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Undergraduate Level Hands-on Ecological Engineering Course with Semester-Long Project and Laboratory Exercises

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Abstract

Our society currently faces many environmental challenges including: depletion of natural resources; pollution of soil, water and air; waste disposal; and climate change. To best solve these environmental challenges, society needs college graduates ready to enter workforce that possess an understanding of natural processes along with the ability to incorporate these processes into traditional engineering solutions. Therefore, a new course in Ecological Engineering and Science (EES) was developed to teach students how to take lessons from nature and utilize them for solving problems in the natural environment and ensuring its sustainability. As the course was being taught for the first time, it was quickly apparent that students majoring in Biological Engineering and Environmental science lacked adequate background and preparation in EES and data science. The course was then adjusted to immerge these students into EES and data science using experiential learning by developing laboratory exercises and a semester long project on wetland design. The project included designed laboratory exercises and hands-on work to teach ecological engineering skills as well as leadership, teamwork, and communication. Other class modules included a lesson on data science and several laboratory exercises on topics of bioretention basins, wetlands, physico-chemical processes, and green roofs. The students' performance in the projects steadily improved each year and grades for the course increased each year. The grades for the 2023 class were significantly higher than the grades for the 2019 class, which was the first year the course was taught. We believe this is likely due to the addition of the experiential learning components to the class. The revised course received positive student comments in the course assessment, which indicated enhanced student interest and learning.

Keywords – Ecological Engineering instruction, experiential learning, project-based learning, nbs, nature-based solutions, EES

1.0 Introduction

Ecological Engineering is relatively new field that has rapidly developed over the past 20 years. It applies fundamental knowledge gained in ecological science into engineering practice to perform a two-fold function: i) to restore already degraded ecosystems and ii) to design new ecosystems to provide ecological services and support sustainability [1], [2]. As fossil fuel-based energy sources deplete, environmental problems increase and the need for nature's ecosystem services increases. Ecological engineering is the key to solving these pollution issues, reduce resource problems, assist recovery from disturbance, and benefit humankind without destroying ecosystems [2]. Ecological engineering finds a "generic approach that aims to cure rather than treat symptoms" [3]. It entails a number of National Academy of Sciences, Engineering, and Medicine identified current grand challenges such as carbon sequestration, managing biogeochemical cycles, ensuring access to clean water, and restoring and improving urban infrastructure [4]. Its uniqueness lies in reliance on self-design of nature, systems thinking, use of natural energy and conservation of nature [5]. It emphasizes shifts away from growth-centered society as it recognizes the biosphere's ecological limits to human actions that conflict with growth and the technology-centered economy [3].

Ecological Engineering is steadily becoming a research and academic program worldwide [6]. Introducing Ecological Engineering into the curricula has changed the way students think about problem-solving and quantitative thinking [7]. It prepares students to solve complex problems and communicate effectively [7]. Ecological restoration courses, one of the foci of Ecological Engineering and Science (EES), are currently offered in most universities through departments of biology, ecology, forestry, landscape architecture, and environmental science [7].

EES is an important component for solving modern environmental problems. Humans face enormous environmental challenges today including natural resources depletion, pollution of soil, water and air, waste disposal, global warming and climate change, deforestation, loss of biodiversity, acid rain, and ocean acidification [8]. There is a need for environmental scientists and engineers to integrate nature as a key component of solutions while developing innovative solutions to complex environmental problems. The need to use nature in environmental problem-solving is epitomized by investment of $8 billion to restore the Kissimmee River in Florida to its original state after it was straightened to canal 30 years ago [9]. In another example, the City of Colorado Springs recently publicized its plans to spend $460 million over two decades in its stormwater infrastructure, maintenance and education programs [10]. Evidences suggests that ecological intensification of agriculture, an integration of nature into environmental solutions, can help sustain agricultural production while minimizing environmental impacts of agriculture [11]. An integration of nature and its processes into environmental solutions requires knowledge of EES so nature can be used effectively and efficiently to restore and design ecosystems for mutual benefit of both human and the environment [9].

