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Teaching Undergraduate Students to Manage Aquatic Ecosystems at the Watershed Level: an Ecological Engineering Approach*

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The Ecological Engineering Group within the Biological and Agricultural Engineering Department at the University of Arkansas applies the principles of ecology and engineering to prepare students to investigate and restore ecosystems degraded by human activity, focusing on the smallest unit of ecosystem management—the watershed. Ecological engineering teaching intertwined with research activities include investigation of the response of aquatic systems to nutrient enrichment from diffuse and point sources, control of biotic and abiotic processes on water quality, combining these investigations to enhance ecosystem management and develop decision support systems. Students are given an opportunity to apply their classroom knowledge to real-world watershed projects. Integration of teaching and research has enabled students to fully publish their research findings in undergraduate research journals.

Keywords: ecological engineering; nonpoint source pollution; watershed management; ecosystem

INTRODUCTION

CONVERGENCE OF DISCIPLINES into more holistic arenas of investigation, often referred to as consilience, is being driven by the increasingly complex problems emerging in society. This complexity, present in both the technical and social landscape within the working environment, requires our students to be creative problem solvers who can recognize and adapt to change rapidly [1]. Preparing engineering students to meet society's changing needs requires a new educational model. This new educational model presents a series of challenges to the current engineering educational structure. These challenges include integrating ecological principles into design practices, integrating uncertainty into design and designing complex systems with no existing design methods or guidance.

Ecological engineering has been defined as the design of ecosystems for the mutual benefit of humans and nature [2], or similarly, the design of sustainable systems consistent with ecological principles that integrate human society with its natural environment for the benefit of both [3]. Matlock *et al.* [4] have defined it as the design of complex biotic and abiotic processes to preserve, restore, and enhance ecological services, which are the benefits from ecological functions that humans derive from the ecosystem, both directly and indirectly. Examples include nutrient cycling, flood attenuation, habitat, carbon fixation and oxygen generation. Ecological Services are declining at increasing rates due to human management and exploitation. There is growing concern that our future demands for ecological services may not be met with current approaches to ecosystem management and conservation. Managing ecological services explicitly will require a new ethic that encompasses risk communication, risk management, policy legitimacy, economic equity and responsibility to generations yet unborn who will also depend on these same ecological services. Ecological engineering is emerging as the applied discipline for designing, restoring and managing those processes.

Ecological Engineering is based on an ethic of conservation of Earth's resources for sustained quality of life for future generations of humans. This ethic is central to the criteria for successful design, and is embedded in the processes and techniques used by ecological engineers. The science of ecology and study of ecosystems provide the foundation for ecological engineering, but the practice of designing sustainable systems requires skills in risk assessment, risk management, public policy and economic theory as well.

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Preparing students at the undergraduate level to deal with issues as broad and complex as these is impractical at best. There is simply not enough time in an ABET-accredited engineering programme to provide ecology, economics, political science, management and other skills necessary to design ecological services. In fact, biological-based engineering curricula that prepare students to be able to solve complex biological engineering problems are not common. There is, however, a method of effectively teaching at least a number of aspects of ecological engineering to undergraduate students so that they can be better prepared to solve complex environmental problems.

TEACHING PARADIGM IN ECOLOGICAL ENGINEERING

The engineer in the 21st century more than ever will be involved in management level decision-making [5]. Modern educational systems must provide tools that can be used to help ecological engineers make sound management decisions in the modern era dominated by global environmental change and deterioration [6]. The focus of teaching in the new millennium must shift from lecture and carefully designed laboratory exercises to more participatory and open-ended pedagogical approaches [1]. This discovery-based approach prepares students to think critically, evaluate results of various options that may be available to solve complex environmental problems and make better decisions.

Matlock *et al.* [4] have argued that ecological engineering should be a graduate area of study due to its complexity. The undergraduate preparation necessary to pursue graduate study should provide a substantive understanding of physical, chemical and biological processes across the biotic spectrum, from cellular to continental. The educational objectives of the Biological Engineering Programme are to produce graduates who:

(a) effectively apply engineering to biological systems and phenomena (plants, animals, humans, microbes and the environment) with demonstrated proficiency in basic engineering skills, technical knowledge and professional and personal skill;
(b) are well prepared for future challenges in biological engineering, lifelong learning and professional and ethical contributions to society through sustained accomplishments.

Undergraduate students interested in ecological engineering develop their skills in solving watershed scale ecological problems by getting involved in collecting and analysing data in field and laboratory conditions, analysing data using a variety of statistical methods and tools, evaluating effects of various land management processes on ecological services using state of the art computer simulation models.

We provide two undergraduate courses at the University of Arkansas. At the same time, several other courses are also available to undergraduate students involving ecological engineering modules that teach them various engineering and design principles. Undergraduate students whose first-choice is Ecological Engineering take these classes as technical/design electives.

