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DEVELOPING A FIELD COMPONENT IN HYDROLOGIC EDUCATION[1]

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ABSTRACT: Recent assessments have emphasized the lack of a field and laboratory component in hydrologic education at the university level. Consequences of this lack include: (1) an unwarranted faith in published data; (2) lack of appreciation for the spatial and temporal variability of most hydrologic processes; (3) lack of appreciation for the difficulty of collecting good quality field data; (4) an inability to design and execute projects to collect field data; (5) a lack of field experience which can be applied when confronted with different problems or new environments; (6) an inability to evaluate published materials or models against "field reality;" (7) an excessive reliance on, and trust in, theoretical or conceptual models; and (8) reduced potential for lifelong learning through observation and analysis. Field courses need not be costly or difficult, but the instructor must be willing to adapt to the uncertainty and problems associated with field measurements. A recently updated course on watershed measurements at Colorado State University illustrates the type of field courses which can be developed if there is the necessary commitment and flexibility. The lack of a current text can be overcome by assembling selected portions of existing government documents, and a sample bibliography is included.
(KEY TERMS: water resources education; hydrology; field measurements; data collection.)

INTRODUCTION

Hydrology is defined as "the science dealing with the waters of the earth, their distribution on the surface and underground, and the cycle involving evaporation, precipitation, flow to the seas, etc." (Guralnik, 1972). Clearly, hydrology is a natural science, yet a recent International Association of Hydrological Sciences (IAHS)/UNESCO panel concluded that hydrology has been slow to develop as a science, and that most of the problems recognized over the last 40 years are still unresolved (Nash *et al.*, 1990). This panel also suggested that the lack of progress stems largely from an overemphasis on empirical problem-solving rather than addressing hydrologic problems through the identification and application of the natural sciences (Nash *et al.*, 1990).

In 1988, the National Research Council (NRC) convened a committee to guide science and educational policy decisions in hydrology. The resulting book, *Opportunities in the Hydrologic Sciences,* argues for and suggests means for building a stronger identity and unity in hydrologic science (NRC, 1991). Eagleson (1991) suggests that the current state of hydrology is analogous to the situation chemical engineering would be in without the underlying science of chemistry. He argues that the practice of hydrology is based largely on oversimplified hydrologic models, and this impedes scientific understanding as well as sound water resources management.

Both the IAHS/UNESCO panel and the NRC committee emphasized the crucial role of education in furthering the science – and ultimately the practice – of hydrology. The IAHS/UNESCO panel recommended that a conscious effort should be made to introduce experimental and field observational material into professional courses in hydrology, and that hydrologic education should stress the central roles of observation and experimentation (Nash *et al.*, 1990). The NRC report devotes a full chapter to hydrologic education, and they highlight the statement that a serious educational problem is **"the lack of field and laboratory experience at the undergraduate level, a situation that has reached crisis proportions"** (NRC, 1991, p. 287).

A recent survey of hydrology courses at colleges and universities in the U.S. and Canada strongly confirmed that field- and lab-based education in hydrology is being neglected. Of 73 undergraduate hydrology courses in civil engineering, only two incorporated an experimental or field component (Groves and Moody,

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1992). In contrast, three-fourths of the instructors required some computer-based work.

A second survey reviewed the number and type of hydrology courses in natural resources programs (Brooks, 1993). Responses from 18 programs listed 74 courses in hydrology. Only eight courses from seven different programs focused on field measurements, laboratory techniques, or instrumentation. In several courses, field trips were used to provide greater "reality" and perhaps make up for the lack of a full-fledged field course (Brooks, 1993).

The inescapable conclusion is that most people with some formal training in hydrology are computer literate, but receive little or no training in field methods. This situation is particularly true in engineering hydrology, which is still the academic base for the majority of those who specialize in hydrology.

The purposes of this paper are to: (1) examine the short- and long-term implications of this deficiency, (2) identify the real and perceived barriers to developing field-based courses, (3) suggest means to overcome these barriers, and (4) provide an overview of a newly-revised undergraduate course in watershed measurements within the Watershed Science Program at Colorado State University. This overview is provided for illustrative purposes, and the modular nature of this course should facilitate its adaptation to other curricula.

RATIONALE FOR FIELD COURSES IN HYDROLOGIC EDUCATION

The relative absence of field and laboratory courses in hydrology has a number of short- and long-term implications, and these are discussed below.

