Assessing Experimental Design in Civil Engineering

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Abstract

One requirement for ABET (Accreditation Board for Engineering and Technology) accreditation for undergraduate Civil Engineering is related to experimental design. Determining and implementing an appropriate assessment metric for this requirement presents challenges in the laboratory setting due to the inexperience of students and interrelated experimental variables to be modified within the constraints of equipment capabilities. A straightforward implementation of an experimental design assessment is presented for a junior-level CE course, Hydraulics and Hydrology. A detailed description is included for the assessment process involving the design of experiments to investigate rainfall-runoff processes using a bench-scale hydrology table. The presentation includes methods for (a) communicating the design process to students, (b) setting expectations for classroom theory to be investigated, (c) working within the capabilities of equipment, and (d) assessing the student-led design process.

Introduction

Experimental design is an important skill for undergraduate engineering students to acquire. Hands-on exposure to the constraints of experimental variables, equipment capabilities, and the resolution of measurement techniques at the stage of experimental design gives students an opportunity to think critically about how theories and equations apply in real world engineering situations. Exposure to experimental design also allows students a concrete, physical illustration of the ways in which interrelated experimental variables depend on one another. For these and other reasons, the Accreditation Board for Engineering and Technology (ABET) outcomes specify that students, by the end of their undergraduate engineering education, demonstrate:

> *"An ability to design and conduct experiments as well as to analyze and interpret data"* – ABET Engineering Outcome B[1].

While the Civil Engineering specific ABET Program Criteria deemphasizes the design aspect of experimentation (since professional civil engineers are not often involved in experimental design[1]), the ABET general criterion for all engineering programs must nonetheless be demonstrated.

Towards this end, the new Department of Civil Engineering (CE) at the University of Minnesota Duluth has chosen to implement the assessment of ABET Outcome B (ability to design and conduct experiments) in its Hydraulics and Hydrology laboratory course. The department has four sophomore-level courses with significant laboratory components that give students hands-on experience. This paper outlines the curriculum setting for assessing the ABET experimental design outcome, introduces the experiment on which the assessment is made, and describes the assessment process from planning and communicating to students through compiling assessment results.

Curriculum Setting

Several required lab courses, taught at the 3xxx level, could have been suitable for assessing experimental design in the UMD Civil Engineering Curriculum. However, finding an appropriate laboratory exercise for design assessment was difficult since most experimental methods in Infrastructure Materials and Soil Mechanics follow well-specified standard methods. Exercises in Transportation Engineering involve complex computer programs are difficult to design without in-depth knowledge of the software. In contrast, most lab exercises in Hydraulics and Hydrology involve collecting and analyzing data from field or laboratory settings that illustrate the theories taught in the lecture portion of the class. Rather than following a standard method precisely, this type of experimental setting leaves the potential for allowing students some freedom in designing an experiment that will illustrate and verify the underlying principles taught in the class. Hydraulics and Hydrology, therefore, was chosen for the assessment of student's competence in experimental design.

The Hydraulics & Hydrology course is structured around 10 laboratory exercises that provide students with hands-on experience in topics ranging from pressurized pipe flow to open channel flow to rainfall-runoff response. As a required course in CE, it is offered every semester and the schedule is altered in the Spring semester to accommodate weather considerations in Northern Minnesota. Table 1 outlines the laboratory exercises for the Hydraulics & Hydrology course and the associated topics.

Table 1 Laboratory exercises for CE 3225 Hydraulics & Hydrology

Lab Exercise	Course Topic
EPA Net simulation (computer)	Pressurized pipe flow applications
Pump Demonstration Lab	Pump performance & water distribution
Stream Velocity (field lab)	Open channel flow
Hydraulic jump (flume)	
Weir discharge (flume)	
Slug test (field)	Groundwater & well hydraulics
Well drawdown (water table)	
N/A	Hydrologic cycle

Lab Exercise	Course Topic
Hydrograph lab (water table)	Rainfall/runoff/ hydrograph
CE building monitoring system	
Hydrologic statistics (computer/GIS)	Probability/frequency analysis

Most lab exercises for the course are carried out in groups of 3-4 to give all students in lab sections of ~15 students plenty of time with equipment. Lab reports are also written in these groups, providing students with experience working in teams, but making individual assessment challenging. Some lab exercises, especially those that are computer based, are carried on an individual basis, but they do not lend themselves to experimental design assessment due to the nature of the exercises and software used. A decision was made to assess experimental design capabilities using a group lab towards the end of the semester, the Rainfall/Runoff Hydrograph Lab. Although students completed the lab exercise in groups, individual reports were required which gave each student the opportunity to think through and document their own experimental design process.

