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Competitive Problem Based Learning in an Environmental Engineering Laboratory Course

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Abstract

The Problem-based learning (PBL) pedagogical approach to instruction has become widely used in engineering courses. This paper describes implementation of the PBL approach for both the lecture and laboratory components of an introductory environmental engineering course. The course serves as an elective option for students pursuing a Bachelor of Science in Engineering degree (BSE). Learning experimental measurement procedures for constituents in water and wastewater has traditionally been the focus of laboratory investigations in this course. The PBL approach was used for the laboratory component to provide an applied context to traditional experiments implemented in this course. Two problems were defined and used to motivate the design of weekly laboratory sessions. The first problem was to design a treatment system to produce drinking water from river water. Laboratory sessions were used to conduct a variety of relevant water quality tests and examine different treatment methods. Relevant drinking water regulations were presented to provide a treatment goal. A water treatment competition was designed to provide a creative outlet for presenting the final treatment schemes. The competition required each team to integrate experience from previous laboratory sessions. Each team was scored based on the quality of the treated water, efficiency of treatment, experimental techniques, and the final design report. The second problem concerned evaluating the performance of an activated sludge wastewater treatment plant. Students visited a local plant and obtained samples for testing. Both problems required extensive use of traditional experimental procedures and reinforced many of the course lecture topics. Students were required to maintain a laboratory notebook and submit two reports detailing the two problem solutions. The PBL approach was implemented in lecture using a series of class problem set packets. Interactive problem solving sessions were conducted to solve the problems with short periods of traditional lecture interjected as needed. Lecture material was introduced as needed to solve the problem sets. Student feedback regarding the lecture and laboratory components of the course was very positive. Student performance on 15 learning outcomes was assessed using both direct (composite scores derived from graded exam and homework problems) and indirect (student survey) methods. All student survey scores for the learning outcomes were above 80% and composite scores were within 10% of the student survey values.

Introduction

Problem-based-Learning (PBL), a pedagogical instructional approach founded in the medical sciences, has found widespread use in engineering[6,11,2] and general science curriculums[12]. The PBL approach requires the instructor to define a problem and use it to motivate learning. This approach is often referred to as a student-centered approach since the students strategy for solving the problem is allowed to dictate how a course or activity proceeds. With this approach, the instructor must be prepared to accommodate a wide variety of paths to a viable solution. The PBL approach is well suited for engineering courses with significant applied design content and is a staple in the full spectrum of engineering design ranging from introductory engineering courses[10] to capstone design courses[4].

Application of the PBL approach to laboratory courses has also been reported in the literature, including a freshmen level chemistry laboratory[7] and electronics laboratory[5]. They note that traditional laboratory activities consist of teacher-structured experiments where step-by-step procedures are followed that requires no significant student engagement. This type of laboratory has been referred to as a "recipe-lab"[3].

The objective of this paper is to describe implementation of a PBL instructional approach for both the lecture and laboratory component of an introductory environmental engineering course taken by upper level engineering students. Learning experimental measurement procedures for constituents in water and wastewater has traditionally been the focus of laboratory investigations in this course. A standard laboratory activity consists of following a specific procedure (i.e., a "recipe-lab") from the reference "*Standard Methods for the Examination of Water and Wastewater*". While there is certainly value in this type of instructional model, the drawbacks to this approach include a lack of connectivity with lecture material and a lack of student engagement in experimental design.

The approach described herein is a hybrid approach consisting of traditional experiments implemented within an overall PBL framework. A unique aspect of this approach is the use of an end-of-semester competition where student teams are required to assimilate knowledge from earlier experiments while solving a design problem. Competitions of this type are common elements of regional student conferences sponsored by professional organizations (e.g., ASCE). Interactive problem solving sessions centered on class problem sets are used to implement PBL in the lecture component of the course.

