Importance of Critical Thinking in Environmental Engineering

Veera Gnaneswar Gude and Dennis D. Truax
Department of Civil and Environmental Engineering
Mississippi State University, Mississippi State, MS 39762

Abstract

This paper overviews three methods to instill critical thinking skills: writing assignments, supplemental instruction (SI), and interactive and collaborative learning. These were applied in two environmental engineering courses; a junior level course (CE 356 - Fundamentals of Environmental Engineering) and a senior level course (CE 4883 – Engineered Environmental Systems) offered in different civil engineering programs. Writing assignments provide a practical context that deepens student understanding and comprehension of the content area. Students develop written communication skills and a process for thinking through and solving civil-environmental engineering problems. Active learning in the classroom and self-directed learning outside of class create opportunities for the students to apply knowledge and identify questions which can be resolved in the SI session. Students follow a set of steps to develop proper questions and find their own solutions by applying critical thinking skills.

The student learning improvement through the SI sessions has been monitored for three consecutive semesters and the results have been compared between the SI group and non-SI group students in terms of academic performance throughout the semester. A summary of the experiences and a critical perspective on enhancing critical thinking skills are discussed.

Keywords

Critical thinking, environmental engineering, supplemental instruction, student learning, technical writing

Introduction

Environmental engineers provide creative and cost-effective solutions to use resources in an efficient and sustainable way, limit the release of contaminants into the environment, develop sensitive techniques to track pollutants once released and find effective methods to remediate impaired resources. They serve as the vital link between scientific discovery, technological development and the societal need for protecting human health and ecological integrity. In the coming decades, environmental engineers will be increasingly called upon to address broader and complex issues of environmental sustainability and resource management. As such, it is urgent to train emerging engineers with adequate critical thinking skills.

Critical thinking is not a matter of evaluating something in a negative sense but rather it is a healthy, constructive thinking process[1]. Critical thinking has to be exercised whenever a decision has to be made on a problem that has more than one solution. Critical thinking requires reliable information and evidence, so one can make decisions based on scientific principles. An individual's experience, technical expertise, basic intuition and engineering reasoning are integral parts of a critical thinking process. Critical thinking involves asking well-reasoned questions and evaluating a variety of potential solutions. A small amount of skepticism is required to improve the thinking process and to evaluate the evidence. Judgment has to be made after weighing the pros and cons in a sound manner. In the civil engineering profession, a successful engineer is expected to exercise the critical thinking process before making a decision as thousands of lives may be affected and millions of dollars spent on a design; whether it is a commercial building, a water or wastewater treatment facility, or transportation infrastructure. The safety of people, the environment and overall project cost are key factors considered for the design to achieve its goals.

In principle, critical thinking goes beyond the classroom activities and student assignments. The core critical thinking skills are identified as interpretation, analysis, inference, explanation, evaluation, and self-regulation as shown in **Fig. 1**[2]. These are integral components of a critical thinking process. Critical thinking skills allow one to approach specific problems, questions, and issues with clarity, orderliness, diligence, reasonableness, care (*responsible care*), persistence, and precision. Each of these components and the associated critical thinking skills are described in **Table 1**.

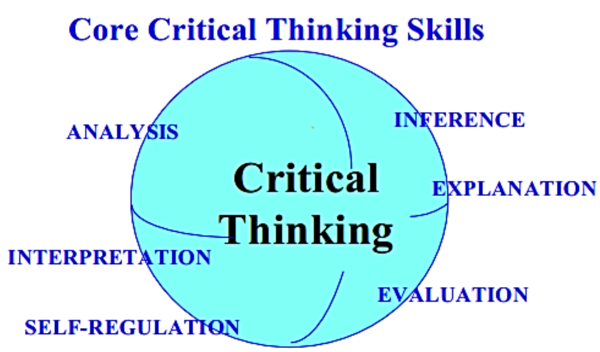

Fig. 1. Components of critical thinking[2]

Table 1. Description of the critical thinking components[2]