Lab Exercise Description

The Rainfall/Runoff Hydrograph lab makes use of the hydrology table pictured in Figure 1. The sand-filled hydrology table has several capabilities, but the ones utilized in this experiment are the rainfall and river simulators. A steady flow of water is maintained using one of the system's two independent flow valves while the second valve is used to simulate a precipitation event by sprinkling water evenly over the table surface. A water collection system is used to continuously monitor the river flow exiting the table and data collected from the system is used by students to quantify the river response of the small-scale "watershed" to a simulated precipitation event.

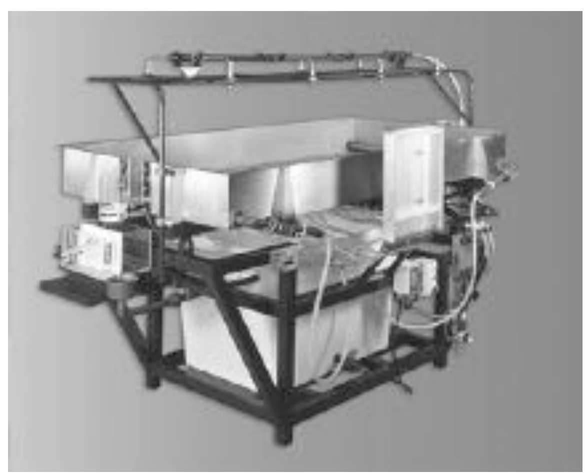

Figure 1 Armfield Advanced Hydrology Demonstration Unit.

The principle to be demonstrated is a method for predicting the response of a river following a rainfall event given the "Unit Hydrograph" for the system. A Unit Hydrograph represents the response of a watershed-river system to one 'unit' of precipitation for a specified duration. For the laboratory system, the “30 second Unit Hydrograph” was defined for students as the river’s response to 1mm of precipitation over a duration of 30 seconds (2mm/min for 0.5min). Unit hydrograph analysis is a well-developed hydrologic tool used to predict the river response from hypothetical or future storms using the principle of superposition. River flow is assumed to scale linearly with intensity and the effects of subsequent increments of rainfall duration are superimposed to predict the total stream response. The Unit Hydrograph analysis process is

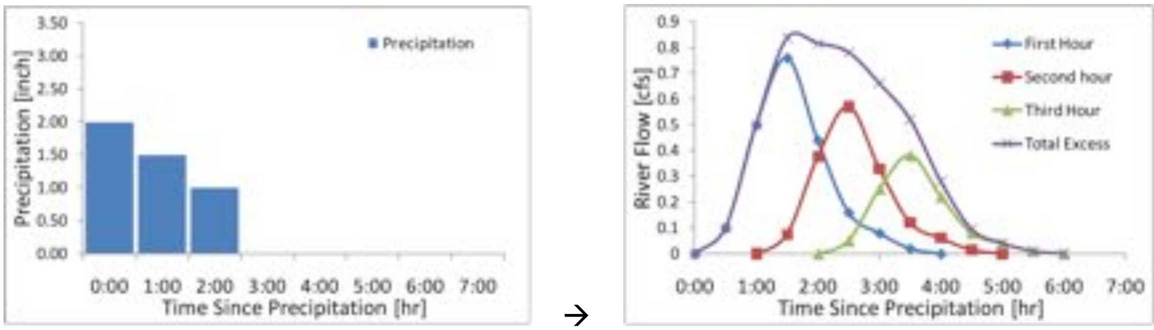

Figure 2 Illustration of Unit Hydrograph analysis. Response from each precipitation duration is scaled and summed to predict total river response.

illustrated in Figure 2.

Students were instructed to design a set of three or four short duration (<15min) experiments on the Hydrology table whose results would demonstrate the theory behind Unit Hydrograph analysis. A Unit Hydrograph is intended to represent and capture the effects of all “unchanging characteristics” of a watershed, and students were also asked to run one experiment by changing one characteristic of the watershed by adding an impervious layer, adding vegetation (carpet) or changing the slope of the watershed.

Although this lab exercise provided a convenient, well-bounded set of experimental variables that could be manipulated by students to design a successful set of experiments, the types of calculations involved in Unit Hydrograph analysis are very different than those used in the rest of the class. For most of the topics in the class, theories which underlie homework and laboratory exercises take the form of continuously-defined numbers and deterministic equations or sets of equations which were manipulated to solve for one or more dependent variables. For Unit Hydrograph analysis, calculations involve simple mathematical functions such as scaling and summing sets of data, but require some level of comfort with discrete sets of numbers and mathematical operations as well as spreadsheet calculations. While this discrepancy from previous mathematical tools did not affect the assessment of experimental design in the lab, some students did not catch on quickly to the different, discrete mathematics involved in the calculations and made mistakes in data analysis.