An Unwarranted Faith in Published Data

Students and practicing hydrologists usually presume that published field data are both accurate and precise. Data are treated as absolute values, particularly for modeling purposes, yet the literature indicates that there is considerable uncertainty associated with nearly all hydrologic data. Precipitation measurements are particularly prone to uncertainty and systematic errors (see Sevruk, 1989), but these problems are rarely emphasized in university courses or hydrologic practice. We seem unwilling to admit that the data for something as basic as precipitation are accurate to only within 10, 30, or 50 percent, depending upon the type of precipitation, the wind conditions associated with that precipitation, and the means of measurement (e.g., Larson and Peck, 1974; Sevruk, 1989).

The use of historic data poses additional problems. We regularly rely on long-term temperature and precipitation records, yet a stringent quality assurance and quality control program has been in place at the U.S. National Climate Center only since 1983 (N. Guttman, National Climate Center, pers. comm., 1992). While the quality of data prior to 1983 generally is very good, the lack of quality control documentation means that it is not certain which data are good and which data are suspect. In discussing the use of secondary data sources, Guttman (1991) states that it is never safe to accept data at their face value, and he suggests steps that both data compilers and data users should take to ensure an appropriate level of scientific integrity.

My experience is that students need direct personal experience with field measurements in order to appreciate the uncertainty of published data. In the watershed measurements course at Colorado State University, students measure flows of approximately 40-70 cfs (1.2-2.0 cms), and they usually report their discharge data to the nearest 0.1 or 0.01 cfs. If one demonstrates that 0.1 ft^3 is about three-quarters of a gallon milk jug and 0.01 ft^3 doesn't quite fill a 12-oz container (a size familiar to most students), they quickly appreciate that their measurement accuracy probably doesn't extend to 0.1 or 0.01 cfs. It is then easier for students to accept that the accuracy of discharge measurements using conventional current meter techniques is probably no better than ±6 percent (WMO, 1980), and that it may not be appropriate to calibrate a rainfall-runoff model to the last few percent.

Students are often disturbed by the revelation that we can't measure or determine the "true" value of such key hydrologic variables as discharge, temperature, and precipitation. Students must appreciate the uncertainties associated with published hydrologic data in order to properly utilize secondary data sources and practice "real-world" hydrology. As water resource professionals, we must recognize and convey the uncertainty associated with hydrologic data to students and our junior colleges.

Lack of Appreciation for the Spatial and Temporal Variability of Most Hydrologic Processes

One of the remarkable attributes of hydrology is the tremendous range in basic properties, such as hydraulic conductivity, over time and space (Eagleson, 1991). Typically, hydraulic conductivity is reported to two or even three significant figures, yet it varies by

more than 12 orders of magnitude in commonly-encountered materials and exhibits tremendous variability in space and over different spatial scales (e.g., Dooge, 1989).

Basinwide precipitation estimates are usually written to the nearest millimeter or hundredth of an inch, and temperatures are given to the nearest degree or even 0.1 degree. Yet nearly every detailed field study in the published literature documents a tremendous spatial and temporal variability in the basic physical processes such as infiltration, precipitation, and snowmelt (e.g., Loague and Gander, 1990). Extrapolating from a standard U.S. rain gage to a one square kilometer basin requires us to multiply our precipitation estimate by a factor of 30,836,332. Can we justify reporting the precipitation over that catchment to one one-hundredth of an inch, and assuming a similar level of precision in our hydrologic models?

The problem is even more acute when we consider that the average density of precipitation gages in the continental U.S. is much less than one gage for every square kilometer. The average density in Colorado, for example, is one gage for every 260 km^2, and the operational requirement for the National Weather Service is one weather station for every 1620 km^2 (N. Doesken, Colorado State Univ., pers. comm., 1993). Given the variability in topography and precipitation from convective storms in Colorado, can we reliably multiple point precipitation by approximately eight billion and then report that value to three or four significant figures?