Component	Description (primary skills)	Sub-skills
Interpretation of an engineering design problem	Comprehend and express the meaning or significance of a wide variety of experiences, situations, data, events, judgments, conventions, beliefs, rules, procedures, or criteria	Categorization, decoding significance, and clarifying meaning
Analysis	Identify the intended and actual inferential relationships among statements, questions, concepts, descriptions, or other forms of representation intended to express belief, judgment, experiences, reasons, information, or opinions.	Examining ideas, detecting arguments, and analyzing arguments
Evaluation	Assess the credibility of statements or other representations which are accounts or descriptions of a person's perception, experience, situation, judgment, belief, or opinion; and to assess the logical strength of the actual or intended inferential relationships among statements, descriptions, questions or other forms of representation	

Inference	Identify and secure elements needed to draw reasonable conclusions; to form conjectures and hypotheses; to consider relevant information and to deduce the consequences flowing from data, statements, principles, evidence, judgments, beliefs, opinions, concepts, descriptions, questions, or other forms of representation	Querying evidence, conjecturing alternatives, and drawing conclusions
Explanation	Able to present in a cogent and coherent way the results of one's reasoning. Provide a comprehensive view at the big picture: both "to state and to justify that reasoning in terms of the evidential, conceptual, methodological, criteria-based, and contextual considerations upon which one's results were based; and to present one's reasoning in the form of cogent arguments.	Describing methods and results, justifying procedures, and presenting full and well-reasoned, arguments in the context of seeking the best understandings possible
Self-regulation	Self-consciously monitor one's cognitive activities, the elements used in those activities, and the results deduced, particularly by applying skills in analysis, and evaluation to one's own inferential judgments with a view toward questioning, confirming, validating, or correcting either one's reasoning or one's results.	Self-examination and self-correction.

Methods to Enhance Critical Thinking Skills in Environmental Engineering Students

A few methods to instill and enhance critical thinking skills of the environmental engineering students are as follow: 1) problem-based learning (solving single and open-ended solution problems); 2) collaborative learning (team and project based learning); and 3) inquiry-based learning (supplementary instruction). Writing assignments provide a unique opportunity to process the given information, data interpretation, developing discussions with evidence, judgment, justification and regulation[3]. Writing activity generates higher cognitive abilities, along with creative thinking, problem solving, and decision making. In recent development of pedagogical approaches, problem based learning (PBL) method has been reported to promote students' critical thinking ability. This method is generally agreed to have important implications for transfer of knowledge and application of problem solving skills to novel situations[4]. This assertion has been supported by several previous research reports[5-7]. Inquiry based learning improves student learning of the subject matter through inquiry, discovery, evaluation and problem solving based activities. The following sections elaborate the exercises and results obtained from implementing these methods in the two civil and environmental engineering courses.

Illustrations
Integrating Writing Assignments

"CE 356 - Fundamentals of Environmental Engineering" is a junior course taught in the Civil Engineering department at New Mexico State University. General course objectives are to learn and apply the engineering design process and develop and apply skills used by successful practicing professional engineers, including critical (reflective) thinking, communication, and documentation. This course teaches the fundamental civil-environmental engineering principles for design of conventional domestic water treatment and wastewater treatment systems. One of the primary learning objectives of the course is for the students to be able to apply fundamental civil-environmental engineering principles and perform fundamental calculations to design water treatment (physical-chemical treatment) and wastewater treatment (physical and biological treatment) systems. The course introduces the students to different levels of critical thinking through various writing assignments pertinent to general engineering design process, population projection report, design statements and preliminary engineering design report (PER).

Engineering Design Process. The foundation of the class is an understanding of the engineering design process. The engineering design process taught to the students involves the following stages1: 1) Identify the problem, 2) Define the working criteria and goals, 3) Research and gather data, 4) Brainstorm and generate creative ideas, 5) Analyze potential solutions, 6) Develop and test models, 7) Make a solution decision, 8) Communicate and specify details of the design, 9) Implement and commercialize or construct, and 10) Perform post-implementation review and assessment. This foundation is developed through an assignment which requires identifying and describing the steps involved in an actual civil engineering design project. This development is documented in a definition-type report which incorporates the civil engineering code of ethics with the design process. Teams of two students read an article from ASCE magazine describing a case study of an environmental engineering project. The case study provides the students the opportunity to identify, analyze, and understand the steps of the engineering design process. This exercise is also intended to help students understand the critical thinking skills an engineer applies in professional practice. For all engineering problems, there are fundamental questions that can be effectively addressed through application of the design process. The process begins with understanding the original problem, researching the problem, gathering information, developing a partial solution and completing the solution through successive cycles of actions.