Course Overview

The environmental engineering course (ENGR428) serves an elective option for students pursuing a Bachelor of Science in Engineering (BSE) at the University of Southern Indiana, an ABET accredited program. It is typically taken by students with a declared emphasis in civil engineering, although it can be taken by any engineering student who has met the prerequisites. Course prerequisites include one semester of general chemistry and fluid mechanics. An approximate topical breakdown is provided in Table 1. Fundamental principles comprise 40% of the course, including a significant environmental chemistry component. The remainder of the semester is devoted to applications in the various subfields of environmental engineering, with an emphasis on water and wastewater treatment. The course is 4 credit hours with 3 lectures (50 mins) and a single laboratory session (2 hrs and 50 mins) each week. The PBL approach was implemented during the Fall 2012 semester with a total enrollment of 7 students and during the Fall 2013 semester with a total enrollment of 4 students.

Table 1. Content of ENGR428 Environmental Engineering

Topic	Percentage of Course
Environmental Chemistry Units of Concentration Stoichiometry, Theoretical Oxygen Demand Kinetics Equilibrium	20
Ecological and Biological Principles Biochemical Oxygen Demand Nutrient Cycles Microbial Growth	5
Mass and Energy Balances	15
Water Treatment	15
Wastewater Treatment	15
Water Quality Management Types of Pollutants and Their Sources Dissolved Oxygen Sag Model	10
Introduction to Hydrology	10
Solid and Hazardous Waste Management	5
Air Pollution	5

Course Implementation of PBL for Lecture Component

Lecture time was devoted primarily to interactive problem solving sessions with brief periods of traditional lecture interjected as needed. Rather than using a single complex design problem as with capstone projects, a collection of simpler problems were used. Each lecture topic was organized around a "class problem set" packet consisting of problem statements and blank space for students to record the solutions and relevant background information (equation development, definitions, etc.). Problems were selected or designed to include not only relevant technical data, but also a real world context. All problems were solved in class with the students completing all calculations and providing input on the general solution strategy.

To illustrate the technique, consider the following problem from one of the class problem sets on "Equilibrium", which included a total of seven problems. It is a textbook problem adapted from Mihelcic (1999) and concerns the removal of atrazine from drinking water.

> Example Class Problem: Atrazine, a widely used herbicide, contained in agricultural runoff has contaminated a reservoir that is used as a source of drinking water. The atrazine concentration in the reservoir was measured to be 0.012 mg/L (12 ppb). In order to treat the reservoir water so that atrazine is removed below the drinking water standard of 0.003 mg/L (3 ppb), powdered activated carbon is added to a contact basin (a mixing tank) to adsorb the atrazine. The PAC is then removed in a settling tank located down gradient. Assume that the city treats 10^6 gallons of drinking water per day, and that the Freundlich isotherm parameters for atrazine and this particular type of PAC are K=287 mg/g $(L/mg)^{1/n}$ and 1/n=0.335. What concentration is found on the PAC (in mg atrazine/g PAC) given that the aqueous concentration is lowered to the drinking water standard? What mass of PAC must be placed in the contact basin daily to ensure that atrazine is removed to concentrations that satisfy the drinking water standard?

At this point in the course, the students have had no exposure to the phenomenon of adsorption or isotherm models, a type of equilibrium model. Before beginning the problem solution, background information on the use of atrazine and drinking water standards was provided. This included displaying a map showing the measured atrazine concentrations in Indiana and a brief discussion of drinking water regulations. A sample of activated carbon was passed around the class while discussing its unique properties. Students were then asked how to compute the total mass of Atrazine that must be removed daily to meet the drinking water standard. This requires a simple mass balance and is a prerequisite skill for the course. A formal definition of adsorption was written on the board and commonly used isotherm equilibrium models were presented. Students then completed the remaining calculations.

Additional problems from the same set addressed acid mine drainage treatment, ammonia removal from wastewater, oxygen solubility in water, and a hazardous waste spill. The final result from the student perspective was a packet of solved problems with all relevant traditional lecture material included. Over the course of the semester, 10 class problem set packets were distributed to students and completed. Each class problem set was accompanied by a homework assignment.