Lack of Appreciation for the Difficulty of Collecting Good Quality Field Data

Practicing hydrologists, researchers, and administrators must regularly decide how to allocate funds and time when conducting a hydrologic investigation. To do this effectively, it is necessary to have some idea of the relative cost and accuracy of the data which might be collected. Is it better to install another rain gage or to measure hydraulic conductivity? Will a one-hour infiltration measurement on a dry soil using a double-ring infiltrometer accurately represent the property of interest? Should measurements be made on the valley bottom or high on the sideslopes? Such decisions are remarkably complex, and can only be made effectively if an understanding of hydrologic processes is combined with a knowledge of, and experience with, hydrologic measurements.

An Inability to Design and Execute Projects to Collect Field Data

As hydrologists, we often have to collect field data or supervise the collection of field data. If we don't have any experience with or understanding of field measurements, what are the implications of this deficiency with regard to the quality of the data we collect and the resulting accuracy of our investigation? One course cannot provide a complete guide to field data collection, but a field-based course can provide a basic foundation for designing and executing projects to collect field data.

A Lack of Field Experience Which Can be Applied When Confronted With Different Problems or New Environments

One of the most commonly-used tools in the hydrologist's arsenal is best professional judgment. Ultimately, professional judgment is a combination of experience and basic scientific understanding, and a key element is the ability to evaluate the relative importance of different processes in a variety of field situations. Although this is one of the most difficult things to teach, it also is one of the most essential. Both the IAHS/UNESCO survey and the NRC report conclude that we currently are doing a very poor job of teaching hydrologic science and professional judgment (Nash *et al.*, 1990; NRC, 1991). Directed field experience is essential for developing good professional judgment.

An Inability to Evaluate Published Materials or Models Against "Field Reality"

As noted previously, hydrology is heavily dependent on oversimplified models. There is an evergrowing suite of models to choose from, with each model having a different conceptual base and underlying set of assumptions. When using a model, it is essential to understand: (1) the explicit and implicit assumptions of that model, (2) the extent to which the model oversimplifies the system being modeled, and (3) the accuracy of the representation of key processes. Many of our rainfall-runoff models, for example, presume that Horton (infiltration-excess) overland flow is the dominant means for generating runoff, yet Horton overland flow is virtually nonexistent in most forested areas, and Dunne (1978) concludes that overland flow is rare in most humid landscapes. Similarly, the Universal Soil Loss Equation is prone to misuse by

applying it to crops, soils, and geographic areas outside of the original data base without an understanding of the applicability of the different factors (Wischmeier, 1976). To maintain our professional integrity, we must attempt to teach our students how to assess the applicability of models and not just the mechanics of model utilization.

An Excessive Reliance On, and Trust In, Theoretical or Conceptual Models

Students generally accept the basic hydrologic models as true and valid unless we teach them otherwise. In many cases, we don't provide the data and understanding necessary for a clearer evaluation of such basic tools as unit hydrographs, SCS curve numbers, or infiltration rates. A simple example is to compare the time base of the infiltration curves presented in two widely used hydrology texts – Viessman *et al.* (1977, Figure 3-11a) and Linsley *et al.* (1982, Figure 8-1). The former indicates that a typical infiltration curve nears an asymptotic value after less than 30 minutes, while the latter suggests that the infiltration rate doesn't begin to approach an asymptotic value until after 12 hours. These two curves have very different implications with regard to the cost of acquiring real data and the accuracy of short-term measurements, and it is disturbing that the simple choice of a textbook can greatly affect students' conceptual model of such a key process. Occasionally, my in-class measurements of infiltration don't coincide with these idealized curves and accompanying mathematical model, and some might argue that this divergence is more the norm than the exception.

We generally seem unwilling to reveal our nakedness as hydrologists by pointing out these types of departures from standard models. Given this attitude, is it any wonder why the science of hydrology lags so far behind the practice?

Reduced Potential for Lifelong Learning Through Observation and Analysis

The accelerating increase in knowledge means that the half-life of our formal education is becoming shorter. If our students are not to become obsolete within a few years, we must provide them with the means to continually update their skills and knowledge. This suggests that we should emphasize the scientific base of hydrology and the scientific method rather than teaching current tools and models, or – worse yet – the tools and models handed down when we were students. Isn't the application and use of the scientific method the best way to teach those skills which will prove useful over the long term? Our choice of subject matter will profoundly affect the ability of the students to continue learning, and this capability will help determine the rate of advances in hydrologic science as well as the practice of hydrology.