In addition to EES, data science skills are increasingly becoming essential for addressing environmental problems as this often requires the handling of big, complex and/or messy data, that is often high frequency and in real-time. Agriculture, environment and food industries are currently entering digital revolutions due to i) recent innovations in robotics and automation, equipment and machinery, and sensor technology such as yield monitors, portable devices, drones and smart phones, ii) low-cost and real-time data collection and transfer systems for virtually everything such as soil condition, crop health and crop development, and iii) cloud computing and machine learning algorithms [12], [13], [14]. The exponentially high volume of available data has dramatically increased our ability to make smart decisions in agriculture and environmental management. However, the lack of data science professionals to collect, store, manage, analyze, interpret and use the big data and to use common language while working with multidisciplinary teams consisting of statisticians, engineers and environmental scientists are the current challenges in agriculture and environmental sciences [14], [15]. In fact, a recent National Academy of Sciences report on '*Data Science for Undergraduates: Opportunities and Options"* recommended "*Recommendation 2.3: To prepare their graduates for this new data-driven era, academic institutions should encourage the development of a basic understanding of data science in all undergraduates*." Therefore, curricula need to include components for training of data science basics to environmental scientists and engineers in addition to disciplinary knowledge [15].

Experiential learning significantly improves learning effectiveness regardless of the background and preparation. "Experiential learning is work outside of an academic setting which provides an academic benefit" [16]. The work involves students, but not like in a traditional classroom-based method. Project-based learning, a type of experiential learning, can immerse students in learning by engaging in real-world problem-solving in a team environment. In a senior level civil engineering class at University College Dublin, project-based learning was found to enhance many skills including problem-solving, innovation, group-working and presentation skills, and students appreciated peer teaching, interaction and problem-solving [17]. Project-based learning was superior to problem-based learning in engineering [18] that was superior to traditional lecture [19] in terms of learning effectiveness.

Today's work environment requires excellence in leadership, communication, and collaboration skills. "Human" skills including communication and teamwork are required for modern engineers to address competing demands from clients, general public, governments, and environmental groups [18]. Currently, engineering curricula are challenged to work within the constraints of the curriculum while producing engineers with leadership skills, an ability to build, work with and lead teams, motivate others, take calculated risk, communicate, listen carefully, respond to stakeholders, all the while possessing vision, empathy, honesty, transparency, and technical skills [20], [21]. Data collected from prominent members of industry and academia ranked communication and teamwork in top three skills required to be a globally competent engineer [22]

The College of Agriculture and Environmental Sciences (CAES) at North Carolina Agricultural and Technical University (NCA&T) offers several bachelor's programs including biological engineering, landscape architecture, and environmental studies that necessitate knowledge of EES and data science to solve environmental problems. Today's biological engineers require an ability to design solutions to complex problems while considering a multitude of factors including the impacts of engineering solutions on the environment. Documenting environmental sustainability is currently a required component for most projects. Landscape architects plan, design and implement projects that address the concerns of people and the environment, including both the natural environment such as wetlands, mined areas, stream corridors, and the built environment such as cities, parks, gardens. Environmental studies graduates need to apply science, and communication and leadership skills to environmental problem-solving. All these disciplines also require knowledge of data science to extract meaningful information from EES data. Therefore, to meet the needs of several undergraduate programs, NCA&T recently added the class BIOE 434 Ecological Engineering. The course is also one of the requisites for students who are interested in a certificate offered by the Interdisciplinary Waste Management Institute (WMI) and an elective course for students in environmental studies. Because of the diversity of students with varying background, their level of preparedness for the course material also varied. For example, the biological engineering program has two concentration tracks: bioprocess engineering, and natural resources engineering. The students in bioprocess engineering concentration track entered the course without having taken a directly relevant courses (e.g. hydrology, soil and water engineering) to build the basic ecological engineering concepts. Whereas, environmental studies students had the environmental science courses, but lacked knowledge in water or design-related courses. While adding a prerequisite to the curriculum is an option, it is not practically feasible because of limitations on total number of credits allowed for a degree by the university. Moreover, since EES is truly interdisciplinary in nature requiring and building knowledge from hydrology, soil science, environmental science, biology, engineering, ecology, and others, no student will have background knowledge of everything needed before enrolling in the class nor is there a single prerequisite course to make up this missing information, which will vary by the student's major. Consequently, we provided more experiential and hands-on learning opportunities to backfill any missing prerequisite information so all students can understand the concepts of ecological engineering. This process also demonstrates the collaborative environment required for science and engineering students to help each other. Additionally, experiential learning will help all students who need knowledge of data science and reinforcement of leadership, communication and collaboration skills in the context of ecological engineering to do well in the work-environment that they face upon graduation.