Course Implementation of PBL for Laboratory Component

All laboratory activities were devoted to the solution of two problems. Both problems were presented to the class and used to motivate laboratory activities throughout the semester. A team format was followed for all activities. Each team (2 total) was required to maintain a standard laboratory notebook with meticulous records of all activities (raw data, measurement procedures, interpretation, etc.). The two problem statements as presented to the students are provided below.

> Problem Statement #1: Our basic goal is to design a treatment system to treat Ohio River water, producing a final product that is in compliance with federal drinking water regulations. To achieve this, we will need to characterize the source water (i.e., water quality parameters) and explore different treatment system designs. Each team will design their own treatment system consisting of conventional treatment (coagulation, flocculation, and sedimentation), filtration, and disinfection. We will visit the Evansville water treatment plant to see a large plant in operation and get some ideas for your own treatment systems. Finally, we will conduct a team competition to see which teams' treatment system produces the highest quality water.

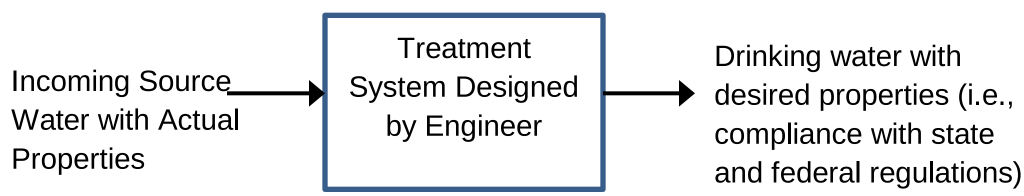

Figure 1. Schematic for problem concerning drinking water treatment

> Problem Statement #2: Our basic goal is to visit and evaluate the performance of a wastewater treatment plant (WWTP). We will tour the WWTP located near the Ohio River on the east side of Evansville, IN. The WWTP is a conventional activated sludge system. Influent and effluent samples will be collected for testing. The samples will be tested for biochemical oxygen demand (BOD) and solids content (total, suspended, and dissolved). We will also collect samples from the aeration basin and compute the sludge volume index (SVI) and sludge density index (SDI). These measures are indicators of settleability and are good performance indicators. The performance of the plant will be

evaluated by comparison of measured values with discharge limits set by the NPDES (National Pollutant Discharge Elimination System) permit and recommended ranges found in design guidance documents.

Both teams were required to submit two comprehensive reports detailing their solutions to each problem. General guidance on report content was provided; both were required to include an overview of the treatment plants visited and a summary of testing procedures and results.

Laboratory Activities

The solution to both problems required extensive use of traditional experimental procedures (techniques, equipment, etc.). The semester began with presentation of problem #1 (drinking water production) using the three basic components illustrated in Figure 1. An interactive brainstorming session was conducted to allow the students input on each aspect of the problem. A number of relevant discussion topics emerged, including specific contaminants of concern (herbicides, hydrocarbons, etc.), disinfection of pathogens, and treatment system design. Typical flow diagrams for surface and groundwater treatment were drawn on the board to aid the discussion. The first meeting concluded with a demonstration of conventional water treatment (coagulation, flocculation, and sedimentation) using standard jar testing equipment.

Beginning with the second meeting, laboratory time was devoted to completion of the experiments described in Table 2. The connection of the various activities to the main problem was emphasized throughout the semester. Most experiments served a secondary role of reinforcing specific lecture materials (unit conversions, stoichiometry, kinetics, etc.). Relevant drinking water regulations were presented throughout the semester to establish a treatment goal. A field trip to a water treatment plant was scheduled early in the semester. Students were required to obtain river samples each week for testing and log water quality parameters such as turbidity, pH, conductivity, and dissolved oxygen concentration in their laboratory notebooks. Additional relevant data was obtained online from the Ohio River Valley Water Sanitation Commission (ORSANCO) website. Approximately 80% of the laboratory time was devoted to the solution of problem #1.