The 1991 NRC report summarized the implications of a lack of field and laboratory experience with the following statement:

> "The consequences of this [lack of field and laboratory experience] are both profound and disturbing. Students have become separated from the realities of the physical world they seek to master, studying only conceptual models in which the rich complexity of nature is replaced necessarily by the convenience of ad hoc simplification. In the absence of experimental validation, these models tend to take an aura of reality in the minds of the users, which may lead to scientific error and stagnation" (NRC, 1991, p. 287).

It should not be regarded as heresy to suggest that "field literacy" in hydrology is of equal importance to computer literacy. The process of determining what, where, and when to measure exemplifies the scientific process in terms of identifying a hypothesis, establishing an experimental design, and then testing the hypothesis. The process of collecting data forces students – and in this sense we all are students – to recognize the spatial and temporal variability characteristic of hydrologic processes, and to appreciate the uncertainty and arbitrariness associated with single observations. The analysis and interpretation of the collected data represents the final, and arguably, most important step in the scientific method, but it also is the most difficult step to teach and the one which we most commonly neglect. Courses which require students to collect and analyze data provide the best vehicle for teaching these critical concepts.

Using the scientific method as the framework for collecting and analyzing data also helps develop observational skills and a field awareness of hydrologic processes. These skills then make the students more aware of the contrast between the complexity of the real world and the simplified models and techniques used in hydrologic practice.

Of particular concern is the long-term implication of omitting a field-based component in hydrologic education. If we consider that today's undergraduates are tomorrow's teachers and practitioners, will they be prepared to teach and practice in ways that are realistic and insightful? Will they have the knowledge and experience to advance this combination of art, craft,

and science that we call hydrology? Or will we be caught in a downward spiral of more models and less data? The NRC report notes that the lack of field-based courses appears to be self-perpetuating (NRC, 1991), and this is one of the most serious implications of the current lack of field-based courses.

In a recent address to the 300-plus hydrologists in the U.S. Forest Service, Dr. Luna Leopold noted that systematic field observations are probably the single most important means by which hydrologists can advance their knowledge and capabilities. Most organizations have limited resources for training and it therefore is incumbent upon the individual to train themselves through a self-imposed regimen of observation and analysis. It is our responsibility as professional educators and hydrologists to ensure that the next generation is adequately prepared both for the tasks which lay before them and the life-long learning necessary for further progress.

BARRIERS AND REMEDIES TO DEVELOPING FIELD COURSES

There are a variety of reasons why people may be reluctant to initiate field courses. First, field courses are presumed to require expensive equipment. Second, the field is unpredictable, and many teachers are hesitant to enter into situations where they have less control than in the classroom. Third, many teachers are unwilling to enter into field situations in which they may appear less than omniscient or omnipotent. Fourth, many teachers do not have much field experience, and there is a natural hesitation to teach in areas where one has little knowledge or experience. Finally, there is no standard text for field measurements in hydrology. In the following paragraphs each of these perceived barriers is discussed, and ways to overcome these perceived barriers are suggested.

Cost

Field courses do not necessarily require expensive equipment. Critical meteorologic data such as precipitation and temperature can be measured very inexpensively. Plastic wedge-shaped rain gages can be bought for around $6 each, or students can simply use empty cans or wide-mouthed bottles. As long as the devices and measurement procedures are similar, the data can be compared and quantitatively analyzed. Discharge measurements can be made with nothing more than a string, two stakes, a line level, a tape measure, and an orange to be used as a float; the total cost of these items can be less than $20. Infiltrometers can be made from sheet metal, and determination of soil water content requires only a weighing scale and an oven.

The critical lessons to be learned in field courses are not dependent on expensive equipment, but involve the process of defining a project, collecting the data, and analyzing the data in a manner appropriate to the question being addressed. Exactly the same principles apply whether one measures precipitation with a tipping bucket rain gage and a data logger or with an old tuna can. Changes in technology mean that instruction in specific techniques will soon be superceded, whereas the processes being measured and the principles of developing and executing a field-based project should remain relatively constant. If a particular piece of equipment is essential, in many cases it can be borrowed on an informal basis from a public agency or a private company. At Colorado State University (CSU), we have successfully solicited donations of prototype or discontinued equipment from companies which specialize in field instrumentation.