Population Projection. Design principles and the design process of water treatment and documentation of the process are built on the foundation of the engineering design process and are taught through an open-ended, team-based project approach. The project begins with assigning the class a municipality in New Mexico for characterizing the city's population growth, water use history, and future water demand. The report consists of a cover letter to the city engineers, an executive summary, followed by a comprehensive report containing the city characterization (historical, geological, community, industrial sectors), a twenty year population projection developed from census data and different growth characterization models, water resources available, present source of water supply and conservation practices, future water demands, and capacities for a new treatment facility. The report also discusses the national and state level regulations and policies required under the Safe Drinking Water Act (SDWA)[8]. Students are required to schedule a consultation with the writing center in the English department to receive a review of their report.

An evaluation heuristic used by the graduate teaching assistant to grade the reports is provided to the students[3]. Evaluation criteria include the following components: 1) Consideration of audience - specifying the client and clearly addressing all the client’s needs, 2) Quality of solution - clear description of the problem and evaluation of the proposed solution with a persuasive argument, 3) Rigor of engineering analysis - relevant data, background and research pertinent to the problem, methods, calculations, analysis, and conclusions based on evidence, 4) Organization and focus - effectively organized, engaging and easily followed, 5) Clarity and coherence - flow in thought, transitions, graphical presentations, grammar/mechanics, and 6) Professional appearance - a consistent professional format. The first three components address the technical/engineering content and the remaining components address effective communication and professional appearance.

Preliminary Engineering (Design) Report. The final assignment is to design the four unit components of the treatment plant, prepare preliminary engineering drawings of each unit operation, as well as a layout of the entire water treatment facility which shows the integration of the individual unit operations into a single treatment plant. The design work is bound as a preliminary engineering report (PER) which includes the following three components: 1) a letter of transmittal to the city engineering staff, 2) an executive summary of the design, and 3) an engineering report summarizing the population and water use histories of the city, the alignment of their design with national and state level requirements of the SDWA, and a summary and persuasive justification for the decisions made in their technical design. The report includes an appendix which documents the design calculations and preliminary engineering drawings of individual unit operations. A summary of the design outcomes for individual unit operations is presented at the beginning of design calculations for each treatment stage. This is one way the students display the confidence of their design work. The PER is evaluated using the same criteria that has been discussed for the population projection assignment.

The course requires students to perform at a variety of cognitive levels as classified by Bloom's taxonomy[9]. In engineering practice, especially in the engineering design process, higher–order thinking is required. Too often junior engineering students are accustomed to learning material at levels 1 through 3 on Bloom's taxonomy scale (knowledge, comprehension, and application). The assignments in this course are created to facilitate student development as a future professional engineer by working at the six cognitive levels of Bloom's taxonomy and also some ABET criteria[10]. These assignments lead to progressive, step-by step growth in the students learning from level 1 to level 6. By the end of the course the students are learning and working at the highest level on Bloom's scale. Table 2 summarizes the Bloom classification for the various assignments.

Table 2. Assignment Classification Based on Bloom's Taxonomy.

Assignment	**Bloom's Taxonomy Level**†					
Description	1	2	3	4	5	6
1) Engineering design process	✓	✓	✓			
2) Population Projection/Water Demands	✓	✓	✓	✓		
3) Single solution problems	✓	✓	✓	✓		
4) Design statements/summary	✓	✓	✓	✓		
5) PER of Water Treatment Facility	✓	✓	✓	✓	✓	✓

†1. Knowledge (list, recite, reproduce), 2. Comprehension (explain, paraphrase), 3. Application (calculate, solve, determine, apply), 4. Analysis (classify, predict, model, derive, interpret), 5. Synthesis (propose, create, invent, design, improve), 6.Evaluation (judge, select, critique, justify, optimize)[9]

Supplemental Instruction

The primary focus of supplemental instruction is to enable the students to apply skills used by successful practicing professional engineers and exercise critical (reflective) thinking in solving the engineering design problems[1]. SI exercise guides the student's development of critical thinking skills through:

- Identifying confusion or lack of understanding of course content and environmental engineering concepts,
- Asking clear and well thought-out questions, and
- Establishing a process for developing and evaluating answers to their own questions.