The second problem was introduced to the students after the course mid-term exam. Considerably less time was required to solve problem #2 due to some overlap in procedures and previous student exposure to wastewater treatment in lecture. A tour of a local wastewater treatment plant was completed first. Samples were obtained and returned to laboratory for testing. A second trip to the plant was necessary later in the semester. A description of the laboratory experiments completed to solve problem #2 is given in Table 3.

Overall, the activities detailed in Table 2 and 3 required full use of the scheduled laboratory sessions.

Table 2. Summary of experiments/activities completed to solve problem #1 (drinking water production)

Experiment	Description
Turbidity	Turbidity is a measure of the “cloudiness” of a water sample and is caused by the presence of suspended material. Calibration and use of a turbidimeter was demonstrated.
Hardness	Water hardness is defined as the total concentration of multivalent cations in a sample (expressed in mg/L as $CaCO_3$). Students determined water hardness by titration with a chelating agent (EDTA).
Water Treatment Plant Tour	Students toured a local water treatment plant. The plant uses a conventional treatment train consisting of course screening, coagulation, flocculation, sedimentation, granular filtration, and disinfection.
Alkalinity/Acidity and pH	The ability of water to resist changes in pH as an acid or base is added is referred to as buffering capacity. Alkalinity and Acidity are measures of this buffering capacity. Calibration and use of a pH meter were demonstrated. Students used titration to determine the alkalinity and acidity. Water deficient in alkalinity may experience pH fluctuations during treatment.
Disinfection and “Ct” Tables	Water for drinking and cooking purposes must be made free from disease-producing microorganisms (pathogens). Students evaluated the use of sodium hypochlorite as a disinfectant. Total, free, and combined chlorine were determined for a range of applied chlorine dosages. The breakpoint chlorine dosage was determined.
Total Coliform	The microbial quality of water is based on testing for indicator microorganisms (those whose presence is evidence that the water has been polluted with feces and indicates the possible presence of pathogens). Students used the membrane filter technique to detect the presence of a group of indicator microorganisms known as coliform bacteria. Positive results indicate inadequate disinfection.
Jar Test	Students conducted a standard jar test to conduct conventional water treatment operations (coagulation, flocculation, and sedimentation). Aluminum sulfate was used as a coagulant.
Solids and Conductivity	Solid matter in water is either dissolved or suspended. Students determined total solids, suspended solids, and dissolved for river water samples. For drinking water, dissolved solids should be less than 500 mg/L to avoid taste problems. The use of a conductivity meter was demonstrated.
Iron and Manganese	Iron and manganese in high concentrations can cause offensive taste, appearance, and staining. Students determined the concentration of both compounds and evaluated the use of potassium permanganate as a pre-oxidant.
Taste and Odor/THM formation	Students were exposed to taste and odor and trihalomethane issues during the treatment plant tour. Students completed jar testing to determine potassium permanganate demand.

Table 3. Summary of experiments/activities completed to solve problem #2 (wastewater treatment plant performance)

Experiment	Description and Relevance
Wastewater Treatment Plant Tour	Students toured a local Wastewater Treatment Plant (conventional activated sludge). Students obtained samples for testing. Sample locations included influent to plant, influent to secondary treatment, aeration basin, and plant effluent.
Biochemical Oxygen Demand (BOD)	The BOD test is performed to characterize the strength of a wastewater. Discharge permits (NPDES permits) for wastewater treatment plants typically require the BOD to be at or below 30 mg/L. Students determined the 5-day BOD and estimated the ultimate BOD.
Solids Analysis	In addition to total, suspended, and dissolved solids, the volatile and fixed fractions were also determined.
Settling	The settleability of primary and secondary sludge was evaluated by settling in an Imhoff cone. The sludge volume index (SVI) and sludge density index (SDI) were determined.
Dissolved Oxygen and Transfer in Aerated Systems	The transfer of oxygen to water is of fundamental importance in the biological treatment of wastewater. Students used a membrane probe and the Winkler-Azide method to determine dissolved oxygen concentration. The kinetics of oxygen transfer was studied using a laboratory scale aeration basin. Kinetics data was collected and a mass transfer rate coefficient determined.