Loss of Control

By definition, the field is much less predictable, and taking classes into the field requires the teacher to be comfortable in situations with less control than in the classroom. If the infiltration curve doesn't follow the conceptual model described in every hydrology text, you either have to provide a valid explanation or directly confront the limitations of the conceptual model being taught. One shouldn't expect that field or laboratory data will always fit a particular construct or model, and the limitations of our conceptual models is an essential lesson for students.

Unwillingness to Be Less Than Omniscient or Omnipotent

It's inevitable that, once you are in the field, questions will be raised, equipment will break, and other applications of Murphy's Law will manifest themselves. One shouldn't expect to handle every question and eventuality with perfect aplomb. Over time one will have encountered more of these situations and be better prepared to make adjustments. Again, it is important for the students to experience the uncertainties and problems associated with field-based data collection programs. Too often students have been led to expect a simple world, one in which experiments are always straightforward and go according

to plan. In reality, hydrology is a dynamic collection of interacting, nonlinear processes. Usually, there is not a "best" procedure or a true value, and it is essential that students recognize the limitations of our ability to define and measure everything relevant to a particular problem.

Lack of Expertise

Often there is a hesitation to teach a field- or lab-based course because one does not have much knowledge or experience with collecting real data. While this does pose an initial barrier, the reality is that it doesn't take decades of experience to teach the basics of measuring key hydrologic processes such as discharge, temperature, and precipitation. For most measurements, there are excellent guides available from the U.S. Geological Survey and other agencies (Appendix 1). By making a few measurements under varying conditions, one can accumulate sufficient experience to take students in the field and teach at least the basics of field observations and measurements. One's awareness is also heightened by knowing that one will be teaching a particular technique or procedure, and this helps provide more knowledge and experience which then feeds back into the teaching of that material.

This sequence of learning suggests that the primary problem is how to effectively teach in the field in the first couple of years when knowledge, experience, and equipment all may be in short supply. One of the best methods to overcome this problem is to draw upon existing local expertise. Very few communities lie outside the reach of hydrologists within the U.S. Forest Service, U.S. Geological Survey, or Soil Conservation Service, and most counties or local governments have some hydrologic expertise. Typically, you can identify a professional hydrologist who is willing to volunteer a few hours to teach a particular topic or assist with a field exercise (this provides them with an opportunity to discuss their work and proselytize hydrology as a career). Even if you can't identify a local professional to assist you, you can always test the techniques yourself, call a local agency to resolve any questions, and then take your class into the field. Again, a lifetime of experience is not required to give the students some field knowledge and experience, and it is this initial barrier that must be broken.

Lack of a Proven Text

At present, there is no comprehensive, up-to-date text on field techniques in hydrology. However, there are excellent guides to selected field measurements from the U.S. Geological Survey, American Society of Agronomy, Soil Conservation Service, and other organizations. At CSU, we have assembled some of these materials into a course reader, and the contents of this reader are listed in Appendix 1. Since the current version of the reader exceeds 400 pages, it probably should be considered as more of a reference book than a true reader. For copyright reasons, this reader contains only materials published by the government or scientific organizations, although specific articles or books may be referenced in the reader and placed on reserve at the library.

With this reference material, students can study the most common hydrologic measurements. Some guidance is also available for some of the more qualitative procedures, such as watershed analysis (e.g., Washington Forest Practice Board, 1992) or the identification of runoff processes (e.g., Dunne, 1978). Concerns over the time required to assemble such a reader can be largely alleviated by copying the appropriate sections of the reader as referenced in Appendix 1.

AN EXAMPLE OF WATERSHED MEASUREMENTS COURSE

The Watershed Science Program at CSU is in the College of Natural Resources, and it offers B.S., M.S., and Ph.D. degrees. All undergraduate majors in Watershed Science are required to take a semester-long, two-credit course in Watershed Measurements. Normally, this course is taken in the first semester of the junior year, but many incoming graduate students also take the course because they have a limited background in hydrology or field methods. The stated purpose of the course is to cover the procedures for collecting a variety of field data, but the underlying objectives – i.e., those which stem from the concerns discussed previously in *Rationale for Field Courses in Hydrologic Education* – are probably of greater importance.

Students in the Watershed Measurements course are required to concurrently enroll in a 3-unit lecture course on land use hydrology. This latter course is required because we believe that students must understand the theory and rationale behind the measurements. The 13 units which comprise the CSU course in Watershed Measurements are listed in

Table 1 and described below. An outline of the Watershed Measurements course is presented in Appendix 2.