BENG 4903: Watershed Ecohydrology

This is a senior level design elective class. This class focuses on engineering principles applied in the design of systems for utilization of surface and ground water. Students work in the field to collect stream flow, geormorphological and meteorological data to determine the hydrological budget in a watershed. They also collect field water samples for subsequent laboratory analyses of water quality parameters such as suspended sediment and nutrients. Students are also required to design

Table 1. Detailed description of materials covered in BENG 4903

Week	Lecture	Laboratory
1	Introduction to water resources engineering. Hydrologic cycle. Hydrologic frequency analysis	Lab planning, Discussion of laboratory procedures and report writing. Discussion of semester project.
2	Infiltration and evapotranspiration estimation	Stream flow frequency analysis
3–4	Rainfall-runoff estimation	Precipitation-runoff analysis
5	Open channel hydraulics	Use of GIS technology in solving ecological engineering problems
6	Hydraulics of structures	GIS and hydrologic modeling
7	Channel and reservoir routing	Analysis of stream water quality
8–9	Sediment erosion: properties and transport	Design of best management practices for flow and water quality control
10	Erosion and sediment yield	
11	Sediment control structures	
12–13	Groundwater	Design of monitoring systems at watershed scale
14–15	Monitoring of hydrologic systems	Project presentation

sediment detention structures, vegetative grass ways and buffer strips and erosion control structures. The detailed course plan is listed in Table 1.

After completion of this class, the students are expected to:

(1) Understand linkages among various components of the hydrological cycle;
(2) Perform stream flow frequency analysis;
(3) Predict runoff from a given watershed under various land use and soil conditions;
(4) Quantify erosion and sediment yield from watersheds;
(5) Design grassed waterways, detention ponds, and rip-rap/filters to minimize flooding, and erosion;
(6) Understand basic watershed monitoring principles;
(7) Communicate laboratory study results effectively.

BENG 4923: Ecological Engineering Design

Nonpoint Source (NPS) Pollution Engineering is another senior design class. This class focuses on engineering principles involved in assessment and management of NPS pollution and its effects on ecosystem integrity. Students taking this class work in the field to collect watershed scale hydrological and water quality data for laboratory analysis and use the geographical information system (GIS) and mathematical models to quantify the extent of pollution. A detailed discussion of best management practices needed to preserve various ecological services at the watershed scale is provided in Table 2.

Students taking this class are expected to:

(1) Understand sources and nature of NPS pollution originating from agricultural and urban land use.
(2) Link nature of diffuse pollution with physical, chemical and biological integrity of ecosystems and water usage.
(3) Quantify amount of diffuse pollution from a watershed using state-of-the-art methods and models.
(4) Design best management practices to minimize nonpoint source pollution from agricultural and urban land use.
(5) Understand TMDL issues and processes involved in developing TMDL plans.
(6) Understand basic monitoring and modelling principles.
(7) Apply engineering principles in developing NPS pollution prevention plan.

STUDENT RESEARCH PROJECTS

We provide opportunities for undergraduate students in the Biological and Agricultural Engineering department to work on research projects related to ecological engineering. Several of those who participate in projects work up a thesis to earn undergraduate credits. For example, one student team quantified the impact of agricultural land use on stream physico-chemical properties. The students monitored two sampling points within the upper reach of Flint Creek in Arkansas. The watershed was impacted by agricultural nonpoint source pollution. At each point, continuous

Table 2. Course outline for BENG 4923: Nonpoint Source Pollution Engineering.

Week	Lecture	Laboratory
1	Introduction to NPS pollution, history, types, current state-of-the-knowledge	Project and laboratory overview. Discussion of NPS resources available on-line
2	Water quality issues. Effect of NPS pollution on ecosystem integrity, hydrologic considerations	Field trip to a watershed impacted by NPS pollution
3	Pollutant interactions with soil, sediment and water.	GIS-Lab1: Use of GIS in watershed NPS assessment
4	Erosion and sediment yield modeling: USLE, RUSLE, and WEPP	GIS-Lab 2: Presentation of watershed scale spatial and non-spatial data in GIS for modeling NPS pollution processes
5	Stream flow measurement and sampling techniques to determine pollutant load.	Stream water quality monitoring: effect of land use on ecosystem integrity
6	Nutrient management at watershed scale.	Field trip to stream bank restoration site
7–8	Best management practices (BMPs): concept, design, and implementation for nutrient and sediment control	Erosion modeling: Revised Universal Soil Loss Equation (RUSLE) approach
9	Urban diffuse pollution	Distributed watershed modeling for NPS assessment and management
10–11	Design of BMPs to control urban NPS pollution	Distributed modeling, cont.
12	NPS pollution assessment—modeling approach	Biological monitoring to assess stream ecosystem integrity
13–14	TMDL: concept, principle, and design	Project presentation
15	Use of GIS and NPS models to develop pollution prevention plan. Design of watershed monitoring plan to assess NPS pollution	

measurement of stream characteristics such as temperature, dissolved oxygen (DO) concentration, depth, pH and conductivity were taken on three different dates. Water samples were collected and analysed for nitrogen (N) and phosphorus (P) concentrations to discern the impact of agricultural land use on water quality. The results indicated that nitrate N (NO_3-N) and phosphate P (PO_4-P) concentrations increased as the agricultural land use increased in the watershed. Fluctuation in the DO concentration also increased with higher agricultural land use. The students concluded that to help decrease the amount of nutrients introduced to the stream, a variety of best management practices (BMPs) could be implemented in the watershed.

