Rainfall Simulators and USDA Erosion Research: History, Perspective, and Future

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Abstract

Erosion problems have perplexed mankind throughout recorded history. Activities which generally accelerate erosion above that known as geologic erosion have been responsible for migrations of major cultures from one area to another. This accelerated erosion has been of major concern to conservationists in the 20th Century as intensive farming has depleted the soil resource.

The earliest quantitative erosion research measurements made in the U.S. were begun by Sampson and associates in 1912 on overgrazed rangelands in Central Utah. Unfortunately, after these efforts, erosion measurements and research to control erosion on rangelands languished until the latter part of the 1970's. Thus, current technology for controlling erosion on rangelands was developed primarily for cultivated croplands and transferred, with minimal validation, to rangelands.

Rainfall simulators have played, and continue to play, an important role in erosion research because they facilitate controlled experiments at known antecedent conditions which permit orderly evaluation of one or more factors known to affect erosion processes. The advantages and disadvantages of some of the more commonly used simulators used by the Agricultural Research Service are discussed.

Introduction

History records many solutions to erosion problems that are no longer viable alternatives to most societies on planet earth. The alternative generally involved abandoning the "worn out land," then moving to "new land." Such was the case in the early history of the U.S., where development of land in the new territories to the west of the original 13 colonies seemed inexhaustable. Clearing forest lands prior to plowing and plowing sod prairies were common practices in the U.S. throughout the 18th, 19th, and part of the 20th Century. As the limit of our "virgin" land resources was exploited, conservationists came to the realization that we must learn to use land use practices that preserve the productive capacity of the soil. Even our ability to replace nutrients lost with erosion by commercial fertilizers which became widely available in the middle of the 20th Century appears uneconomical as a long term solution to food production for the burgeoning world population. Thus, the science of erosion research developed within the last century as an attempt to maintain long-term production of our land.

As recently as a century ago, soil erosion research was almost nonexistent in the United States; yet today, U.S. scientists and engineers are world leaders on the subject (Meyer and Moldenhauer 1985). Whereas early erosion research focused on finding simple solutions to erosion problems, current research tends to be analytical and directed toward predicting the consequences of management alternatives. The early research, which was mildly successful, was short-sighted in the approach used, but did lead to the recognition that basic research would be necessary to provide a foundation for comprehensive solutions. Current emphasis includes a balance between fundamental process research, control technology, and prediction or assessment technology (ARS, 1983).

History of Erosion Research

Although his early work was often overlooked until the 1930's (Nelson 1958), the German scientist Ewald Wollny (1888) is generally credited as being a "pioneer in soil and water conservation research" (Baver 1938). His early work included the effects of soil and topographic properties on runoff and erosion , including factors such as slope steepness, aspect, plant cover, and soil type. The earliest quantitative erosion measurements in the U.S. were begun in 1912 on overgrazed rangeland in central Utah. Sampson and others showed how overgrazing on two 10-acre plots in the Manti National Park allowed erosion to reduce the soil's water-retaining ability and fertility (Sampson and Weyl 1918, Chapline 1929, Stewart and Forsling 1931). Unfortunately, such early work on rangelands was not continued, and the problems they studied are even more perplexing today with the advent of concerns for how erosion affects soil productivity. Much of the technology being used on rangelands in the 1980's evolved from research on croplands, with little validation for rangeland-specific conditions.

Miller and colleagues at the Missouri Agricultural Experiment Station are generally credited with the concept of erosion plot research such as is used today (Duley and Miller 1923, Miller 1926, Miller and Krusekopf 1932). These early plots, which were 90.75 feet long and 6.0 feet wide, are now a national historic monument on the University of Missouri campus in Columbia.

Hugh H. Bennett undoubtedly had more influence on soil conservation efforts in the U.S. than any single person, and his early work led to his recognition as the "father of soil conservation." His crusades concerning soil erosion as a national menace, along with his evangelistic zeal to start needed research, led to Congressional action in 1929 which established 10 experiment stations at Guthrie, OK; Temple, TX; Tyler, TX; Bethany, MO; Statesville, NC; Hays, KS; Pullman, WA; Clarinda, IA, LaCrosse, WI; and Zanesville, OH. Most of the plots installed at these locations were patterned after the earlier work of Miller, although the now familiar 72.6 foot long and 6.0 or 12.0 foot wide plot (0.01 or 0.02 acre) was used for ease in computing runoff and erosion on a per-unit-area basis. Other field experiments, and more locations, were added in the 1940's and 1950's to investigate a wider range of conditions. These additional locations also represented areas where cultivated cropping practices were involved (selected because they were perceived as having the dominant erosion problem) and rangelands were conspicuously absent.

Bennett served as the first Chief of the Soil Conservation Service, and during this time, the Agency achieved considerable stature because of his speaking eloquence, prolific writings, and the quality of scientists involved in the erosion work (for example: L.A. Jones, H.E. Middleton, J.F. Lutz, R.E. Horton, G.W. Musgrave, L.D. Baver, J.H. Neal, J.O. Laws, and W.D. Ellison, toname a few). These pre-World War II years were "relatively golden years for soil conservation research" (Nelson 1958). As Meyer (1982) stated:

> . . . the problem had been recognized, research procedures had been established, a spirit of pioneering and enthusiasm was found among the researchers, fundamental research was encouraged, the need for results was recognized nationally, and adequate funds were available for staff-

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ing and facilities. Yet, research techniques were relatively crude in many respects. Runoff and erosion for each entire storm were usually caught in large tanks for measurement, often with no indication of time-rate information. A common experimental design was followed, but treatments were seldom randomized or replicated. Conditions studied were very limited, and plot conditions were often quite different than natural farming conditions. Nevertheless, a large quantity of data was obtained, although the usefulness of any part of it beyond the local situation was quite limited. In Bennett's (1939) classic book "Soil Conservation," considerable data are presented, but there are no mathematical relationships concerning the effects of different factors on erosion, nor is there any discussion of erosion prediction techniques.

Early Erosion Equations

Most of the early erosion prediction equations began with regional analysis of the plot data from the experiment stations developed in the 1930's. Cook's (1936) noteworthy effort to identify the major variables involved in erosion was a predecessor for many efforts that followed. For example: Zingg (1940) reported on the effect of degree of slope and slope length; Smith (1941) added crop and supporting-practice factors; Browning et al. (1947) adopted Smith's equation to conditions in Iowa, added soil erodibility and management factors, and prepared extensive tables of factor values for many additional conditions. Following a workshop of SCS employees in Milwaukee, WI, Musgrave (1947) broadened the Corn Belt "slope practice equation" for farm planning, and added a rainfall factor to facilitate extending the relationship to wider geographic conditions. Meyer (1984) reported that "most details of the Musgrave equation, its use, and appropriate factor values were reported only in unpublished agency handbooks and mimeographed tables." Although subsequent work showed that some of the relationships used in Musgrave's equation were not adequate, it was widely used until recent years, primarily because of the ease of its use. Its widest use has been for estimating gross erosion from large, heterogeneous watersheds and for flood abatement programs.

Smith and Whitt (1948) presented a "rational" erosion estimating equation for the principal soils in Missouri that is very similar to the structure of the Universal Soil Loss Equation (USLE) as it is used today. While the work was specific for one location, they acknowledged the need for a rainfall factor to make the equation applicable over several states. Van Doren and Bartelli (1956) also produced an erosion prediction equation that presented factor values for application on soils and cropping conditions throughout Illinois. Their equation considered 9 factors, including previous erosion history.

The National Runoff and Soil Loss Data Center was established by USDA-ARS at Purdue University in 1954, under the direction of W.H. Wischmeier, with the intention of developing an erosion prediction equation compatible with data available throughout the United States. Between 1956 and 1970, many additional plot-years and watershed-years of data from continuing studies, and about 20 additional locations, were added to the data bank at Purdue. Data from these locations were then used in the development of the original USLE (Wischmeier and Smith 1965) and the revision (Wischmeier and Smith 1978).

The term "Universal" in the USLE has been criticized. Wischmeier's explanation (1972) clarifies its use:

> The name 'universal' soil loss equation originated as a means of distinguishing this prediction model from the highly regionalized models that preceded it. None of its factors utilizes a reference point that has direct geographic orientation. In the sense of the intended functions of the equation's six factors, the model should have universal validity. However, its application is limited to states and countries where information is available for local evaluation of the equation's individual factors.

Use of Rainfall Simulators

Rainfall simulation is the technique of applying water to plots in a manner felt to emulate some aspects of natural rainfall. Thus, it is a tool that has been used for many years in erosion, infiltration, and runoff research. Neff (1979), in his introduction to a rainfall simulator workshop report, cited the common features of simulators as: portability; water available when and where needed; defined plots that are treated or maintained according to the study objective(s); sprinkling mechanism with control over application rate and amount; and devices and/or procedures for measuring the output from the plot. Neff (1979) went on to list some advantages and disadvantages of simulators as follows:

Advantages

1. Rainfall simulators are cost-efficient. Because of the degree of control that can be exercised over simulator operation, the cost per unit of data collected is quite low when compared to unit costs of long-term experiments depending on natural rainfall. Long-term experiments require not only the cost of initial instrumentation, but also a great deal of personnel time for plot and instrument maintenance and servicing during periods in which little or no data are being collected. We realize that people are probably the most expensive thing we pay for in an experiment.
2. Rainfall simulators provide a maximum of control over when and where data are to be collected; plot conditions at test time; and, within, design limitations, rates and amounts of rain to be applied. If an investigator must depend on natural rainfall, it may take many years to collect data with the required combinations of rainfall amounts and intensities, land management sequences, and crop growth stages for valid analysis and interpretation. The degree of control afforded by rainfall simulators provides a technique for collecting a great deal of data in a relatively short time.

Disadvantages

1. Rainfall simulators are expensive to construct and use because of the cost of components and assembly, and the number of people required to operate them.
2. The areas treated are small, ranging from a fraction of a square meter, up to several hundred square meters, depending on the simulator design. These small areas may or may not be representative of the general area of concern. For example, things such as rodent holes, large bushes and plants, etc., on the plots can have a disporportionate effect on the results.
3. Most simulators do not produce drop-size distributions that are representative of natural rainfall. Simulators with tube-type drop formers produce drops within a narrow range of sizes, and drop size can be adjusted only by changing the size of the tubes. Simulators with nozzle-type drop formers produce drops over a wide range of sizes, but they are smaller than some natural thunderstorm-type raindrops.
4. Most simulators do not produce rainfall intensities with the temporal variations representative of natural rainfall. Some simulators can produce different intensities, but they are usually varied between runs, and not within runs.
5. Some simulators do not produce drops that approach the terminal velocity of corresponding size drops of natural rainfall. The lower velocities, in combination with smaller drop-size distributions, result in lower kinetic energy than that produced by natural rainfall. Kinetic energy of simulators with nozzle-type drop formers and free-falling drops may be only 40–50% of natural rain. There are, however, simulators designed with nozzles pointed down and the drops applied under pressure which do approach the energy of natural rain.

Neff (1979) further stated that although the list of advantages is shorter than the disadvantages (and more items can probably be added), the key item to be evaluated is whether the advantages are important enough to accept the tradeoffs imposed by the limitations. In many instances, the use of simulated rain is the only way to obtain results in a reasonable time period. Furthermore, the data obtained from carefully controlled rainfall simulator experiments are providing fundamental information on the cause/effect relationships which result in erosion.

It is important to realize that the research approaches being used in the 1980's involve a combination of hypothesis development using physical laws to assemble cause-effect relationships into involved models which often require digital computers for solution (DeCoursey 1983), known as causal models, and then designing prototype experiments to collect data with which to accept or reject the concepts involved and calibrate model parameters. It is in this latter area that rainfall simulators make their most important contribution. Thus, with the simulator, we can make measurements for variable conditions that we seek to study in order to validate physically based concepts, rather than use the statistical approaches which heretofore have dominated erosion research.

Bubenzer (1979) inventoried the many different types of rainfall simulators reported in the literature, and categorized them according to whether the simulated rainfall was produced by a nozzle or by a drop former. From the extensive list he developed, it seems obvious that users of such data can expect serious problems when comparing data from one simulator with that from another. The difference in plot sizes alone leads to serious problems for anyone attempting to utilize such data. Suffice to say that the early nozzle simulators generally involved some modification of the Type F infiltrometer (Wilm 1943), followed by the complicated ARS rainulator (Meyer and McCune 1958), and the rotating boom simulator (Swanson 1965). Drop forming simulators have evolved from the use of yarn (Barnes and Costel 1957) for forming drops to stainless steel or polyethelene tubing for better intensity and dropsize control (Bubenzer 1979, Robinette and McCool 1984). Most of the work subsequently reported in this current workshop has involved use of the rotating boom simulator.

Future Erosion Research

Had computers been available in the 40's, current erosion prediction methods might appear more like the theory contained in Ellison's classic paper (1947) than the empirical form of the USLE. The USLE, and its predecessors, were very much structured to be "user" friendly, because erosion equations were accepted by the USDA-Soil Conservation Service in the early 50's as a powerful tool for tailoring erosion control practices to the needs of specific fields and farms.

Following the release of the USLE in a series of workshops in the early 1960's, followed by the 1965 Agriculture Handbook (Wischmeier and Smith 1965), the SCS and other user agencies switched from the regional agronomic planning concepts for erosion abatement to the USLE, and by the mid 1970's, there was an interest in using the technology of western rangelands. Unfortunately, during the period of the USLE development, no comparable erosion research program on rangelands in the western U.S. was underway; thus, recent efforts to develop erosion prediction and control methods for rangelands have lacked an extensive data base upon which to build. Thus, requests were made for a "best estimate" approach for the rangeland cover-management factor. Wischmeier developed Table 10 in Handbook 537, which was to be used until such time that research could provide data for a rangeland table or an alternative.

Research is underway to provide USLE parameter values for western U.S. rangelands. The current work involves an intensive effort to collect data from scattered sources (simulators and plots) and to incorporate such data in a subfactor approach for evaluating the cover-management factor (C) of the USLE. Although the results are encouraging, much additional research is required to facilitate handling the various conditions encountered in the western U.S.

It is now 25 years since the first USLE publication. Although there is additional technology more sophisticated than the USLE (Knisel 1980, Beasley et al. 1977, Simons et al. 1977) for estimating erosion, such technology has generally been used on a limited basis, and parameter values to use the technology are incomplete. Rapid developments in computer technology have made it possible to include much of the newer technology in a new second generation erosion estimation model. Planning for such research is now nearing completion, with the end product envisioned within 5 years. I anticipate such a model will:

(1) Operate on a personal computer;

(2) have a climate-generating routine to simulate storm inputs on at least a daily basis;

(3) have a physically based hydrology routine to provide spatially variable runoff;

(4) have erosion routines for water detachment and transport by raindrop impact and overland flow for both interrill and rill areas;

(5) have a concentrated flow erosion subroutine;

(6) route sediment for the size distributions as it erodes;

(7) include sediment deposition in ponded areas, vegetated areas and/or at changes in the energy grade line;

(8) consider a variety of topographic forms;

(9) sum soil loss over various time periods as the total of individual storm period soil loss;

(10) be capable of considering conditions for all types of land use (agricultural, urban, disturbed, rangeland, and forest land), and

(11) be "user friendly" so that estimates can be made with minimal effort, and that user errors in parameter estimation are minimized.

It is important to remember that the USLE was developed by researchers in ARS and state Agricultural Experiment Stations, along with users in action agencies such as the SCS. Thus, the USLE represents the collective input of a wide variety of researchers and users. This same concept is being pursued in developing a replacement for the USLE. Much of the data to conceptualize and validate the algorithms which will be a part of the new technology is likely to be developed with carefully conceived and conducted rainfall simulator experiments.

Discussion and Summary

Erosion research is now almost a century old if the Wollny work of 1888 is recognized as the start of such work. Furthermore, 1984 was recognized as the 50th anniversary of the soil conservation movement in the United States, started by H.H. Bennett and others in USDA. Yet many problems remain in understanding fundamental water erosion mechanics, predicting erosion with the many types of land use and environmental conditions encountered, and developing practices which control, or at least reduce, erosion.

Past erosion research which led to the development of the USLE is not adequate to meet the environmental questions being posed in the 1980's. Whereas most erosion data from past plot studies involved estimates of total soil loss from storm periods (prediction technology was generally directed toward seasonal or annual soil loss), current questions involve the need for loss rate data (sedigraphs) by particle-size class (important for adsorbed agricultural chemicals on fine soil particles), as well as information on rill and interrill erosion, concentrated flow erosion, channel erosion, and deposition from complex landscape configurations. Such answers cannot be obtained from simple models structured like the USLE, but require a physically-based model with algorithms solved on a computer in an iterative way to accommodate the temporal and spatial variability encountered in prototype situations. Given the more involved nature of these second generation erosion prediction models, additional experiments will be required to evaluate the parameter values necessary to operate such models for the wide variety of conditions that will be encountered.

Rainfall simulators will necessarily play an important role in the research to develop parameter values for the models. Despite the limitations of simulators to reproduce natural storm conditions, the advantages of simulators to perform controlled experiments leads to the obvious conclusion that they must be used to obtain many parameter values. Furthermore, when used in concert with long-term plot experiments using natural storm inputs, the resulting information becomes powerful for model development, validation, and finally, for parameter determination. On rangeland areas where precipitation is limited and it may take years to collect the necessary information from natural storms, rainfall simulators facilitate collecting such data in a relatively short time.

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