The Watershed Measurements course is taught during one three-hour lab period each week. Topics range from stream classification and channel measurements to experimental design, soil hydrologic properties, and snow measurements (Table 1). The course is structured around two major exercises (meteorologic data collection and stream channel measurements) and a series of smaller exercises and field trips (Table 1; Appendix 2). There also is a one-day field trip to a nearby stream where the students make a variety of in-channel measurements (see *Stream Measurements* below). Grouping the in-channel measurements into a single field trip greatly reduces travel time and enables the students to collect a variety of data which must then be synthesized into a cohesive story.

TABLE 1. Units in the Colorado State University Course on Watershed Measurements.

1. Meteorologic measurements (temperature, precipitation, relative humidity).
2. Stream classification; habitat types.
3. Basic surveying.
4. Stream channel measurements (cross-sections, discharge, thalweg profile, bed material particle size, Manning's n, Pfankuch (1978) channel stability rating).
5. Other types of discharge measurements (flumes, weirs, dilution techniques).
6. Topographic maps (watershed delineation, watershed area, hypsometric curves, areal precipitation, drainage density, use of a digitizer).
7. Soil moisture measurements (gravimetric, resistance blocks, thermocouple hsychrometer, neutron probe, tensiometers, time-domain reflectometry).
8. Infiltration and hydraulic conductivity.
9. Statistical design and paired watersheds.
10. Sediment sampling (bedload and suspended load); sediment rating curves.
11. Snow measurements and runoff forecasting.
12. Framework and procedures for watershed analysis.
13. Electronic data acquisition.

The course could easily be expanded to three or more credits by assigning portions of the text as required reading, increasing the number of assignments, or adding an independent field project. The following paragraphs provide a brief overview of the course as currently taught. Adjustments in the topics and assignments can easily be made to adapt the course to local conditions, student interests, and program needs.

Meteorologic Measurements

In this unit, the students are introduced to the basics of measuring precipitation, temperature, and humidity. Each student is responsible for a traditional weather station for approximately five days, and this station includes a hygrothermograph, maximum and minimum thermometers, recording rain gage, and a sling psychrometer. The collected data are then compared to data from the official Fort Collins weather station and the historic data available on CD-ROM in the CSU library. Students are also loaned wedge-type rain gages for the semester with the intent of assessing the spatial variability of rainstorms during the semester. The latter effort proved unsuccessful in fall 192, as there was only one rain event larger than 0.01 inches during September and October. In November and December, all precipitation fell as snow, and wedge-type rain gages can't be used for measuring snowfall because they are so easily capped.

Stream and Habitat Classification; Surveying

This class period introduces the topic of stream and habitat classification, and then presents the basic principles of surveying. Pairs of students must complete a simple surveying exercise on the CSU campus.

Stream Measurements

This unit requires two class periods and an all-day field trip. The first class period is devoted to the procedures which will be used in the field to survey a channel cross-section, measure discharge, conduct a Wolman pebble count (Wolman, 1954), estimate Manning's n, classify the stream according to both Rosgen (1985) and Montgomery and Buffington (1993), evaluate channel stability (Pfankuch, 1978), and make a sketch map. The class then spends a full day in the field making these measurements in a reach. Typically, the class is divided into teams of two or three, with each team setting up a cross-section within a designated 40-m reach. During this field session, the instructor and the teaching assistant survey a thalweg profile through the entire reach (approximately 200-300 m).

Each team tabulates and plots their cross-section, discharge, and pebble count data. These data are collected, photocopied, and distributed at the next class session. At this session, the results of each group are compared, and we discuss the precision and accuracy of the data. I also have the students visually estimate the discharge when they first arrive at the field site,

and I give a small prize to the student whose estimate was closest to the class mean. A homework assignment requires the students to assemble and evaluate the collected data, and then use these data to qualitatively evaluate stream channel condition and the effects of human impacts. Copies of an EPA book on monitoring the effects of forestry on streams (MacDonald *et al.*, 1991) are handed out to the students as background information.

