decision. Some modifications to lecture content may also be undertaken to try to address some of the areas in which students seem to continue to demonstrate incorrect understanding.

Some of the challenges of PBL identified in literature, specifically those related to activities limiting students' acquisition of content knowledge and student resistance, were absent from this study. All areas of the mixed-methods study provided evidence that students generally increased in their understanding as a result of completing the project. Additionally, students self-assessed that the project was a valuable learning experience and that they enjoyed the responsibility of learning on their own. However, this study also affirmed two other common pitfalls of PBL: some students still ended the project with incorrect understanding, and the activity did require a more significant time investment from the instructor than would have been needed to present additional lectures or conduct simple, structured lab exercises.

With this study representing multiple years of development, it is recommended that a PBL project of this level is best undertaken in stages, rather than implemented all at once at the scale described. Adapting this project into an existing course could be structured in three stages. An instructor demonstration could be performed in the first stage. With a foundation of water quality and treatment-related lab experiences, one class or lab period could be dedicated to showing students a small version of a water treatment plant with prefabricated containers as unit processes. The next stage could include increasing the scale of the project to span over 1-3 weeks and incorporating student participation. As a class or in groups, students could collaborate on construction of a single miniature water treatment plant, for a total volume production of less than 5 gallons in a 1 or 2-hour period. The final stage could increase the timeline up to 7 weeks and push students to participate in experimentation and design before larger-scale construction, testing their ideas of each unit process and supporting their final designs with data. Cost sheets, CAD drawings, a final report or presentation could be incorporated during the second or third stages.

While the level of investment required may vary depending on the exact situation and instructor, the data collected from this study largely supports the idea that PBL exercises may well be worth the effort, despite the potential challenges it presents to both students and instructors. Both the quantitative and qualitative results indicate that the project was particularly effective at developing students' synthesis abilities, despite more mixed results related to analysis and evaluation. When these results are considered alongside the more obvious increases in student enthusiasm and motivation, there exists the potential for significant gains in both cognitive and affective domains for those instructors who are willing to undertake the challenges associated with presenting their students with these kinds of learning opportunities. The results of this study support the effectiveness of PBL and suggest that its implementation was able to inspire higher level cognition related to water treatment and environmental engineering concepts.

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Appendix A: Seven-Week Project Schedule from Fall 2023

Note the implementation of scaffolding through the clear delineation of weekly tasks and regular communication with the course instructor.

Week	Deliverable – Due weekly @ 5:00 PM	Weekly Work
1	No memo due	• Topic assigned • Group meetings • Consider initial tasks
2	*Team Memo 1 includes*: ☐ Delineation of teammate roles ☐ Unit process selection ☐ Cost of materials	• Research & design effective design(s) for component scale-down • Consider next week's tasks
3	*Team Memo 2 includes*: ☐ Progress update ☐ Preliminary CAD schematic(s) ☐ Brief explanation of component compatibility with upstream/ downstream component(s) ☐ Cost of materials & list of additional purchase(s)	• CAD schematic approval • Begin building • Consider next week's tasks
4	*Team Memo 3 includes*: ☐ Progress update ☐ Polished or approved CAD schematic ☐ Further explanation of component compatibility with upstream/ downstream component(s) ☐ Cost of materials & list of additional purchase(s)	• CAD schematic approval • Continue building • Integrate system components • Consider next week's tasks
5	*Team Memo 4 includes*: ☐ Evaluation of component functionality ☐ Evaluation of system integration ☐ Progress update	• Continue building • Flow tests • Leak tests • Consider next week's tasks
6	*No team memo due* unless approving a new CAD schematic	• Finish building • Flow & leak tests • Report & presentation prep • Integrated system test
7	☐ Final Report ☐ Group presentations ☐ Completed peer evaluations	

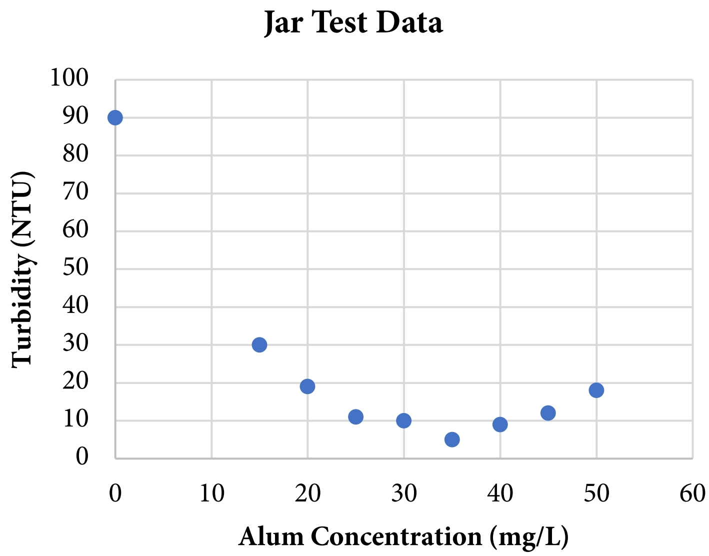
Appendix B: Project Materials and Costs from Fall 2023