Assessment Process

Communicating expectations to students

After the concepts of Unit Hydrograph Analysis were covered in class with concrete examples, students were provided a lab handout (2 concise pages), similar to one they receive before every other lab, which described the objectives and experimental procedures as well as the required data analysis and discussion questions for the lab report. In addition to the usual questions related to theory and analysis, two additional questions were added to the discussion requirements for the lab report:

1. *Describe the process of choosing experimental design variables to illustrate concepts related to unit hydrograph analysis. Why did you choose the variables the way you did?*
2. *…*
3. *…*
4. *Did the experiments you designed successfully illustrate the concepts of unit hydrograph analysis? What would you do differently if given another opportunity?*

The answers to these questions provide the material for assessing the student's ability to think critically about experimental design in fulfillment of the ABET Objective B. Students were informed that the lab report for this lab exercise would be completed on an individual basis and used as an assessment tool for ABET. Students were also informed that the ABET assessment would take place using a grading scheme independent from the scheme used to assign a grade for the report, and would be used by the department to demonstrate student competence in experimental design.

Guidance on design variables & expectations

The lab handout included an additional section (~1 page) that (a) briefly summarized the expectations for number and type of experiments and (b) defined the variables that could be modified by giving appropriate equipment limitations. The following is a summary of the summary of experimental design variables given to students:

> ***Appendix A: Experimental design variables***
> *Use the following as a guide to design your experiments. The standard watershed has a 1% slope, no impervious cover, and no vegetation.*
>
> *Your group will design experiments that will allow you to investigate the application of unit hydrograph analysis. You should design four different experiments:*
>
> - *3 varying rainfall characteristics (duration and intensity) on the standard watershed,*
> - *1 varying the watershed properties.*
>
> *The following information will give you some parameters to work with when choosing your experimental variables. Once you have your 4 experiments chosen, guess the resulting shape of the unit hydrograph. Present your planned experiments and expected results to the instructor for feedback*

Rainfall Characteristics:

- *Three unique combinations of rainfall duration and intensity should be chosen*
- *Intensity:*
    - *A flow of 2 L/min corresponds to 1 mm/min of rainfall over the watershed area* $1\frac{mm}{\min} = \frac{2000\frac{cm^3}{\min}}{20{,}000cm^2} = 0.1\frac{cm}{\min}$
    - *Flows between 0.5 L/min and 3 L/min will give reasonable responses for this watershed*
- *Duration:*
    - *The unit hydrograph is for a 30second rainfall duration*
    - *Choose storm durations to be a multiple of 30s*
- *For the third storm, vary both duration and intensity to give a realistic storm*

Watershed Characteristics:

- *The final experiment should use one of the three storms from before, but change one or more of the watershed characteristics to determine the effect on the shape of the hydrograph*
- *The parameters available for changing the watershed are:*
    - *Slope (between 0.25% & 2.5% will give results in reasonable time-frames)*
    - *Impervious cover (plastic is available to cover ~30% of the watershed)*
    - *Vegetation (a piece of carpet can be used to simulate vegetative cover)*

During the final 20-30 minutes of the lecture before the Hydrograph Lab, students gathered with their 3-4 person groups and worked to design a set of experiments within equipment limitations that would successfully illustrate Unit Hydrograph analysis. Students were instructed to think critically about the known effects of independent variables involved in Unit Hydrograph calculations. Each group of students was required to hand in a description of experiments by the end of the class period that they would implement in the lab on the following day along with the expected river response.

Creating and implementing a metric for assessment

The grading scheme used for most lab reports was modified to accommodate assessment for ABET Outcome B. All lab reports for the course are graded by assigning points to 5 different categories:

Lab Report Grading Sheet

Overall Understanding	*/15:*
Organization / Structure	*/5:*
Calculations / Data Analysis	*/10:*
Presentation / Readability	*/10:*

Interpretation / Discussion	*_/10:_*
Total	***50***

Points for two of these categories (Overall Understanding and Organization/Structure) are assigned based on an overall reading of the report and assessment of its organization. Points for the other three categories (Calculations/Data Analysis, Presentation/Readability, and Interpretation/Discussion) are assigned by looking for specific items in the report that were outlined in the initial lab handout. An example of this normal laboratory assessment is illustrated in Table 2.

Table 2 Example of standard assessment matrix used for all lab reports.

	Calcs/Data Analysis	**Pts**	**Presentation/ Readability**	**Pts**	**Interpretation/Discussion**	**Pts**
Overall Report			Theory presentation	2	Overall discussion quality	2
			Overall readability	2	Correct data interpretation	2
Predictions & comparisons	calculate total streamflow	2	present precip event summary	3		
			present comparisons	2	how did predictions work?	2
	calc predicted	5				
Total streamflow / changed watershed			present changed watershed	1	how did changed watershed work?	1
Design process	what should have happened	3			comment on design process	3

The metric for assessing ABET Outcome B was developed to incorporate each element of the outcome including an evaluation of each action: *design, conduct, analyze,* and *interpret* [2]. While students have had experience with conducting experiments, analyzing and interpreting data by this point in the course, the design component was new for them. The formalized assessment matrix with definitions for Excellent, Very Good, Adequate, and Poor performance is outlined in Table 3. An attempt was made also to choose assessment questions that spanned the breadth of Bloom's taxonomy from lower level skills (comprehension) to higher level skills (synthesis/evaluation) [3].