Another student team assessed longitudinal base-flow and storm-flow water quality at War Eagle Creek and quantified linkages between stream water quality and land-use conditions within the sub-watershed of the Beaver Lake watershed located in northwest Arkansas. Beaver Lake is a drinking water supply for more than 300,000 residents. Students involved in this project collected six water samples: three from base-flow conditions and three from storm-flow conditions during Spring 2002. The students analysed the trend in the water quality data and corrected it to land use pattern to discern any effect of land use on stream water quality.

In a third example of the ecological engineering training provided, students demonstrated the technologies and methods by which ecological services could be restored in a distributed urban system. Specific objectives included bioretention of stormwater and parking lot runoff, reestablishment of fish pool habitat, implementation of natural bank stabilization, integration of riparian zone buffers, regulation of stream flow for maximum in-stream ecological services. These objectives were accomplished by integrating basic hydrological, ecological and modelling processes. The student involved in this project worked in field to collect data on current hydrological, geomorphological and water quality conditions. In addition, computer models were used to design retention pools and stable banks for design storms. Finally, project findings were presented to municipal government where the project was located and at regional and national conferences.

Two Senior Design Teams have completed projects that also represent the demand for this integrated ecological engineering approach. One team worked with the City of Rogers, Arkansas, the Nature Conservancy, USEPA, the Arkansas Soil and Water Conservation Commission and the Arkansas Game and Fish Commission to restore a half-mile reach of an urban stream below the Rogers High School. This project involved habitat assessment, habitat design (riverine, wetland and terrestrial), fluvial mechanics, geomorphology and hydrology. The team designed, simulated and constructed the restoration project over nine months. The project was so successful that an additional half-mile of stream was funded for restoration in 2006.

Another Senior Design Team worked with the City of Fayetteville, Arkansas, Fayetteville Independent School District and Leverett Elementary School to develop a courtyard outdoor classroom featuring an artificial stream, a 1/10-scale water wheel and a rain harvest system. This project, completed in 2005, provides pedagogical tools developed by undergraduate engineering students to teachers of 3–5 grade science curricula.

We have also integrated undergraduate and graduate student workers into ecological engineering design response teams to address a variety of challenges. These include assessment of the ecological and water quality conditions of the Illinois and Kings Rivers in Arkansas for Parsons Engineering and assessment of the impact of pulp and paper mill effluent on stream ecosystem integrity of the Ouachita River in Arkansas, also for Parsons Engineering. Teams have also participated in the USEPA National Wadeable Streams Assessment, sampling 30 sites in Arkansas in three months for geomorphological, ecological and water quality conditions. Finally, they have initiated a project with Habitat for Humanity to design and develop a model eco-community in Rogers, Arkansas on a 10-hectare site.

All of these projects conducted by undergraduate and graduate students had three important elements of ecological engineering training:

(1) working in the field to collect data, including hydrological, ecological and water quality data;
(2) working in laboratory to analyse these data and quantify trends and thresholds;
(3) working with geographical information systems-based and/or other computer models to analyse results.

These projects enabled students to apply their classroom learning to real-world problems. The findings from several of these projects were published in *Discovery*, a University of Arkansas undergraduate research journal [7, 8].

SUMMARY AND CONCLUSIONS

We have presented some examples and case studies of undergraduate biological engineering courses that prepare students for pursuing ecological engineering at the graduate level. We believe that ecological engineering training must involve both traditional and experience-based pedagogies intertwined in a way that students can effectively apply their classroom education to quantify and solve real-world ecological problems. An undergraduate curriculum intended to prepare ecological engineers should include opportunities to work at a watershed scale in field, enable students to collect physical, chemical and biological data for watershed assessment, provide laboratory environments to analyse data and use state of the art models and tools (such as a geographical information system).

This approach is not without its significant challenges, however. The continuing pressure to produce more student graduates with less faculty effort undermines the mentorship required in this approach to education. Resources for students to conduct research in a meaningful way are often not available. Research supervision is often very time-consuming, and very seldom valued by university administrators. Finally, student time requirements for this approach are significant. Students often are reluctant to commit to this level of effort; however, the opportunity to work closely with a faculty mentor has generally been adequate incentive. The ecosystem management challenges that our society will face in the near future are dauntingly large; the skills our students will need to meet those challenges are equally large. The approach presented in this manuscript has been effective at training and preparing undergraduate students to begin the process of preparing to meet those challenges.

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