End-of-Semester Laboratory Competition

A water treatment competition was held during the last laboratory session of the semester. The purpose was to provide a creative and fun outlet for each team to present their solutions to problem #1. Students were provided with competition details and all required materials 2 weeks before the actual event. The competition was designed by the instructor to require both teams to use results and procedures from earlier experiments (Table 2). Each team was required to make several design decisions and work effectively as a team to minimize the total treatment time.

Each team was provided with the following supplies:

- Two coagulants (A and B): polyaluminum chloride and aluminum sulfate
- Potassium Permanganate, $KMnCl_4$
- Chlorox Bleach (5.25% Sodium Hypochlorite)
- Powdered Activated Carbon (PAC) solution (concentration not specified)
- Sodium Hydroxide (0.02 N)
- Sulfuric Acid (0.02 N)

- Sodium Bicarbonate ($NaHCO_3$) powder
- Filter media: anthracite coal, sand, and gravel
- Filter materials: 3 ft section of cylindrical pipe and perforated cap

Students constructed granular filters and developed flexible chemical dosing schemes prior to the competition. Design variables also included jar test operational parameters (mixing time and speed). A flexible treatment scheme was necessary since the quality of the water to be treated (turbidity, pH, etc.) was not known ahead of time. On the day of the competition, each team was provided with 35 L of raw water and required to produce 6 L of treated water. Each team was scored based on the quality of the treated water, efficiency of treatment (teamwork), experimental techniques, response to questions by the instructor, and the final design report. The two designs varied significantly; Table 4 summarizes two of the designs from the Fall 2012 course offering.

Table 4. Comparison of two team designs for the drinking water competition

Parameter	Team A	Team B
Initial Turbidity (NTU)	55	72
Initial pH	7.8	7.8
Coagulant	B	B
Coagulant Dosage (ppm)	190	70
Potassium Permanganate Dosage (ppm)	0.3	0.3
Turbidity Before Filter (NTU)	1.20	2.40
Powdered Activated Carbon Dosage (mL/L)	0.5	0.1
Filter Flow Rate (Lpm)	1.0	0.4
Filter Overflow Rate (m/day)	734	315
Applied Chorine Dosage (ppm)	1.25	4
Final Turbidity (NTU)	0.93	0.7
Final pH	7.15	7.08
Free Chlorine Residual (ppm)	0.60	1.54
Total Treatment Time (hrs)	3.2	2.18

Course Evaluation

A survey was administered at the end of the course and completed by 6 of the 7 students. The survey asked the students to evaluate how well 15 course performance outcomes were achieved using a scale ranging from 0 to 100. The outcomes addressed specific competencies related to the course content and are reported in Table 5. Average scores, as a percentage, are shown in Figure 2. For comparison, a classroom composite score, derived from specific assignment and exam questions, was computed for 13 of the outcomes. Graded material was not available for 2 of the outcomes. All student scores were above 80%, indicating the students felt they achieved the course outcomes. Classroom composite scores were within 10 percentage points of the student values. Students were also asked to score their overall satisfaction with the course and laboratory. Scores averaged 95% for the course and 90% for the laboratory.