	Description	Cost	Per Unit	Unit Cap
Fasteners & Seals	8d x 2-½” common nails	$3.50	Per lb	1.5
	16d x 3-½” common nails	$2.49	Per lb	2
	2-1/2” Exterior Screws	$6.00	Per lb	3
	Hot glue stick	$0.10	Per stick	2
	Silicone Caulk	$10.07	Per bottle	1
	Duct tape	$0.12	Per ft	2
Structural	2”x4”	$4.50	Per 8 ft	10
	5/8” OSB (plywood)	$1.00	Per sq ft	20
Piping	¼” ID plastic tubing	$0.50	Per ft	5
	3/8” ID plastic tubing	$0.60	Per ft	8
	1/2” ID plastic tubing	$0.62	Per ft	12
	5/8” ID plastic tubing	$0.57	Per ft	8
	1” ID plastic tubing	$1.10	Per ft	8
	½” SCH 40 PVC	$4.26	Per 10 ft	3
	½” SCH 40 PVC fittings	$0.72	Per 1	12
	½” Bulkhead fitting	$4.00	Per 1	3
	¾” SCH 40 PVC	$6.03	Per 10 ft	3
	¾” SCH 40 PVC fittings	$1.02	Per 1	12
	¾” Bulkhead fitting	$4.00	Per 1	3
Unit Processes	Small (1.2 gal) prefab. plastic bins	$1.00	Per 1	2
	Medium (7.5 gal) prefabricated plastic bins	$8.00	Per 1	2
	Large (18 gal) prefabricated plastic bins	$12.00	Per 1	1
	5-gallon bucket	$5.50	Per 1	2
	¼” Plexiglass	$0.19	Per sq in	800
	3” SCH 40 PVC	$36.40	Per 10 ft	0.4
	3” SCH 40 PVC end cap	$8.95	Per 1	2
	4” SCH 40 PVC	$46.20	Per 10 ft	0.4
	4” SCH 40 PVC end cap	$16.95	Per 1	2
Reagents & Materials	Pea gravel (Quikrete)	$0.13	Per lb	8
	Play sand (Quikrete)	$0.15	Per lb	5
	Filter sand (AquaQuartz)	$0.50	Per lb	5
	Filter powder (Diatomite)	$3.50	Per lb	1
	Activated carbon	$8.00	Per lb	0.75
	Free Chlorine, (NaOCl) 5%	$0.25	Per mL	10
	Alum (aluminum sulfate, hydrated)	$0.02	Per gram	10
	Cotton balls	$0.02	Per each	5
	Cheesecloth	$0.01	Per sq in	150

Appendix C: Pre-Activity and Post-Activity Quiz Questions

(Pre-Activity) Research Quiz 1

1. As a water treatment plant operator, you perform jar tests weekly to inform the plant staff about adjusting coagulant dosage within the clarifier. You plot the data from your latest test with concentrations of 15-50 mg/L, in increments of 5 mg/L. Determine the coagulant dosage you would recommend and defend your choice with at least 1 sentence.



(Evaluation)

2. After multiple hours of increasing turbidity, the water treatment plant's effluent increases above 1.0 NTU. What might be the likely cause(s) of this issue, and what can be done to remedy it? Make reasonable assumptions about the upstream unit processes.

   List any number of "causes" but narrow your "remedy" answer to a single, likely cause.

(Analysis)

3. Given the influent water quality below, make recommendations on **all** unit processes that **should** be present in a water treatment facility. Include any chemical additions (types, not quantities) for those unit processes to be effective.

(Synthesis)

Source Water	Surface water / River
Demand	8.1 MGD
Settleable solids	100 mg/L
Turbidity	42 NTU
NOM	15 mg/L
Conductivity	75 µS/cm
Alkalinity	50 mg/L $CaCO_3$
Hardness	25 mg/L $CaCO_3$
Viruses, Pathogens, Bacteria	Present
pH	7.3
Temperature	10°C

(Post-Activity) Research Quiz 2

1. (a) Identify all relevant considerations for a water treatment plant operator to make an informed decision about chemical coagulant addition with regard to (1) which coagulant to choose and (2) how much to add. Make reasonable assumptions about the upstream & downstream unit processes.

(Analysis)

(b) Rank the considerations above in order of importance.

(Evaluation)

2. (a) Make recommendations on all unit processes and chemical addition(s) that should be present in a water treatment facility to treat the water characterized in the table below.

(b) Furthermore, draw a line connecting the feature(s) and/or constituent(s) in the table that affect your choice of unit process from (a). Support your decision with one statement per unit process.

(Synthesis)

Influent Characteristics	
Source Water	Surface water / River
Demand	0.75 MGD
Settleable solids	100 mg/L
Turbidity	80 NTU
NOM	22 mg/L
Conductivity	75 µS/cm
Alkalinity	40 mg/L $CaCO_3$
Hardness	12 mg/L $CaCO_3$
Viruses, Pathogens, Bacteria	Present
pH	7.0
Temperature	14°C