Engineers must have command of the skill of developing and articulating well defined problems and questions. Problem definition is a key factor in developing the most appropriate solution for a given set of conditions[1]. By working through identifying confusion and misunderstanding, formulating the right question, applying previous knowledge and experience (intuition) to the question, and identifying appropriate sources of information, the students apply a critical thinking process that will lead them to developing answers to their own questions.

The SI session is designed to develop this skill by applying collaborative learning methods. The SI session meets once per week to resolve student's questions in the topics of water and wastewater treatment. The students work in groups and strive to develop solutions to their questions using problem solving methods typically applied by practicing engineers. The facilitator for the SI session is a graduate teaching assistant (TA) majoring in environmental engineering. The TA typically serves as an SI facilitator for 3-4 consecutive semesters. The first semester, the TA is required to attend all class sessions to learn the content of the course and to identify areas of concern where students may have difficulty by observing student-to-student and student-to-instructor interactions that occur during class.

Prior to meeting in the SI session, students submit questions on the engineering and design concepts discussed within the previous week of class. Active learning in the classroom and self-directed learning outside of class create opportunities for the students to identify questions which can be resolved in the SI session. The first step of the SI assignment is to construct a question that is comprised of the following four parts:

- Clearly describe the confusion or lack of clarity on the topic of discussion during the past week.
- Why is this aspect of the topic confusing or unclear? Explain the specific details that are not clear.
- Describe the "engineering intuition" that you can apply to this concept that will assist you in developing logic or rationale that will guide you to a description or answer clarifying the confusion. What knowledge and background from other classes or practical experiences can you draw on to help yourself resolve this confusion?
- Use your textbook (or other appropriate sources) to find information that can be used to clarify your confusion. Cite a specific reference you have identified in the book (cite all of the following that apply: chapter and section numbers, paragraph, figure or table number, and page number), summarize or paraphrase your finding, and apply the information to clarify your confusion.

SI Session – Mix of Collaborative Learning Techniques. The actual method that students apply to learn critical thinking is a mix of approaches that follow a progressive pattern. Progression from individual learning, to small group learning and classroom level learning provides a good opportunity for discovering various aspects of a topic. Each group is assigned one question for a 15-20 minute discussion period. As the groups review their questions the facilitator observes the discussion to ensure that the students are engaged in developing an appropriate response to their questions. When deemed appropriate, the facilitator may interject comments or questions that will guide the discussion toward a constructive outcome. Each group elects a leader, a note-taker and a reporter. Most of the time, the volunteers rotate freely without dominant repetition. The facilitator sometimes appoints the leader and reporter in order to give an opportunity to all the students to participate effectively in discussion. The reporter takes notes of the relevant outcomes while the leader leads the discussion by asking fellow members questions and also contributing to the discussion.

As the course requires the students to exercise critical thinking skills which is a higher order thinking and learning, it becomes necessary to evaluate the student performance on the basis of Bloom's levels of learning. As shown in **Fig.2**, in most of the cases, the SI participants perform better or at the same level compared to the non-SI participants. Quizzes (**1**), the water treatment exam (**2**), wastewater treatment exam (**3**) and preliminary engineering design report (**4**) require the students perform and be evaluated at higher levels of Bloom's learning (Level 5: synthesis - propose, create, invent, design, improve: Level 6: evaluation - judge, select, critique, justify, optimize)[9].