Field Trip to the Fort Collins Weather Station

This unit begins with a lecture on the networks of weather stations in the U.S. and the overall trends of station automation and instrumentation. The class then spends two hours at the official Fort Collins weather station. Observing protocols, instrument comparisons, and the problems of obtaining consistent, high-quality data over long time periods are discussed while reviewing the various instruments.

Field Trip to Engineering Research Center (ERC)

The ERC is the facility on the CSU campus used for physical models. It includes a variety of flumes, wind tunnels, rainfall-erosion simulators, and other scale models. The purpose of this unit is to expose students to the concept of physical models. My experience is that most students are aware of computer models and field studies, but aren't familiar with the intermediate approach of physical models. Seeing the various facilities then raises questions of scale, model verification, and the limitations of field studies in terms of controlling and manipulating key variables.

Soil Moisture

This is a laboratory session which demonstrates and compares the various methods to measure soil moisture content, matric potential, and soil moisture release curves. Tensiometers and soil moisture resistance blocks are installed in two freely-draining buckets, one containing a relatively coarse sand and one containing a local clay loam. Each soil is saturated and the change in matric potential and water content is monitored. The students generally are surprised when the center of the coarse sand dries out much more slowly than the clay loam.

Infiltration and Hydraulic Conductivity

This unit consists of a brief presentation on how soil physics affects measurements of infiltration and hydraulic conductivity. Infiltration is measured with a traditional double-ring infiltrometer and subsurface hydraulic conductivity with a Guelph permeameter (Soilmoisture Equipment, Goleta, California). The data provide the basis for a short homework involving moving averages, data aggregation, and the physical concepts behind measurements of infiltration and hydraulic conductivity.

Topographic Maps, Hypsometric Curves, Areal Precipitation, Drainage Intensity, and Use of a Digitizer

In this unit, students are required to delineate a mountainous catchment (St. Louis Creek on the Fraser Experimental Forest, Fraser, Colorado) and produce a hypsometric curve using a digitizing tablet. Monthly and annual precipitation data from five gages in and around this catchment are used to develop regression equations to predict precipitation from elevation for a winter month, a summer month, and the annual total. Average precipitation over the basin is determined by combining the hypsometric curve with the elevation-precipitation equations. Morphometric measurements of drainage basins also are discussed, and each student is required to measure drainage density on a specified sub-catchment.

Field Trip to Pawnee Grasslands

The Pawnee Grasslands contain a National Science Foundation Long-Term Ecological Research site, as well as a series of runoff plots and a weather station established by the USDA Agricultural Research Service. These study sites provide a case study of field research and the accompanying procedures to measure climate, soil moisture, discharge, etc. Of particular interest is the near absence of surface runoff and the spatial variability of soil depth, soil moisture, and bulk density within individual runoff plots.

Statistical Design and Paired Watersheds

This unit discusses the need for replication if statistical inferences are to be made, and the difficulties in replicating experiments in watershed science. The statistical trade-offs among sample size, variability,

level of significance, and power also are presented. The students are given a short homework on the analysis of runoff from a paired-watershed experiment (Troendle and King, 1985).

Sediment Sampling

This unit focuses on the procedures for measuring suspended sediment and bedload, and how to extrapolate from individual measurements to the total sediment load. Since streamflow in Colorado is at a minimum in autumn, little or no sediment is being transported and field measurements are not attempted.

Snow Measurements and Runoff Forecasting

This lab demonstrates the use of a Federal snow sampler and describes the SCS snow survey and SNOTEL networks. The use of precipitation and snow survey data for runoff forecasting is described, and runoff prediction equations for a local snowmelt-dominated river (Cache la Poudre) are distributed to the students. Monthly updates in predicted runoff illustrate the changing uncertainty associated with runoff forecasts.

Watershed Analysis

This lab is still in an active stage of development, but the intent is to provide a conceptual framework and procedure for analyzing a watershed. I suggest the first step is to identify the relative importance of the different hydrologic and erosion processes. The next step is to ascertain the extent of existing data, and only then should one proceed with designing a field experiment and collecting original data. Issues of data quality are addressed, and I emphasize the need to clearly specify the objectives and establish data collection protocols to ensure that the data will have the desired reliability and meet the objectives. Since one can't measure everything everywhere, an explicit, conscious process is needed to determine the what, where, and how of data collection. The state of Washington has recently adopted a procedure for conducting watershed analyses, and their manual illustrates how one can analyze the effects of forest management on the catchment scale (Washington Forest Practice Board, 1992).