Thus, the overall goal of this project was to design hands-on learning components of the EES course for undergraduate students in diverse majors to improve the teaching and learning effectiveness of EES. While the course learning outcomes are provided in the Appendix, the specific objectives of the hand-on projects are listed in [Fig. 1].

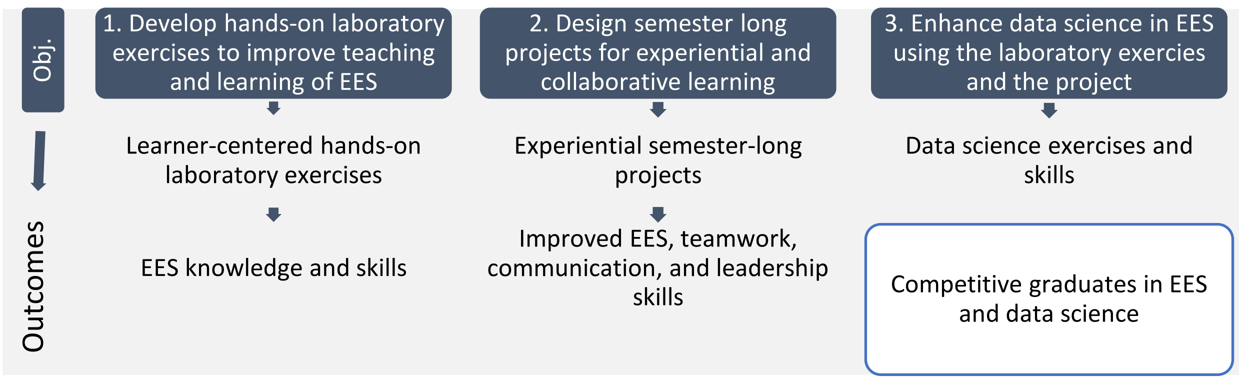

Figure 1 Objectives and outcomes of the project

2.0 Methods

2.1 Overview

In order to incorporate the addition of the experiential learning projects, the EES course format was changed from a 3-hr lecture only to lab and lecture (1-hr lab that meets for 2 contact hours and 2 contact hours lecture per University policy). The course materials were developed to meet the learning outcomes and the required materials, supplies, and sensors were purchased. Each year, students were divided into several interdisciplinary teams of students by considering major, concentration, gender, and prior knowledge on the topic. Students were assigned the semester-long project in groups and asked to produce deliverables and meet several milestones during the semester. While students were allowed to work on the project each week during in-class time, the project often required students to meet outside of the class. While some laboratory exercises were assigned to the group, some were assigned individually. Subsequent revisions on the semester-long project and lab exercises were carried out each year following student feedback and instructor's assessment.

For the performance analysis, the year 2019 was taken as the baseline year as the course was offered in a traditional format without the hands-on laboratory exercises and the semester long project. Year 2020 was impacted by COVID and the method of instruction was virtual and was not included. The implementation of the revised materials began in year 2021 and the data from the years 2021-2023 were compared against the baseline year 2019 to evaluate the impacts of the course changes.

2.2 Hands-on content

The semester long project and a few laboratory exercises that were developed and integrated into the course are presented below.

2.1 Semester-long project

The semester-long project was developed to provide experiential learning opportunities for students in ecological engineering design and develop soft skills. The project was chosen to simulate real situations relevant to EES, had multiple problem-solving steps, required high level of student initiative, motivation, self-direction and organization, was open-ended, and relied on group-work [18]. Students worked in an inclusive and collaborative team throughout the semester to create economically and ecologically sustainable ecosystems and apply principles of ecological engineering design for the required ecological functions or services.

The project's main objective was to design a wetland ecosystem to treat stormwater from a parking lot on campus [Table 1]. A specific area was identified and assigned as the location for the the parking lot and the wetland.

Table 1 Details of the semester-long project on design of a stormwater wetland

Purpose	**Provide experiential learning in Ecological Engineering Design to enhance disciplinary knowledge (ecological engineering, ecology, data science, water quality) and soft skills (ethics, collaboration, leadership, communication).**
Task	1. Design a wetland for stormwater treatment from a given area on campus (a map was provided). Evaluate all relevant design parameters and test it against the NC State Minimum Design Criteria. Make assumptions as necessary and justify your assumptions. 2. Create a scaled down version of the wetland that was designed in task one.
Provided	Map of the parking lot area and wetland location area, construction materials (sand, gravel, soil, tote), sensors and data logger, laboratory space, collaboration space in blackboard, faculty advising, interdisciplinary and diverse groups as much as possible.
Requirements	Participate in group work at every stage; work ethically; work at least two hours each week (equivalent to 1 lab credits); each group member should have a defined role (project manager, data specialist, water quality specialist, ecologist, hydrologist, etc.) and lead at least a component of the project; report the progress during milestone dates and meet milestones.