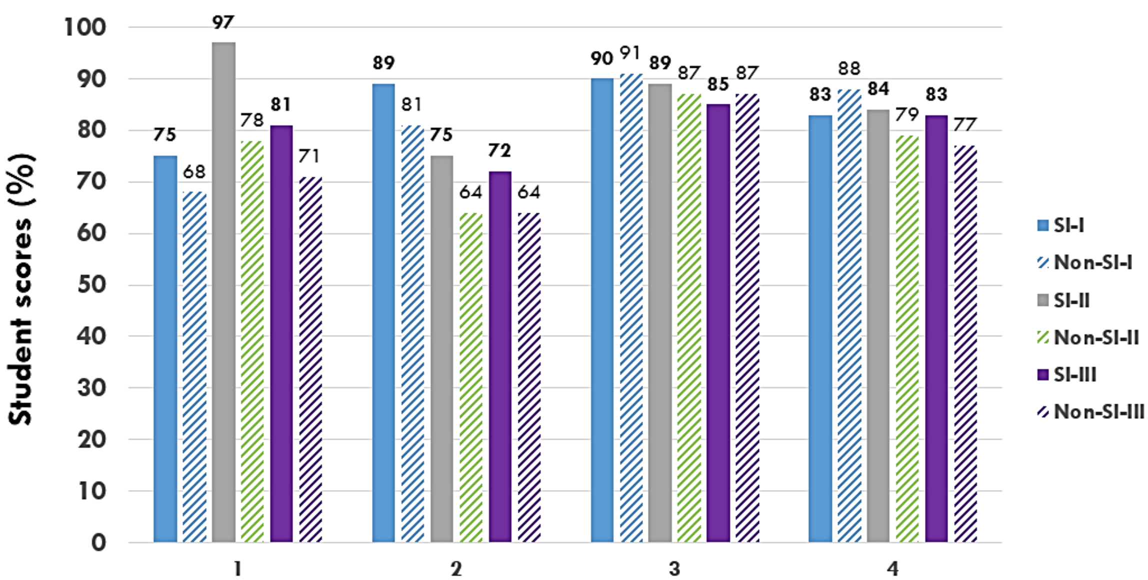

Fig. 2. Student scores for the four major exercises (Note: **1**- Quizzes, **2**- water treatment exam, **3**- wastewater treatment exam and **4**- preliminary engineering design report; SI – students who attended SI, Non SI – students who did not attend the SI sessions, I, II, III semesters)

Students improved grades by participating in the SI sessions (**Fig. 3**). It should be noted that the grade improvement from B to A is observed to be common and the percentage of grade improvement is acceptable which does not skew the overall grade of the class. Students who achieve a grade of A without attending the SI sessions, but who voluntarily attended and earned the bonus points, are not reported in the analysis because an actual grade improvement was not measured. The data primarily indicates that students who utilized the opportunity and are hardworking by nature have progressed to a higher grade. Also, the underlying factor with those students who attended the SI session is that they are inherently hard working. Though this study evaluated the performance of the SI and non-SI groups based on monitoring work examples and grades, a pre and post SI assessment will be considered to evaluate the effectiveness of the SI sessions in improving a student's critical thinking skills.

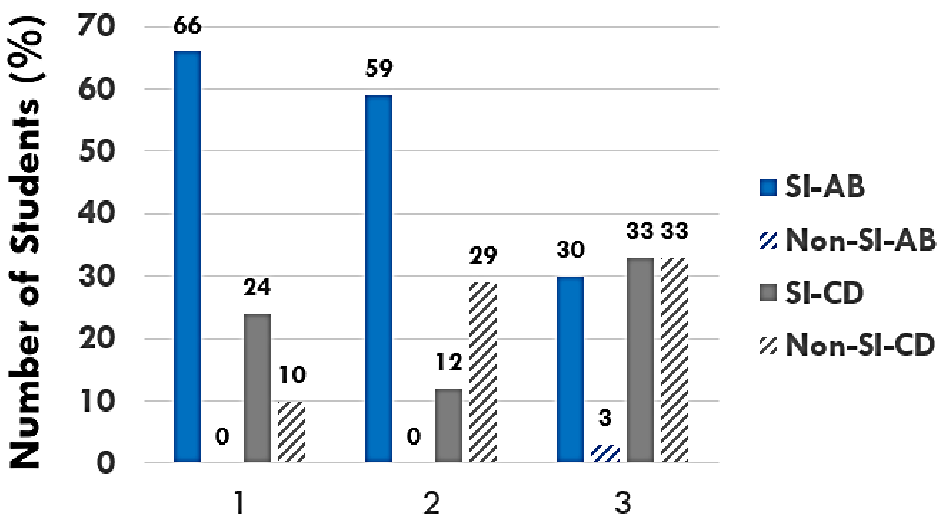

Fig. 3. Student grade comparison between SI and non-SI groups (Note: 1, 2, and 3 refer to semesters; AB = students who earned an A or a B grade; CD = students who earned a C or a D grade)

Collaborative Learning

Project based learning (PBL) is often theorized to promote students' critical thinking, especially reasoning skills[11, 12]. PBL is suuported by *Students Centered Learning* approach that follows constructivist learning theory principles[13]. In this context, knowledge acquisition becomes one of the prerequisites in developing students' critical thinking ability[13]. According to Winterton et al.[14], knowledge and working memory play major roles in the acquisition of complex cognitive skills. This is particularly true since knowledge is operational and working within a social and attitudinal environment. The development of students' critical thinking ability however depends on willingness and an awareness of own thinking (self-reflection), as well as foundation skills as explained earlier[15]. The following illustration describes a project-based critical thinking activity and the student experiences and opinions from the evaluation survey.

The students' responses are shown in Fig.4. Among the 30 respondents, about 73% (22 out of 30 respondents) of the students have answered that SWPPP exercise has improved their understanding environmental engineering and management principles. About 37% (11 out of 30 respondents) answered that this exercise improved their critical thinking skills while 40% (13 out of 30 respondents) of the students mentioned that their critical thinking skills were the same after the exercise. However, majority of the students agreed that SWPPP exercise has improved their critical thinking and decision-making skills, and team work and communication skills (2a, b, and c). Again, 63% (19 out of 30 respondents) of the students responded that this exercise has improved their understanding of engineering design and practice which were the main goals of this assignment (2f). A few students responded with the items that were not effective under SWPPP exercise. About ten percent responded that the exercise was not helpful in improving their ability to use given information and to research for available resources (2a). This is a major drawback with the current learning methods. The students are accustomed to work on single solution problems based on given set of conditions and narrative descriptions. They are disinclined to acquire additional information required to provide a comprehensive solution to a complex problem which are common in environmental engineering design and practice. It is interesting to note that 53% (16 out of 30 respondents) of the respondents mentioned that their ability to use given information and to research for available resources was improved through this exercise (2a).

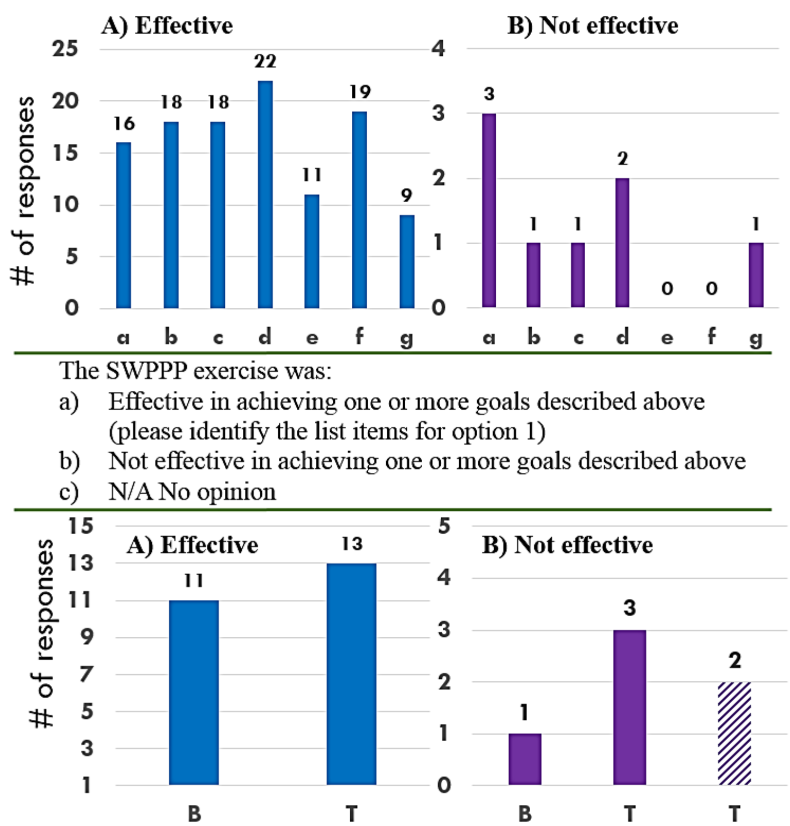

Fig. 4. Student responses to SWPPP exercise evaluation survey (line fill = No opinion; B = better; T = the same)