Table 5. Summary of 15 course performance outcomes

Course Performance Outcome
1. Identify and convert between different units used to measure pollutant levels in aqueous, soil/sediment, and atmospheric environmental systems
2. Compute water hardness (as $CaCO_3$)
3. Formulate equilibrium expressions for precipitation-dissolution reactions, acid-base reactions, gas solubility reactions, and sorption-ion exchange to solid surfaces
4. Examine the carbonate system and its relationship to alkalinity and buffering capacity of natural waters
5. Formulate rate laws for zero- and first-order reactions and determine the rate constant given experimental data of pollutant concentration verses time
6. Review stoichiometric analysis and apply to common environmental problems
7. Write and solve mass balance equations for systems with and without transformation. Emphasis is placed on formulation of mathematical models for pollutant concentration in reactors modeled as a batch reactor, a completely mixed flow reactor (CMFR), or a plug flow reactor (PFR)
8. Formulate the energy balance equation and use it to analyze environmental problems (examples include thermal pollution, waste incineration, and earth's energy balance)
9. Discuss physical, chemical, and biological parameters of water quality and identify common water pollutants and their sources
10. Compute the theoretical oxygen demand (ThOD) given the concentration and chemical formula of a waste and compute biochemical oxygen demand (BOD) given relevant laboratory data
11. Analyze the effect of waste characteristics and stream temperature on downstream oxygen deficits using the Streeter-Phelps equation
12. Demonstrate knowledge of regulatory requirements in the environmental field; the Safe Drinking Water Act (SDWA) and Resource Conservation and Recovery Act (RCRA) are emphasized
13. Draw a flow diagram for a typical rapid sand filtration water treatment plant with different water source quality (i.e., surface water or ground water) and a typical activated sludge wastewater treatment plant and explain the treatment processes involved
14. Perform basic component design calculations for a water treatment plant
15. Perform basic component design calculations for a wastewater treatment plant; emphasis is placed on the activated sludge process