Electronic Data Collection

Electronic data collection is rapidly supplanting traditional chart recordings and manual measurements. To be current, students should have a basic familiarity with data loggers and downloading data. The recent donation of a prototype data logger and sensor by Stevens Water Monitoring Systems will allow us to add a unit on electronic data acquisition.

We expect that each student will be responsible for programming the data logger and downloading data while operating the weather station described in *Meteorologic Measurements*. Electronically-collected data will be compared to the data obtained with the traditional weather station. Again, the type of data is not as important as the hands-on experience and basic concepts of programming a data logger, collecting the data, and then downloading the data through a portable PC or other interface device.

CONCLUSIONS

There is a serious deficiency of field-based courses in hydrologic education. This is a self-perpetuating situation and has adverse consequences for the future development of hydrologic science, the competence of newly-graduated professionals, and the quality of hydrologic practice.

Field-based courses can be developed at minimal cost. Even if one does not initially have the necessary expertise, one often can draw on hydrologists within public or private organizations. The development of a field-based hydrology course requires only commitment, enthusiasm, and a willingness to learn and adapt.

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Appendix 1
CONTENTS OF THE COURSE READER FOR WATERSHED MEASUREMENTS (ER 417) FOR 1993

1. Meteorology

Brakensiek, D. L. *et al.* (Editors), 1979. Field Manual for Research in Agricultural Hydrology. Agriculture Handbook 224, U.S. Department of Agriculture, Washington, D.C., pp. 3-15, 23-31, 217-226 (out of print).

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3. Channel Measurements

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5. Soil Moisture

Hillel, D., 1980. Fundamentals of Soil Physics. Academic Press, New York, New York, pp. 156-162 (book on reserve).

Cassel, D. K. and A. Klute, 1986. Water Potential: Tensiometry. *In:* Methods of Soil Analysis: Part 1, A. Klute (Editor). American Society of Agron., Madison, Wisconsin, pp. 563-571.

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Campbell, G. S. and G. W. Gee, 1986. Water Potential with Electrical Resistance Sensors. *In:* Methods of Soil Analysis, Part 1, A. Klute (Editor). American Society of Agron., Madison, Wisconsin, pp. 620-625.

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7. Statistics and Paired Watersheds

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Edwards, T. K. and G. D. Glysson, 1988. Field Methods for Measurement of Fluvial Sediment. U.S. Geological Survey Open-File Report 86-531, Washington, D.C., 118 pp.

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10. Watershed Analysis

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Appendix 2
OUTLINE OF THE WATERSHED MEASUREMENTS COURSE AT COLORADO STATE UNIVERSITY (ER 417)

Objectives: The purpose of this course is to provide both a theoretical and practical knowledge of the most common types of measurements related to land use hydrology and watershed management. The course also will provide some training in collecting, analyzing, and presenting data in written reports. The methods used to achieve these objectives will include lectures, outside reading, directed field exercises, lab and homework assignments, field trips, and a take-home final exam.

Grading:

Major Lab Reports	
Meteorologic Measurements	20%
Stream Measurements	20%
Lab Exercises (4)	30%
Participation	5%
Take-Home Final	25%
Total	**100%**

Course Content and Schedule (1992):

Aug. 28 Course introduction; meteorologic measurements

Sept. 4 Stream classification; habitat types; basic surveying

Sept. 11 Stream channel measurements (cross-sections, discharge, thalweg profile, bed material particle size, Manning's n, channel stability rating)

Sept. 14 Field trip to Little South Fork of the Poudre River (approx. 8:00-5:00)

Sept. 18 Distribute data from field trip; other types of discharge measurements

Sept. 25 Weather stations; visit to CSU weather station

Oct. 2 Topo maps (hypsometric curves, areal precipitation, drainage density, digitizer)

Oct. 9 Soil moisture

Oct. 16 Infiltration and hydraulic conductivity

Oct. 23	Field trip to Pawnee grasslands
Oct. 30	Statistical design and paired watersheds
Nov. 6	Sediment sampling
Nov. 13	Field trip to Engineering Research Center
Nov. 20	Snow measurements and runoff forecasting
Nov. 27	Thanksgiving break
Dec. 4	Framework and procedures for watershed analysis