Activities	Safety training, design of the experimental reactor/systems, sketches, hands-on construction, testing, reconstruction, instrumentation, monitoring, data acquisition, data analysis, demonstration, reporting.
Milestones	Team role assignment Binding contract Prequalification letter Design on paper Prototype construction and testing Final demonstration, presentation and report.
Skills and outcomes	Ecosystems concepts, EES, ecosystems monitoring, instrumentation, data science, material balance, water balance, water quality, wetland processes, ethics, collaboration, leadership, communication, evaluation.

2.2 Laboratory Exercise 1- Data Science

The goal of the data science laboratory was to introduce students to the importance of monitoring and measurement, and to the data science continuum of collecting, storing, managing, visualizing, analyzing, interpreting and using the data [Table 2]. Students were given a real dataset consisting of hourly measurements of pH and temperature between the floating-plant-cover pond vs no-plant-cover pond and were asked to evaluate the role of plants on temperature and pH at different temporal scales. Students also watched an hour-long data science industry panel video, which was a discussion of several data science trends in the industry among industry professionals.

Table 2 Details of the data science lab exercise

Purpose	**Enhance knowledge of ecological engineering, stormwater monitoring and measurement, data science, and water quality.**
Task	1. Visualize and compare full high-frequency data set 2. Convert the hourly dataset to daily and compare them 3. Find missing, maximum, and minimum values on a daily or an hourly temporal scale and errors 4. Evaluate diurnal variation of pH and temperature in aquatic systems and study the effect of plants on these variables 5. Determine if the recorded values were out of compliance as it pertains to human health and environmental compliance by comparing against a threshold
Provided	Dataset with hourly measurement of pH and temperature from two ponds, one with floating plant cover and the other without floating plant cover. Computer loaded with MS Excel in the computer lab.
Requirements	Participate in a short introduction lecture and demonstration of MS Excel Complete the tasks and submit
Activities	Short lecture, demonstration, and exercise
Skills and outcomes	Ecosystems concepts, EES, ecosystems monitoring, instrumentation, data science, water quality, evaluation.

2.3 Laboratory Exercise 2- Design of Bioretention Basin

The goal of the bioretention basin laboratory was to teach students the importance of stormwater management, introduce stormwater control measures (SCMs), a bioretention basin or raingarden and its regulations, and design a bioretention basin using the RECARGA model [23] [Table 3].

Table 3 Details of the bioretention design laboratory

Purpose	**Enhance knowledge of ecological engineering, stormwater management, water quality, modeling, bioretention basin design, and role of design variable on the performance of bioretention basin.**
Task	1. Find when runoff begins under given scenario in a bioretention basin 2. Illustrate the role of soil depth on the runoff quantity 3. Demonstrate the effects of media type on the hours of ponding, which is regulated
Provided	Computer, RECARGA model software v2.3, and its manual
Requirements	Participate in a short introduction lecture and demonstration of RECARGA tool Complete the tasks and submit
Activities	Short lecture, demonstration, and exercise
Skills and outcomes	Stormwater management, SCM's, stormwater control measures, raingarden or bioretention basins, water quality, modeling, design, evaluation.

2.4 Laboratory Exercise 3- Wetland hydrology and processes

The goal of the wetland laboratory was to introduce wetland hydrology and processes. A research scale or mesocosm scale constructed hybrid wetland consisting of surface flow and subsurface flow wetland was used for demonstration and study of wetland design parameters for hydrology and discussion of processes that help clean up the pollutants [Table 4].