Table 3 Formalized assessment matrix for ABET Outcome B.

		Design: Formulates the control and evaluating alternatives of the experiment	**Conduct:** Facilitates use of modern data collection techniques (computer for data logging)	**Analyze Data:** Selects and uses appropriate, self-explanatory graph formats for data	**Interprets Data:** Interprets results with regard to how they relate to the theoretical state of nature or system
Excel-lent	4	*Chooses control and variables to examine each aspect of experiment (intensity, duration, watershed properties) independently*	*Understands and documents method for obtaining data with computer and explains how the data collected relates to the desired quantity (streamflow)*	*Produces a concise number of graphs which illustrate the effects of modifying independent variables experimentally*	*Substantial discussion of how results illustrate principles of hydrograph analysis including superposition, precip delay, and unchanging properties. Judgement about how well experimental results support theory & why*
Very good	3	*Chooses control and variables to examine 3 of 4 experiment aspects (intensity, duration, watershed properties) independently*	*Understands and documents method for obtaining data with computer*	*Produces graphs which illustrate the effects of modifying some independent variables experimentally*	*Brief discussion of how results illustrate the principles of hydrograph analysis superposition, precip delay, and unchanging properties.*
Ade-quate	2	*Demonstrates clear knowledge of a need to design experiment to examine effects of variables*	*Uses computer generated data to get to desired quantity (streamflow)*	*Uses graphs that show all experimental results with correct labels, titles, axes, etc.*	*Some discussion of how results illustrate the principles of hydrograph analysis including one or more of: superposition, precip delay, and unchanging properties.*
Poor	1	*Demonstrates no knowledge of the reasons for choosing experimental variables appropriately to examine effects*	*Serious mistakes made in analysis of computer generated data*	*Mistakes made in graph text or incorrect data plotted*	*Missing discussion of how results support theory of hydrograph analysis*

Results

The results of implementing this ABET assessment in the first two semesters of Hydraulics and Hydrology yielded concrete data on the performance of students in the area of experimental design, but also brought out some general lessons for assessing a skill that is not practiced repeatedly in a course. One lesson learned is that the expectation of documenting the design process to students must be stressed and required as a component of the lab report. During the first year of the course, in an effort to separate the ABET assessment from the course grade assessment, the importance of documenting the design process in the lab report was not emphasized enough to students. As a result, little discussion of the design component of the experiment was included in the lab report. For the second semester, a discussion of experimental design was required in the lab material and this resulted in a much better response in students' lab report discussion.

Another productive portion of the lab exercise which was improved upon during the second year was the iterative process of designing experiments. Following the initial classroom design that students participated in with their small groups, designs were shared with partner groups immediately prior to starting the experiment during the lab meeting time. Students were able to hear how other groups had thought about the design and then choose between several alternative designs before proceeding. This gave students from groups who had struggled with the design process peer-level feedback and helped them to see the benefits of the designs proposed by other groups. For students who had already come up with a good experimental design, this process gave them an opportunity to practice communicating the reasons for their design and an exposure to some alternative perspectives.

The results of the ABET assessment according to the rubric outlined in Table 3 are included below in Table 4. Overall, scores increased during the second year of implementation, likely due to a clearer presentation of expectations to students.

Table 4 Results from ABET assessment for experimental design in first two semesters of Hydraulics & Hydrology.

	Fall 2010	Spring 2011
Design…	3.1	3.5
Conduct…	3.5	3.6
Analyze…	3.3	3.6
Interpret…	2.9	3.4

Conclusions

Although some small modifications to the assessment methodology may be necessary for the 2011-2012 school year, the foundation for successful assessment is largely in place. The primary lesson learned during the design and implementation of an ABET assessment methodology for experimental design (Outcome B) was that communicating clear expectations to students in preparation of asking them to demonstrate a skill that is not typically assessed in a class is critical to success. Additionally, a group design exercise followed by individual descriptions of the design process appeared to work successfully for assessing individual capacities for experimental design. The UMD Department of Civil Engineering will rigorously document assessment methods and data will be collected in more than 12 courses during the 2011-2012 school year in support of program assessment in the fall of 2012. The process outlined herein will be directly used in this effort, will be useful in communicating expectations to future instructors for the course, and could also provide a guide to other instructors needing to implement an assessment of experimental design in another course.

Bibliography

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