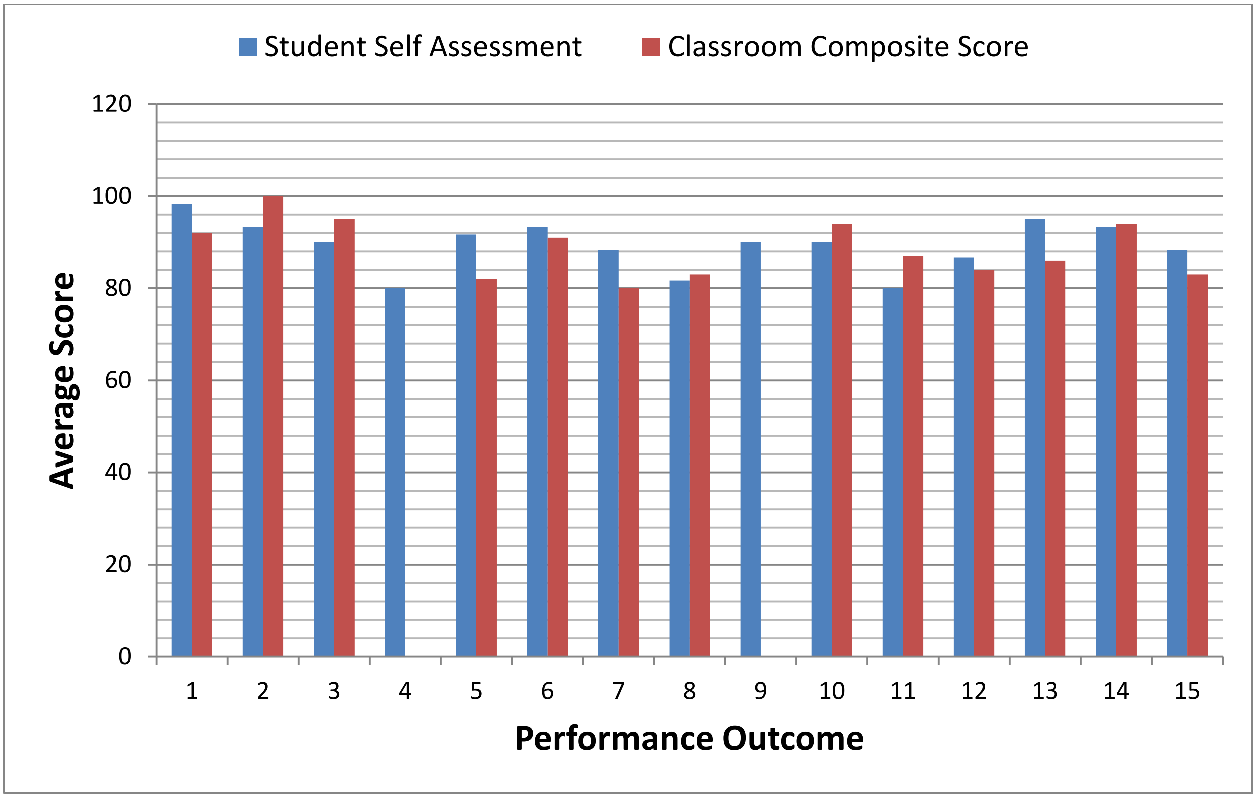

Figure 2. Assessment of 15 performance outcomes including both a self-assessment score and a composite score derived from graded assignments and exams

Students were also given the opportunity to provide written comments regarding the course. The following comments [unedited] specifically addressed the use of in-class problem sets and the laboratory format:

> *I actually really do like your teaching style with the use of class problem sets and working through these during lecture to learn the material. I feel this is a great way for me to learn. (Fall 2012)*
>
> *This is an excellent course, and I feel that I have learned more in this course than any other single course. I really like in class problems and the lab format. (Fall 2012)*
>
> *The lab activities reinforced ideas from lecture. I really like the format of lab such as not having weekly lab reports and a big report and project at the end. I feel this is a lot more manageable. I liked the field trips and gained a lot of knowledge from each one. Great class and great lab! (Fall 2012)*
>
> *Liked how all labs came together at end and were used in water competition. (Fall 2013)*
>
> *The layout of Lab was a lot more interesting than a standard lab where an experiment is performed and then a report is written. (Fall 2013)*

By directing the class toward a competition at the end, it reinforced the importance of understanding not just how to execute lab tests, but what they mean, and how to use them to produce a valuable end product. (Fall 2013)

This lab was run in a new way for me personally. I have never had a lab which was geared toward a final project. Having to know all the processes practiced in each lab to be successful at the competition helped me commit them to memory. Fun lab. (Fall 2013)

Overall student enrollment for two offering of the course using the PBL approach was low (11 students). Despite the relatively low enrollment, student comments are compelling and suggest the PBL approach was successful. Compared to previous course deliveries (non-PBL based), the students displayed more enthusiasm for the laboratory component of the course.

On the negative side, informal feedback by select students suggested that time demands near the end of the course were excessive. This was anticipated and addressed by eliminating a third exam and increasing the weight of the laboratory portion of the course. Writing the final reports proved to be a daunting task for both teams. In the future, the instructor plans to require intermediate submissions and reviews prior to the final end-of-semester submission. An advantage of using a more substantial project report, rather than weekly reports, is that the final product is more representative of engineering consultancy reports.

Conclusions

A PBL instructional approach was shown to be effective for both the lecture and laboratory components of an introductory environmental engineering course. Compared to previous course deliveries, the instructor found considerably more enthusiasm displayed toward the laboratory component of the course. This is attributed primarily to the use of real world problems that provide an applied context to traditional laboratory experiments focused on measurement procedures. The laboratory problems provided greater connectivity with the lecture component of the course and included design components, thus shifting greater decision making responsibility to the students than with traditional "recipe-labs".

An end-of-semester water treatment competition was used successfully. The competition required students to integrate experience from previous laboratory sessions. Competitions are commonplace in engineering departments, but are often connected with student groups (ASCE, SAE, etc.) and participation is voluntary. These types of activities bring a fun and creative component to laboratory courses and are becoming more common in engineering curriculums[8]. Laboratory instruction is a very important component of engineering curriculums and this study supports the use of a goal-driven competitive framework for delivery.

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