Table 4 Details of the wetland laboratory

Purpose	**Enhance knowledge of ecological engineering, lab safety and practices, wetland hydrology and processes, water quality.**
Task	1. Observe wetland setup 2. Measure the dimensions of the wetland 3. Use the measured and provided data to calculate discharge, volume, retention time, loading rate, and expected removal of a pollutant
Provided	A mesocosm scale hybrid constructed wetland setup Measuring tape

	Stopwatch Lab coat, gloves, and goggles Measuring cylinder, 100 mL
Requirements	Observed a hybrid constructed wetland and participate in discussion of wetland processes in a surface and subsurface flow wetland Complete the tasks
Activities	Short lecture, measurement, and exercise
Skills and outcomes	Ecosystems concepts, wetlands, surface and subsurface flow wetlands, hydrological variables in a hybrid wetland, processes that remove pollutants from a wetland, water quality, evaluation.

Several other lab exercises are being developed and are at various stages of implementation. They include green roof, sand filter, biogeochemical cycling, and physicochemical removal of pollutants [Table 5].

Table 5 Other laboratory exercises being developed

Lab exercises	**Learning Outcomes**	Activities
Green roof	Explain green roof and its components; quantify its benefits by measuring hydrological and environmental parameters between green roof and conventional roof prototypes	Measure runoff and temperature between two doghouses, one with green roof and the other without the green roof
Sand filter design	Design a sand filter for removal of target contaminants	Utilize sand, gravel, biochar, and other materials to design a biofilter to remove a given contaminant
N and P Cycling	Explain fundamental differences between Nitrogen and Phosphorus cycling in the environment and how these differences can be used to design N and P removal systems	Compare leaching and sorption of N and P from similar terrestrial ecosystems
Adsorption isotherm	Create P adsorption isotherm for biochar	Utilize various concentrations of P to create a sorption isotherm

3.0 Results and discussion

Students used most of their in-class times for experiential learning. Students met weekly with the instructor to clarify major ecological engineering and data science principles, and to provide updates on the exercises and projects. The project required teams to define and serve in an identified role on the team (e.g. project manager, biologist, engineering manager, liaison etc.)

and complete deliverables at several intermediate deadlines throughout the semester (similar to a real-world engineering design project). A project manager reported progress each week to the entire class. Active collaboration and leadership activities were observed by the instructor.

Two performance indicators: final grade during the baseline period as compared to during the project implementation period, and the grades in the semester long project were used to evaluate the results. An increase in average final grade was observed each year and grades for all treatment years exceeded the average final grade in the baseline year [Figure 2]. The average GPA increased from 2.96 (n=9) in 2019 to 3.29 (n=15) in 2021 to 3.50 (n=12) in 2022 to 3.73 (n=8) in 2023. Statistical analysis indicated that the final grades in 2023 was significantly higher than that in 2019 (p=0.046) [Figure 2]. Additionally, the grades in the semester-long project increased each year. The average grade on the project in 2023 were significantly higher than the average grade on the project in 2021 (p=0.04). The course was taught by the same instructor using the same grading criteria every year so fair comparisons for grades between years can be drawn. End-of-semester evaluations of the course by students was positive and students expressed appreciation for the hands-on learning assignments and a desire for more such activities. In addition to the semester long project and the laboratory exercises, the course also included a poster presentation on applications of ecological engineering and field visits to the weather station, wetlands, and stormwater BMPs in all years.