SWPPP Exercise

Your consulting firm has been asked to generate a construction storm water pollution prevention plan (SWPPP) for the proposed civil and environmental engineering complex at the Mississippi State University. Assume that the area of the construction site is less than 5 acres. About 93000 ft^2 of the land area is to be developed into a teaching and learning facility with classrooms, laboratories, student/faculty/staff offices, auditoriums and conference rooms. An outline (topography) of the site map and the location details are provided in the handout. Please do the following:

1. Conduct a site visit to identify the pre-construction conditions and research any available documentation on the site at the library and other online sources.
2. Prepare a complete SWPPP for the proposed site development activity which should include “during construction” and “post construction” BMPs for the site.
3. Detailed justification of the chosen “control measures” or “BMPs” for the given site on their purposes.
4. Provide an appendix with important assumptions, calculations, site maps and other pertinent information on the site.

CE 4883-6883 SWPPP Exercise Evaluations

Question 1: As a result of the “Stormwater Pollution Prevention Plan (SWPPP)” assignment, my critical thinking skills are:

1. Worse (W)
2. The same (T)
3. Better (B)
4. Significantly better (S)
5. N/A no opinion (N)

Question 2: The goals of this course and the SWPPP exercise include improving students’:

a) ability to use given information and to research for available resources;
b) critical thinking and decision-making skills;
c) team work and communication skills;
d) understanding of environmental engineering and management principles;
e) knowledge about engineering professionalism/ethics;
f) understanding of engineering design and practice;
g) ability to use the computer tools such as Excel and stormwater design tools

The SWPPP exercise was:

1. Effective in achieving one or more goals described above (identify and list items)
2. Not effective in achieving one or more goals described above (identify and list items)
3. N/A No opinion

SWPPP exercise and the evaluation survey

Conclusions

Various approaches can be considered to instill and enhance critical thinking skills of students taking in environmental engineering courses. This paper has presented an overview of a research based teaching process which was found to be successful and improving critical thinking and engaging students more fully in the learning process. This approach is but one of the important strategies to consider when designing course assignments that encourage the students to think. It challenges students to look outside the routine sources for information while forcing them to be thinking about the problem as they harvest data. This "broad horizon and focused goal" approach appears to make students more reflective of the experiment and its design, the data and its value, and the uniqueness of the solution. Because of personal perspectives and educational background, the students are also exposed to the importance of non-biased self-regulation when it comes to developing hypotheses, drawing conclusions, and devising solutions.

Acknowledgements

This work was supported by the Department of Civil and Environmental Engineering, the Bagley College of Engineering, and the Office of Research and Economic Development (ORED) of Mississippi State University (MSU).

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Biographical Data

Dr. Gude is an assistant professor at Mississippi State University (MSU). He has over 14 years of academic, industrial, and research experiences on various projects related to chemical and environmental engineering disciplines. He has published over 75 scholarly articles, peer-reviewed conference proceedings and invited book chapters. He is a licensed professional engineer (PE) in the state of New Mexico and a board certified environmental engineer (BCEE). His research interests include water and wastewater treatment, bioelectrochemical systems, desalination, algae, biofuels, and sustainability. He enjoys teaching environmental engineering courses and mentoring undergraduate and graduate students in research activities at MSU.

Dr. Truax is James T. White Chair, Head and Professor of Civil and Environmental Engineering at MSU. On the faculty for 34 years, he has published over 110 refereed and reference papers, reports and book or book chapters and has made over 170 paper or poster presentations. His funded research has focused on environmental and water resources engineering projects related to modeling of surface waters and pollutant transport, evaluating watersheds and management, managing hazardous wastes, and improving or optimizing physicochemical processes at water and wastewater treatment facilities. He has also worked on curricular development, creative instructional pedagogies, alternative laboratory designs, and student engagement.