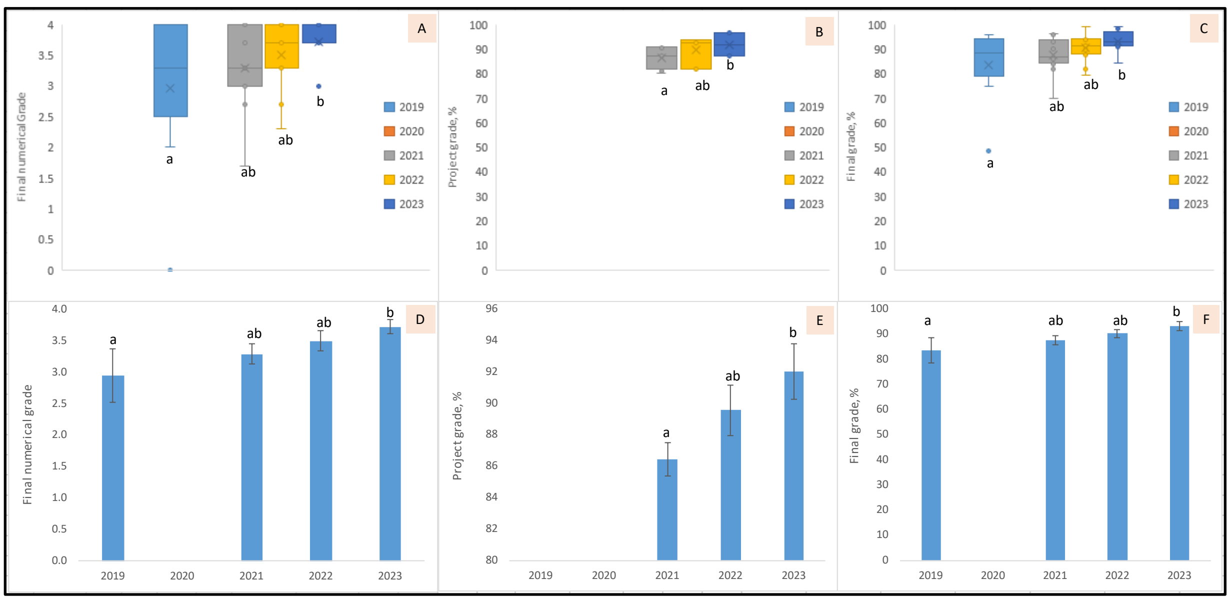

Figure 2 Student performance on the project and the course across years. Panels A and D represent the final grades in the course, panels B and E represent the project grade in percentages, and panels C and F represent final grade in percentages. Lower case letters above each bar or below each box indicate the statistical results for the panel. Different letters indicate statistical significance (p<0.05). The number of students for year 2019, 2021, 2022, and 2023 were 9, 15, 12, and 8, respectively.

During the project, the instructor also observed that students learned from failure, demonstrated appropriate level of thought, creativity and real-world problem-solving, communicated efficiently, worked effectively in a team, and followed appropriate ethical and safe engineering practices. The collaborative learning in teams that closely replicated a real-world problem-solving environment appeared to enhance student learning.

The development of the exercise, practice, and real implementation in the classroom required more time at the beginning (2021 class) mainly because the instructor spent more time to prepare and deliver the hands-on learning activities. However, the results and positive outcomes support the extra time for these activities. A revision and shortening of contents other than the experiential learning modules discussed here was required. The implementation of some of the activities in a large class would be a challenge though the student enrollment ranged from 8 to 15 and was manageable in this class. Another challenge during implementation of the project prototype was winter weather at the end of the fall semester when the course is offered. Because of cold and wet weather and outdoor setting, the implementation schedule was affected and limited.

4. Conclusions and recommendations

The projects supplemented the current lecture method with experiential and project-based learning activities. In addition to semester-long project and laboratory exercises implemented from 2021 onwards, the course also involved lecturing, field visits, and poster presentation on case studies of ecological engineering applications since 2019.

The most important outcome was improvement of both course grades from year-to-year and student satisfaction with the course as expressed in both end of course evaluation and informal discussions with students. Student feedback was extremely positive and they expressed a desire for more experiential, hands-on learning activities.

The semester long project required students to build and test the wetlands prototype in the outdoor environment. Often, it was interrupted by cold or wet climate. This issue would be resolved if the course is moved to spring semester or if the indoor space or the greenhouse is made available for the project.

While the implementation in a large classroom would be a challenge, adequate resources, space, and availability of teaching assistants can help implement the course activities in a large classroom.

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Appendix: Course learning outcomes

Student Learning Outcomes:

1. Develop a systems view of ecosystems emphasizing the relationship between human and environmental systems.
2. Recognize the governing principles of the field of ecological engineering and how they apply to biological engineering.
3. Identify and describe the contemporary issues and emerging fields in which ecological engineers will be called upon to use their expertise.
4. Describe important physical, chemical, and biological processes that occur in natural ecosystems and use such processes to engineer ecological systems for restoration and water quality improvement.
5. Explain, use, and illustrate mass balances, water balances, energy balances, and chemical balances as tools to help understand and describe ecosystem functions.
6. Explain the approaches to ecological restoration of streams and rivers, wetlands and riparian areas, lakes and reservoirs, and coastal ecosystems.
7. Apply techniques to design natural treatment ecosystems for stormwater and wastewater (e.g., treatment wetlands, land treatment systems, stormwater management).
8. Analyze and illustrate the impact the ecosystems design to solve engineering problems on societal and global issues.

SACS Outcomes:

SLO 3 Disciplinary expertise

ABET Outcomes:

Outcome 2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors
Outcome 3. An ability to communicate effectively with a range of audiences
Outcome 5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives