EROSION ON RANGELANDS: EMERGING TECHNOLOGY AND DATA BASE

Proceedings of the Rainfall Simulator Workshop

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COVER: Operation of the rotating boom rainfall simulator on rangeland erosion plots on the Walnut Gulch Experimental Watershed in southeastern Arizona. Photograph by J.R. Simanton.

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Preface

Rainfall simulator studies are being used by a number of individuals at several locations in the West to provide artificial, but controlled, rainfall input to runoff and erosion plots. Increasing complexity of land use and management problems affecting rangeland hydrology and erosion, require increasingly powerful modeling techniques and more extensive and intensive experimentation. The result has been an increase in the number and sophistication of rainfall simulator studies and an increase in the emphasis on validation of simulation models with data from runoff and erosion plots.

Therefore, it became apparent that descriptions of rainfall simulator studies and the resulting data should form the basis for design of future studies of this type. Moreover, it was thought that much could be gained through discussions of procedures and findings and through sharing of pooled data and information. This is the reason that T.E. Hakonson, E.M. Romney, and L.J. Lane organized the 1985 Rainfall Simulator Workshop.

We thank the sponsoring organizations for support of the participants' research and the workshop. We thank the participants for their efforts in behalf of the workshop and its purpose.

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Introduction

Soil erosion by water can be defined as the processes of "detachment and transportation of soil materials by erosive agents" (Ellison 1947), and can be further defined as detachment by rainfall, detachment by runoff, transportation by rainfall, and transportation by runoff (Foster and Meyer 1972). Of necessity and due to tradition, most of the existing erosion prediction and control technology is based upon data from cultivated agricultural lands. Subsequent to its development, the technology was extended to rangelands where experience, data, and experimental facilities to validate the extensions or extrapolations were not available. Very real differences in scale, processes, variability, resource uses, and data availability raise the question of direct applicability of this erosion prediction and control technology on arid and semiarid rangelands.

Efforts are underway to determine parameter values for the Universal Soil Loss Equation (USLE, see Wischmeier and Smith 1978) under rangeland conditions or to modify the USLE for special circumstances such as rangelands. The workshop participants dealt in detail with these USLE parameter determination and modification efforts because of continuing requests for USLE related information (e.g., see USDA-ARS 1982, pp. 209-213). However, most participants seemed to recognize that some situations and some applications require alternate or improved erosion prediction methods.

The Need for New Technology

Recent evaluations of traditional erosion prediction methods have resulted in calls for improved methods to predict erosion. Some notable applications where traditional methods such as the USLE appear to need modification and/or replacement include: (1) adsorbed chemical transport associated with sediments of various sizes and characteristics (e.g., Massey and Jackson 1952, Menzel 1980, Watters et al. 1983), (2) complex slope shapes inducing erosion and sediment deposition at different points on the slope (e.g., Foster and Meyer 1977, Neibling and Foster 1980), (3) simulations for individual storms rather than annual averages, and (4) arid and semiarid rangeland areas (e.g., SRM 1984).

An important point is that predicting erosion on rangelands includes (but is not limited to) the other three applications listed above. Nonpoint source pollutants are present on rangelands (e.g., herbicides, pesticides, radionuclides as the result of weapons testing and worldwide fallout, etc.) so that adsorbed chemical transport prediction is necessary on rangelands. Complex slope shapes are present on rangelands and often a single extreme event can dominate erosion rates at a given site for many years. Therefore, there is a wide recognition of the need for an improved erosion prediction and control technology applicable to rangelands. This recognition is documented in professional society publications (e.g., ASCE 1982, SRM 1984) as well as in individual manuscripts and papers. Perhaps it was best expressed in a recent memorandum by an Agricultural Research Service administrative scientist (R.A. Rhodes 1985. USLE Replacement. Personal communication as an unpublished memorandum) as follows:

> All this leads inescapably to the conclusion that you must take the route of developing the means to predict soil erosion based on fundamental principles. However imperfect, such an approach will allow future adjustments as new knowledge is developed. The alternative approach of continued temporary fixes of the USLE will only further exacerbate the problem. Burdened by more and more empirical approximations, the equation ultimately will collapse."

Emerging Technology

Two general types of technology are discussed here. The first type is apparatus for improved field and laboratory experiments and analyses. The second type is in the general area of modeling, and especially computer implemented mathematical models. Both types of technology are undergoing significant changes with profound implications for future erosion prediction technology.

Selected Field and Laboratory Apparatus

In 1979 a workshop entitled "Rainfall Simulator Workshop" was held in Tucson, Arizona. The Proceedings of this workshop (USDA-SEA 1979) provide a compendium of many rainfall simulators and rainfall simulator studies in the United States as of that date. Moreover, Appendix II of the Proceedings is a bibliography of rainfall simulator design and operation. One particular rainfall simulator of interest at present is the Swanson Rotating Boom Rainfall Simulator (USDA-SEA 1979) and H. D. Larsen's slightly modified versions of it (Simanton and Renard 1982).

The 1982 paper by Simanton and Renard described the rainfall simulator and the associated paired-plot experimental design now being used in Arizona, Nevada, and New Mexico. This portable rainfall simulator and the associated experimental design and data collection procedures have allowed development of replicated experiments in several Western ecosystems.

Concurrently with and in support of the rainfall simulator studies, has been the development of new sedimentation laboratory procedures to determine sediment concentration by particle size classes. Procedures were developed (e.g., Cooper et al. 1984, Haverland and Cooper 1981) to employ a laser light scattering technique, called the Microtrac[1] particle-size analyzer, to rapidly and efficiently process the hundreds of sediment samples collected during the rainfall simulator studies.

Taken together, the development of easily portable rainfall simulators, easily replicated experimental design and data collection techniques, and more rapid and less expensive sediment particle size analysis techniques have led to a significant increase in our ability to conduct large-plot rainfall simulator studies. This increased ability to conduct field experiments in turn has provided a stimulus to develop new and improved methods of interpreting and synthesizing research data toward the purpose of understanding processes and mechanisms controlling erosion on arid and semiarid rangelands.

Example of an Emerging Modeling Technique

In 1981 a workshop entitled "Estimating Erosion and Sediment Yield on Rangelands" was held in Tucson, Arizona. The Proceedings of this workshop (USDA-ARS 1982) describe a great deal of erosion research underway at the time of the workshop. The bulk of the Proceedings was devoted to the USLE and USLE related research and discussion. However, there was some discussion of alternative and new erosion modeling techniques (i.e., the CREAMS model, a kinematic cascade runoff model with rill and interrill erosion, and sediment yield from small rangeland watersheds as estimated by several currently used methods).

A modeling technique emerging in part from the second Tucson workshop and other research is the coupled kinematic wave-rill and interrill erosion/sediment yield model (e.g., Foster and Meyer 1972, Hjelmfelt et al. 1975, Shirley and Lane 1978, Lane and Shirley 1982, Singh 1983, and others). Some advantages of this approach are as follows:

1. The models are hydrologically driven in that precipitation and infiltration are used to compute rainfall excess rate and runoff volume.
2. The models are hydraulically driven in that the kinematic wave equations are used to route the rainfall excess and thus to develop the runoff hydrograph.
3. The main processes of interrill erosion and transport and rill erosion, transport and deposition are represented separately and explicitly in the model.

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[1] Trade names are included for information of the reader and do not constitute endorsement by an agency of the United States Government or the Society for Range Management.

4. Most of the parameters in the model can be determined experimentally using rainfall simulators and laboratory flume facilities.
5. The models are computer-based so that electronic calculation, information storage, and communication are compatible with the model structure and function.

The main disadvantage, with respect to earlier and simpler models such as the USLE, is in model complexity. Model users will need more technical skills in mathematics, physical sciences, and computer applications.

The Third Tucson Workshop

The third workshop was held in Tucson, Arizona on January 14–15, 1985 and was jointly sponsored by the U.S. Department of Agriculture, Agricultural Research Service, the U.S. Department of Energy, Office of Health and Environmental Research, and the Society for Range Management. The theme of the workshop was erosion and sediment yield, water balance studies, and contaminant transport studies in the West which were in some way using rainfall simulators or rainfall simulator data. With this theme, the third Tucson workshop built upon the 1979 Rainfall Simulator Workshop and the 1981 Estimating Erosion and Sediment Yield on Rangelands Workshop.

However, a unique feature of this workshop was that extensive rainfall simulator-erosion plot data were presented as a basic data source in support of the emerging technology. As organizers of the workshop, we felt this to be an efficient and cost-effective way of making these valuable experimental data public and available to all scientists and engineers working in erosion prediction and control. In so doing we hoped to provide a basic data source, but also, a stimulus to continued and improved research on soil erosion and related problems in arid and semiarid areas.

Literature Cited

ASCE. 1982. Relationships between morphology of small streams and sediment yield. Report of the Task Committee on Sedimentation of the Hydraulics Div., J. Hyd. Div., ASCE 108(HY11):1328-1365.

Cooper, L.R., R.L. Haverland, D.M. Hendricks, and W.G. Knisel. 1984. Microtrac particle-size analyzer: an alternative particle-size determination method for sediment and soils. Soil Sci. 138(2):138-146.

Ellison, W.D. 1947. Soil erosion studies. Agric. Engr. 28:145-146, 197-201, 245-248, 297-300, 349-351, 402-405, and 442-444.

Foster, G.R., and L.D. Meyer. 1972. A closed-form soil erosion equation for upland areas. *In:* H.W. Shen (ed.). Sedimentation. Proc. Symposium to Honor Prof. H.A. Einstein. Colorado State Univ., Ft. Collins, CO, pp. 12-1 to 12-19.

Foster, G.R., and L.D. Meyer. 1977. Soil erosion and sedimentation. *In:* Proc. Nat. Symp. on Soil Erosion and Sedimentation by Water, ASAE, St. Joseph, MI, pp. 1-10.

Haverland, R.L., and L.R. Cooper. 1981. Microtrac: a rapid particle-size analyzer of sediments and soils. Hydrol. and Water Resources in Ariz. and the Southwest, 11:207-211.

Hjelmfelt, A.T., R.F. Piest, and K.E. Saxton. 1975. Mathematical modeling of erosion on upland areas. Proc. 16th Congress International Assoc. for Hydraulic Research, Sao Paulo, Brazil, Vol. 2:40-47.

Lane, L.J., and E.D. Shirley. 1982. Modeling erosion in overland flow. *In:* Proc. Workshop on Estimating Erosion and Sediment Yield on Rangelands. USDA, Agricultural Research Service, Agric. Reviews and Manuals, ARM-W-26/June 1982. pp. 120-128.

Massey, H.G., and M.L. Jackson. 1952. Selective erosion of soil fertility constituents. Proc. SSSA 16:353-356.

Menzel, R.G. 1980. Enrichment ratios of water quality modeling. *In:* W.G. Knisel (ed.). CREAMS: A field scale model for chemicals, runoff, and erosion from agricultural management systems. USDA Conservation Research Report No. 26:486-492.

Neibling, W.H., and G.R. Foster. 1980. Sediment transport capacity of overland flow. *In:* W.G. Knisel (ed.). CREAMS: A field scale model for chemicals, runoff and erosion from agricultural management systems. USDA Conservation Research Report 26:463-473.

Shirley, E.D., and L.J. Lane. 1978. A sediment yield equation from an erosion simulator model. Hydrol. and Water Resources in Ariz. and the Southwest 8:90-96.

Simanton, J.R., and K.G. Renard. 1982. Seasonal change in infiltration and erosion from USLE plots in southeastern Arizona. Hydrol. and Water Resources in Ariz. and the Southwest 12:37-46.

Singh, V.P. 1983. Analytic solutions of kinematic equations for erosion on a plane II. Rainfall of finite duration. Adv. in Water Resources 6:88-95.

SRM. 1984. Position statement on the use of the USLE on rangelands. Society for Range Management, Rangelands 6(3):139-140.

USDA-ARS. 1982. Proceedings of the workshop on estimating erosion and sediment yield on rangelands. USDA, Agricultural Research Service, Agric. Reviews and Manuals, ARS-W-26/June 1982.

USDA-SEA. 1979. Proceedings of the rainfall simulator workshop. USDA, Science and Education Administration, Agric. Reviews and Manuals, ARS-W-10/July 1979.

Watters, R.L., T.E. Hakonson, and L.J. Lane. 1983. The behavior of actinides in the environments. Radiochimica Acta 32:89-103.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses—a guide to conservation planning. Agric. Handbook No. 537, USDA, Washington, D.C., 58 p.

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

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Key Words: soil conservation, rangeland, natural plots

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 drop-size 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.

Literature Cited

Agricultural Research Service. 1983. Agricultural Research Service Program Plan, USDA, ARS, 32 pp.

Barnes, O.F., and G. Costel. 1957. A mobil infiltrometer. Agron. J. 49:105-107.

Baver, L.D. 1938. Ewald Wollny - a pioneer in soil and water conservation research. Soil Sci. Soc. Am. Proc. 3:330-333.

Beasley, D.B., E.J. Monke, and L.F. Huggins. 1977. ANSWERS: a model for watershed planning. Agric. Exper. Stn. J. Paper No. 7038, Purdue Univ., W. Lafayette, Indiana, 34 pp.

Bennett, H.H. 1939. Soil Conservation. McGraw-Hill, NY, 993 pp.

Browning, G.M., C.L. Parish, and J.A. Glass. 1947. A method for determining the use and limitations of rotation and conservation practices in control of soil erosion in Iowa. J. Am. Soc. Agron. 39:65-73.

Bubenzer, G.D. 1979. Inventory of rainfall simulators. *In:* Proc. Rainfall Simulator Workshop. USDA-SEA ARM-W-10, p. 120-130.

Chapline, W.R. 1929. Erosion on range land. J. Am. Soc. Agron. 21:423-429.

Cook, H.L. 1936. The nature and controlling variables of the water erosion process. Soil Sci. Soc. Am. Proc. 1:60-64.

DeCoursey, D.G. 1983. Mathematical models: research tools for experimental watersheds. Research Oriented Workshop on Experimental Watersheds, U.S.-Uruguay Bilateral Cooperation, Montevideo, Uruguay, 30 pp.

Duley, F.L., and M.F. Miller. 1923. Erosion and surface run-off under different soil conditions. Res. Bull. 63, Mo. Agr. Exp. Sta., Columbia, 50 pp.

Ellison, W.D. 1947. Soil erosion studies. Agric. Engr. 28:145-146, 197-201, 245-248, 297-300, 349-351, 402-405, 442-444.

Knisel, W.G., Jr. 1980. Erosion and sediment yield models - an overview. Proc. Symp. on Watershed Manage. '80, ASCE, p. 141-150.

Meyer, L.D., and D.L. McCune. 1958. Rainfall simulator for runoff plots. Agric. Engr. 39:(10):644-648.

Meyer, L.D. 1982. Soil erosion research leading to development of the universal soil loss equation. *In:* Proc. Workshop on Estimating Erosion and Sediment Yield on Rangelands. USDA-ARS ARM-W-26, p. 1-16.

Meyer, L.D. 1984. Evolution of the universal soil loss equation. J. Soil and Water Cons. 39(2):99-104.

Meyer, L.D., and W.C. Moldenhauer. 1985. Soil erosion research: a historical perspective. Agricultural History (In press).

Miller, M.F. 1926. Waste through soil erosion. J. Am. Soc. Agron. 18:153-160.

Miller, M.F., and H.H. Krusekopf. 1932. The influence of systems of cropping and methods of culture on surface runoff and soil erosion. Res. Bull. 177, Mo. Agr. Exp. Sta., Columbia, 32 pp.

Musgrave, G.W. 1947. The quantitative evaluation of factors in water erosion, a first approximation. J. Soil and Water Cons. 2:133-138.

Neff, E.L. 1979. Why rainfall simulation? *In:* Proc. Rainfall Simulator Workshop. USDA-SEA ARM-W-10, p. 3-7.

Nelson, L.B. 1958. Building sounder conservation and water management research programs for the future. Soil Sci. Soc. Am. Proc. 22:355-358.

Robinette, M.J., and D.K. McCool. 1984. Techniques for producing and measuring water drops: a literature review. U.S. Dept. Agr., Agr. Res. Ser., ARS-11, 20 pp.

Sampson, A.W., and L.H. Weyl. 1918. Range preservation and its relation to erosion control on western grazing lands. Bull. 675, U.S. Dept. Agr., Washington, D.C., 35 pp.

Simons, D.B., R.M. Li, and T.J. Ward. 1977. A simple procedure for estimating on-site soil erosion. Proc. Intern'l Symp. on Urban Hydrology. Hydraulics, and Sediment Control, Univ. Kentucky, Lexington, Ky., p. 95-102.

Smith, D.D. 1941. Interpretation of soil conservation data for field use. Agr. Eng. 22:173-175.

Smith, D.D., and D.M. Whitt. 1948. Evaluating soil losses from field areas. Agr. Eng. 29:394-396.

Stewart, G., and C.L. Forsling. 1931. Surface runoff and erosion in relation to soil and plant cover on high grazing lands of central Utah. J. Am. Soc. Agron. 23:815-832.

Swanson, N.P. 1965. Rotating boom rainfall simulator. Trans. ASAE 8(1):71-72.

Van Doren, C.A., and L.J. Bartelli. 1956. A method of forecasting soil losses. Agr. Eng. 37:335-341.

Wilm, H.G. 1943. The application and measurement of artificial rainfall on types FA and F infiltrometers. Trans. AGU 24:480-484.

Wischmeier, W.H. 1972. Upslope erosion analysis. *In:* Environmental Impact on Rivers. Water Res. Publ., Ft. Collins, Co., p. 15-1-15-26.

Wischmeier, W.H., and D.D. Smith. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. Agr. Handbook No. 282, U.S. Dept. Agr., Washington, D.C., 47 pp.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses - a guide to conservation planning. Agr. Handbook No. 537, U.S. Dept. Agr., Washington, D.C., 58 pp.

Wollny, E. 1888. Untersuchungen uber die sickerwassermengen in verschiedenen Bodenarten. Forsch, a.d. Gebiete d. Agr. Physick. Band II, Seite 1-68.

Zingg, A.W. 1940. Degree and length of land slope as it affects soil loss in runoff. Agr. Eng. 21:59-64.

An Overview of Los Alamos Research on Soil and Water Processes in Arid and Semi-Arid Ecosystems

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Key Words: contaminant transport, waste disposal, hydrology of disturbed ecosystems, rainfall simulator studies

Abstract

Some important research needs to improve understanding and forecasting ability on water balance and erosion in arid lands are discussed along with new approaches, using remote sensing technology, that may improve this ability. Relationships on radionuclide distribution and transport in the Los Alamos and Trinity site environs in New Mexico are described to add historical perspective to current Los Alamos and Nevada Test Site studies using the rainfall simulator. A brief description of current rainfall simulator studies is given with emphasis on applications of the resulting data.

Introduction

Some of the current environmental research at Los Alamos and Nevada Test Site emphasizes surface water hydrology and erosion, including the use of the rainfall simulator as an experimental tool. Much of that work, which involves collaboration with several organizations, is described in these workshop proceedings.

The purpose of this paper is to review the results of early DOE-sponsored research at Los Alamos to add historical perspective to the Los Alamos and Nevada Test Site studies described in these proceedings. Information needs and some newly emerging technology are also identified that may improve our understanding and ability to predict soil and water processes in arid lands.

Background

Contaminant Distribution:

In the early 1970's, the Atomic Energy Commission (now the Department of Energy) began a major research program to investigate the behavior of transuranic elements in the environment (Hanson 1980). The interest in these radionuclides arose because some of them are long lived (e.g., ^{239}Pu has a 24,000 year physical halflife) and are widely distributed in the environment as a consequence of nuclear weapons testing and disposal of wastes generated by the nuclear industry.

In support of the AEC effort, Los Alamos began studies on the distribution and transport of plutonium (and other radionuclides) in ephemeral stream channels used for liquid waste disposal at Los Alamos and in the fallout zone created by the atomic bomb test in 1945 at Trinity Site in south central New Mexico. We were especially interested in the behavior of two isotopes of plutonium, ^{238}Pu and ^{239,240}Pu, although data were also gathered on ^{137}Cs, ^{3}H and stable mercury.

The results from the Los Alamos studies (Hakonson 1975, Hakonson and Nyhan 1980, Nyhan et al. 1976), as well as those from a number of other locations (Hanson 1980), revealed that plutonium (and, in fact, several other radionuclides), deposited almost quantitatively in soils and sediments. Furthermore, the importance of soil and sediment as a reservoir for many radionuclides was often independent of the source term (i.e., weapons fallout, effluent release, accidental release, etc.) and the type of ecosystem (i.e., arid, humid, terrestrial, freshwater aquatic; Watters et al. 1983).

At Los Alamos and Trinity Site, over 99% of the plutonium inventory was found in soils and sediments, while very small percentages were associated with the biological components of study area ecosystems (Table 1). We also found that the concentrations of plutonium in soil (pCi/g) were a strong function of soil particle size. For example, the silt-clay size fraction (<53 μm in diameter) often contained as much as a factor of 10 times higher concentration of plutonium than coarse sands (Fig. 1). With few exceptions, strong relationships between concentration and soil particle size fraction would also be expected for most other environmental pollutants in soil.

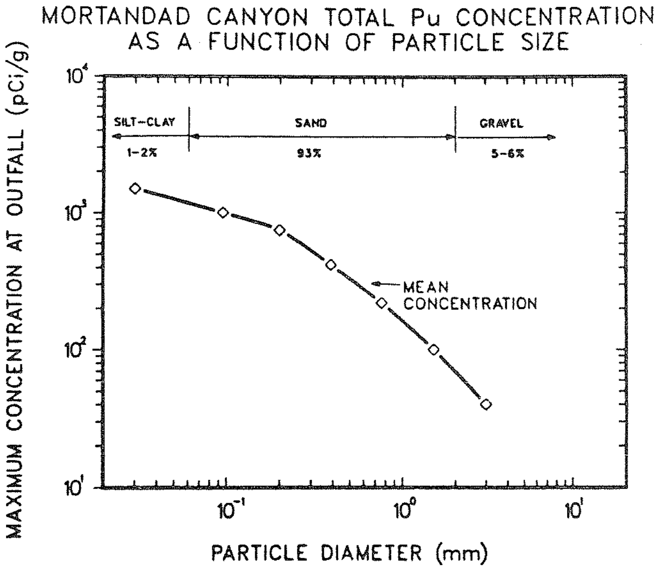

Figure 1. *Plutonium concentrations in sediment from Mortandad Canyon as a function of soil particle size fraction. Contribution of various size fractions to whole soil mass are shown as percentages (from Lane and Hakonson 1982).*

A further consideration arises from the fact that the relative contribution of a particular particle size class to the whole soil mass is variable from location to location. Consequently, while the silt clay size fraction may contain relatively high concentrations of plutonium, the total amount of plutonium in that fraction may be relatively small. For example, the silt-clay fraction of sediments from Los Alamos stream channels contained relatively little of the plutonium inventory owing to the small contribution of this size class to total sediment mass (Table 2). In contrast, at Area 21, in the Trinity fallout zone, about 75% of the plutonium inventory in whole soil was present in the silt-clay fraction, which comprises 36% of the whole soil mass.

The importance of contaminant distribution relationships in soils stems from the fact that erosion by water may selectively sort

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Table 1. Mean plutonium inventory ratios for some components of Los Alamos and Trinity Site study areas in New Mexico (from Hakonson and Nyhan 1980).

	Plutonium inventory ratio[1]							
	Los Alamos				Trinity			
Component[1]	n	Mortandad Canyon	n	Acid-Pueblo Canyon	n	Area GZ	n	Area 21
Grass	24	4.1×10^{-5} (0.90)	20	5.6×10^{-4} (1.6)	13	2.0×10^{-5} (0.99)	16	1.3×10^{-4} (0.76)
Forb	16	4.8×10^{-5} (1.2)	11	1.7×10^{-4} (1.0)	17	1.7×10^{-4} (1.0)	21	3.5×10^{-5} (0.77)
Litter	--	---------------	--	----------------	5	1.6×10^{-4} (2.0)	3	1.1×10^{-4} (0.81)
Rodents	33	1.5×10^{-9} (0.77)	48	4.5×10^{-10} (0.99)	40	3.7×10^{-8} (1.7)	20	2.3×10^{-9} (0.47)
Soil	29	0.99 (0.00009)	23	0.99 (0.001)	8	0.99 (0.0003)	8	0.99 (0.0008)

[1] Inventory ratio = (pCi Pu/m^2 in component)/total pCi Pu/m^2). All plutonium values are ^{239,240}Pu except Mortandad Canyon which is ^{236}Pu; parenthetic value is coefficient of variation (CV = standard deviation/mean).

Table 2. Plutonium in the <53μm soil size fraction at Los Alamos and Trinity Site (from Hakonson and Nyham 1980).

	Los Alamos		Trinity	
	Mortan-dad	Acid-Pueblo	GZ*	Area 21
Pu Concentration (pCi/g dry wt)	1500	85	0.07	3.8
% contribution to whole soil mass	2.2	3	8.9	36
% Pu in fraction	14	7	0.78	73

*Ground zero

soil particles during all phases of erosion. Consequently, the amount of contaminant transported during an erosion event is dependent not only on the physical relationships of the contaminant with soil but also on hydrologic variables which influence the kinds and amounts of sediment that are detached, transported, and deposited in the watershed.

At Area 21 (Table 2), the preferential transport of silt-clay particles would have the potential for transporting a significant fraction of the plutonium inventory in the soil. In contrast, transport of the silt-clay fraction of stream channel alluvium in the canyons at Los Alamos would be mobilizing a soil component with a relatively small fraction of the plutonium inventory.

The complex distributional and hydrologic relationships that potentially influence the redistribution of soil and sediment associated contaminants led to the need to further characterize and begin to model runoff, erosion, and contaminant transport. At Los Alamos, transport studies were initiated in the stream channels contaminated with treated radioactive liquid effluents.

Contaminant Transport:

Los Alamos receives an average of 46 cm of precipitation per year with 75% of it falling during intense thunderstorms that occur in late summer. These short duration, high intensity storms often produce runoff in the ephemeral streams at Los Alamos, leading to the potential for downstream transport of sediment-associated radionuclides.

Rainstorm runoff at Los Alamos was first implicated in the transport of sediment associated plutonium in the mid-1940's (Kingsley 1947). In subsequent years, several studies were conducted to determine some of the relationships between rainfall, runoff, erosion, and contaminant transport (Purtymun 1974, Purtymun et al. 1966, Hakonson et al. 1976, Lane and Hakonson 1982).

Results of those studies demonstrated that snow melt and rainstorm runoff transported radionuclides attached to sediment and that the magnitude of transport was highly dependent on the hydrologic characteristics of the watershed. The dependency of concentrations of suspended sediments and plutonium in runoff on flow rate is indicated by the data from one runoff event in Mortandad Canyon (Fig. 2; Hakonson and Nyhan 1976). The nonlinearity in the curves was attributed to the relationships of flow rate to the particle size of suspended material. At flows less than 0.25 m^3/sec, only the silt-clay particles, which comprise less than 2% of the alluvium by weight (Table 2), were in suspension in the runoff. However, at flow rates in excess of 0.25 m^3/sec, fine to coarse sands, which contain about 85% of the plutonium inventory, were in suspension. Higher flow rates typically occur during the early phases of rainstorm runoff events at Los Alamos owing to the short duration and intense nature of local rainstorms. For the runoff event depicted in Fig. 2, we found that 80% of the sediment and 70% of the radioactivity was transported within the first half of the runoff event.

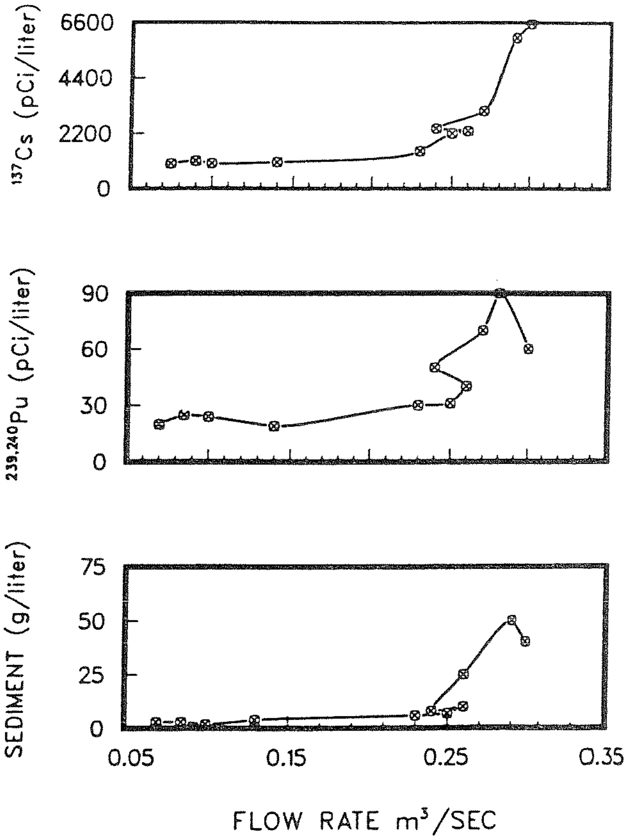

Figure 2. *Concentration of sediment and plutonium in unfiltered runoff water from Mortandad Canyon as a function of runoff flow rate (from Hakonson et al. 1976).*

Table 3. Average (n=2) sediment yield (g/m²) from erosion plots at Nevada Test Site using rainfall simulator to apply precipitation at 60 mm/hr. Sediment yield normalized to 60 mm total precipitation input.

Location	Cover Treatment	Spring 1983 Dry[1]	Spring 1983 Wet	Spring 1983 Very Wet	Fall 1983 Dry	Fall 1983 Wet	Fall 1983 Very Wet
Area 11	Natural[2]	1.3	12.0	24.3	4.4	3.6	9.2
	Clipped	1.2	16.4	32.2	72.3	22.4	25.0
	Cleared	82.6	208.0	358.0	304.9	349.0	438.8

[1] Antecedent soil moisture

[2] Natural = vegetation and erosion pavement intact,
Clipped = vegetation removed,
Cleared = vegetation and erosion pavement removed.

Procedures were developed to predict runoff, sediment yield, and contaminant transport from semi-arid watersheds with alluvial stream channels (Lane et al. 1985). The procedures represent a mix of mathematical models and data from our studies to approximate the complex processes of runoff generation, stream flow-routing and hydrograph development, sediment transport and yield, particle sorting and enrichment, and transport of sediment associated contaminants.

The procedure was applied to a Los Alamos canyon system that received radioactive liquid wastes from 1942 to the present. Results suggest that runoff transport of plutonium out of the study reach was about 90% of that added to the reach during the period 1942–1980 (Fig. 3). In addition, calculated estimates of the residual inventory of plutonium in the canyon compared reasonably well (within a factor of 3) with estimates based on sediment sampling and chemical analysis (Fig. 3).

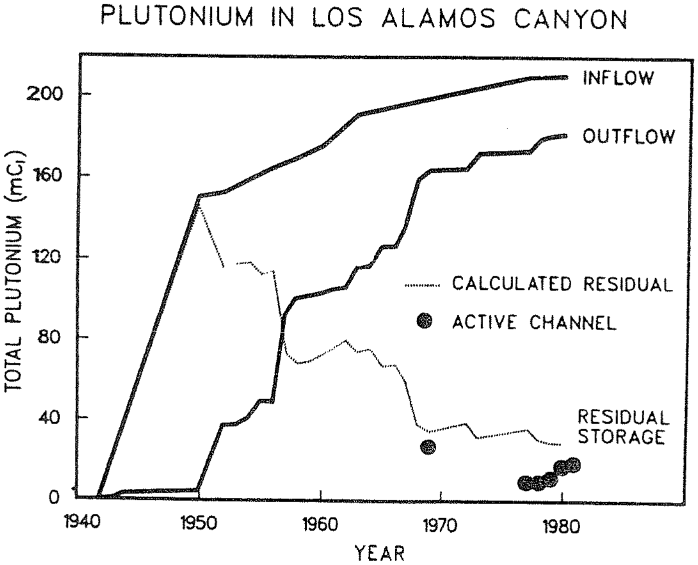

Figure 3. *Calculated and measured residual inventory of plutonium released to a canyon at Los Alamos. Data Points (solid circles) are estimated residual plutonium inventories based on sediment sampling and chemical analysis.*

Current Programs

Studies on the distribution and transport of radionuclides in Los Alamos and Trinity ecosystems demonstrated the importance of hydrologic processes in redistributing soil contaminants. In addition, complex physical, chemical and hydrologic relationships were identified that limited our ability to assess the long term fate and effects of those contaminants without better understanding of the fundamental mechanisms and relationships controlling transport. The key to resolving some of these problems lies with better understanding of the hydrology of study sites. Water is the driving force that leads to many of the environmental issues concerning land and water quality and human health and safety. Concern about non-point source pollution, radioactive and chemical waste disposal, rangeland agriculture and recovery of disturbed ecosystems all center on the need for better information and models describing surface and subsurface hydrology and erosion.

Hydrologic and erosion processes in arid and semi-arid ecosystems are highly variable in time and space and do not easily lend themselves to study under controlled field conditions. The use of the rainfall simulator in our studies of waste disposal at Los Alamos is an attempt to control some of the variables that influence the hydrologic response of waste sites. A clear understanding of the physical and biological factors controlling water balance and erosion on waste trench caps opens the opportunity to modify the cap design in ways most beneficial to insuring the long term integrity of the site. For example, models such as CREAMS (Knisel 1980), when properly calibrated for trench cap components, can be used to evaluate the benefits (i.e., reducing erosion and/or percolation) of modifying the depth and type of cap soil, the effect of changing slope and cover management practice, and the type and density of vegetation cover. During the operation and close-out phases of a waste site, a properly calibrated model can also be used to design monitoring programs and to predict long term site performance.

The rainfall simulator has proved particularly useful in evaluating the effects of animal burrowing on water balance and erosion in disturbed soil profiles. The ability to quantitatively measure the influence of pocket gopher *(Thomomys bottae)* burrowing and erosion is noteworthy on two accounts. First, pocket gophers commonly invade disturbed sites (i.e., waste burial sites) at Los Alamos leading to the potential for influencing waste site integrity and, secondly, existing water balance and erosion models do not account for the influence of burrowing activity primarily because of the lack of appropriate data.

The rainfall simulator studies at Nevada Test Site are descirbed in several workshop papers by E.M. Romney, E.H. Essington, J.R. Simanton, and R.B. Hunter. In addition to the basic research questions being addressed by the study, some of the treatments imposed on the plots simulate a cleanup operation that was conducted on a nearby area highly contaminated with plutonium (Orcutt 1982). The cleanup involved complete removal of the plant and erosion pavement cover similar to the treatment imposed on some of our erosion plots at NTS.

Erosion estimates from rainfall simulator runs (in Area 11) at NTS are presented in Table 3 to illustrate the value of simulator data in evaluating some of the consequences of a cleanup practice. Sediment yield from the undisturbed (or natural) plots, even under very wet antecedent moisture conditions, averaged less than 30 g/m² (0.3 T/ha). Removal of the plant cover had little additional effect on sediment yield from the plots. However, removal of both the plant and erosion pavement covering the ground surface increased sediment yield by a factor of about 10 to 100 over the natural plot treatment. The implication for site cleanup is that the contamination in an undisturbed site is relatively resistant to transport by erosion. A cleanup operation that involves plant and erosion pavement removal, if not 100% effective in removing the contaminant, exposes the residual contaminant to highly accelerated rates of transport from the site. Results of the cleanup operation conducted at Area 11 indicated that about 10% of the initial activity remained in the soil following treatment for plutonium removal (Orcutt 1982).

New Directions

Remote sensing capabilities are being incorporated into the NTS studies to determine the feasibility of using satellite and aircraft based imagery for parameterizing watershed scale hydrologic models. Ground based data, obtained from the rainfall simulator studies and field reconnaissance, will provide estimates of soil characteristics, soil erodibility, infiltration, runoff, and erosion. Satellite and aircraft based imagery will be used to estimate topographical features (e.g., slope, aspect, drainage network) using a digital elevation model generated from low altitude stereo pairs. Surface features of the watershed (vegetation, soil types) will be obtained from digital multispectral scanner data while surface roughness will be determined from digital Seasat radar imagery. The ground based and remote sensing data will be used to parameterize a watershed scale model, focusing on a small contaminated watershed in Area 11. The distribution of contaminant in the area downstream from the source area will be used to partially validate the modeling results.

A critical weakness in our understanding and ability to model water balance is the lack of data and methods to measure evapotranspiration. In arid sites, a very large fraction (>80%) of annual precipitation may be lost to evapotranspiration. A major problem at waste disposal sites may result from water that percolates below the root zone where it is free to interact with waste and possibly move, along with solutes, outside the waste site boundaries. Because plants play such a dominant role in the water balance, revegetation with species that maximize water use may resolve the problem of percolation into waste sites. Unfortunately, data on evapotranspiration from plant canopies as a function of species and season, that could be used in selecting an optimum cover, are generally unavailable.

Estimates of evapotranspiration from stands of vegetation by measuring profiles of water vapor, temperature and wind above the canopy, have always been difficult, especially without perturbing the profiles in the process. Recent developments in **LI**ght **D**etection **A**nd **R**anging (LIDAR) technology for remote monitoring of the concentration of atmosphere constituents such as water vapor, and temperature, have created an unprecedented opportunity for obtaining data on these processes by non-interfering means both at ground level and aloft. We are planning to develop and apply specific LIDAR techniques for measuring evapotranspiration (ET) over a variety of native plant canopies under well defined plant physiological conditions. Important links will be established between the flux of water vapor up to the boundary layer and both environmental variables and plant physiological states.

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Literature Cited

Hakonson, T.E. 1975. Environmental pathways of plutonium into terrestrial plants and animals. Health Phys. 29:583-588.

Hakonson, T.E., J.W. Nyhan, and W.D. Purtymun. 1976. Accumulation and transport to soil plutonium in liquid waste discharge areas at Los Alamos. *In:* Transuranium Nuclides in the Environment, STI/Pub/410, IAEA, Vienna.

Hakonson, T.E., and J.W. Nyhan. 1980. Ecological relationships of plutonium in southwest ecosytems. *In:* W.C. Hanson (ed.), p. 403-419. Transuranic Elements in the Environment, TIC-22800. U.S. Department of Energy, NTIS, Springfield, VA.

Hanson, W.C., (ed.) 1980. Transuranic elements in the environment. DOE/TIC 22800. U.S. Department of Energy, NTIS, Springfield, VA.

Kingsley, W.H. 1947. Survey of Los Alamos and Pueblo Canyons for radioactive contamination and radioassay tests run on sewer-water samples and water and soil samples taken from Los Alamos and Pueblo Canyons. Los Alamos Scientific report, LA-516.

Knisel, W.G. Jr., ed. 1980. CREAMS: a field scale model for chemicals, runoff, and erosion from agricultural management systems. U.S. Dept. of Agriculture, Conservation Research Report No. 26, Washington, D.C.

Lane, L.J., and T.E. Hakonson. 1982. Influence of particle sorting in transport of sediment associated contaminants. P. 543-557, *In:* Proc. Waste Management '82 Symp., Univ. of Arizona Press, Tucson, AZ.

Lane, L.J., W.D. Purtymun, and N.M. Becker. 1985. New estimating procedures for surface runoff, sediment yield, and contaminant transport in Los Alamos County, New Mexico. Los Alamos National Laboratory report, LA-10335-MS.

Nyhan, J.W., F.R. Miera, and R.J. Peters. 1976. Distribution of plutonium in soil particle size fractions of liquid effluent-receiving areas at Los Alamos. J. Environ. Qual. 5:50-56.

Orcutt, J.A. 1982. Cleanup and treatment (CAT) test: a land area decontamination project utilizing a vacuum method of soil removal. U.S. DOE report, DOE/NV/00410-70.

Purtymun, W.D., G.L., Johnson and E.C. John. 1966. Distribution of radioactivity in the alluvium of a liquid waste disposal area at Los Alamos, New Mexico. U.S. Geol. Survey Prof. Paper 550-D.

Purtymun, W.D. 1974. Storm runoff and transport of radionuclides in DP Canyon, Los Alamos County, New Mexico. Los Alamos Scientific Laboratory report, LA-5744.

Watters, R.L., D.N. Edgington, T.E. Hakonson, W.C. Hanson, M.H. Smith, F.W. Whicker, and R.E. Wildung. 1980. Synthesis of the research literature *In:* W.C. hanson (ed.) Transuranic Elements in the Environment, DOE/TIC-22800, U.S. Dept. of Energy, NTIS, Springfield, VA.

Watters, R.L., T.E. Hakonson, and L.J. Lane. 1983. The behavior of actinides in the environment. Radiochemica Acta 32:89-103.

Rainfall Simulation on Rangeland Erosion Plots

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Key Words: soil loss, rangeland, rainfall simulator, USLE

Abstract

Rainfall simulator studies on erosion plots have been made on rangelands in Arizona, Idaho, New Mexico, and Nevada. An extensive data base has been developed for various ecosystems in these western states. Because the same simulator and similar experimental design were used for all the studies, results can be easily transferred across ecosystems. The experimental design included the use of large plots (10.7 m × 3 m); 60 mm/hr rainfall rate; and natural, bare, clipped, grazed and tilled treatments. Results from these studies have been related to USLE parameters and to effects of various surface and canopy characteristics. The importance of erosion pavement on the erosion process of western arid and semiarid rangelands has been demonstrated, and, in some cases, appears to be more dominant than vegetation canopy.

Introduction

Rainfall simulation is a valuable research tool used in the study of the hydrologic and erosional responses of the natural environment. Pros and cons of rainfall simulation have been well documented (Neff 1979). The major objection to rainfall simulators is that they do not produce natural rainfall energies or variable intensities. However, the major advantage of simulators is that maximum control can be achieved over where, when, and how data are collected and results can be easily compared among ecosystems. Data from rainfall simulation studies can be used by researchers, land managers, and planners to evaluate management or treatment effects on ecosystem response.

The main objective of our rainfall simulation studies was to quantify Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) parameters for rangeland conditions in various western ecosystems. The USLE is used to estimate the long-term average soil loss from agricultural fields. It was not originally intended for western rangelands, but has been adapted as a guide for predicting rangeland erosion.

The equation is:

$$A = RKLSCP$$

where A = estimated soil loss (t/ha/yr),
R = rainfall erosivity factor (EI units/year)*
K = soil erodibility factor (t • ha • h/ha • MJ • mm),
LS = slope-length gradient factor,
C = cover and management factor, and
P = erosion control practice factor.

These factors reflect the major variables which influence erosion by rainfall and resultant overland flow. The equation is primarily based on plot data collected mainly in the eastern United States. Because the equation factor relationships vary in different climatic areas, special considerations are required to extend the USLE to the western United States. The EI for a given storm equals the product of total storm kinetic energy (E) times the maximum 30-min intensity (I_{30}). Our research plan included procedures used in simulator studies conducted to quantify cropland values for the USLE factors. Cropland rainfall simulation erosion research used relatively large plots, a standard surface treatment, 9 percent plot slope and standard sequences of rainfall input (Wischmeier and Mannering 1969). Similar standards were used in our simulator studies so direct comparison could be made to other USLE research.

Method and Materials

Erosion plot studies were conducted using a Swanson rotating boom simulator (Swanson 1965) on 3.05 m × 10.7 m plots in rangelands of Arizona, Idaho, New Mexico, and Nevada. The rotating boom rainfall simulator is trailer mounted and has 10- 7.6 m booms radiating from a central stem. The arms support 30 V-Jet 80100 nozzles positioned at various distances from the stem. The nozzles spray downward from an average height of 2.4 m, apply rainfall intensities of about 60 or 130 mm/hr (depending on nozzle configuration), and produce drop-size distributions similar to natural rainfall. Simulator energies are about 80 percent of those of natural rainfall and the simulator produces intermittent rainfall impulses at the plot surface as the booms pass over the plot. Spatial distribution of rainfall over each plot has a coefficient of variation of less than 10 percent. Changes in rainfall intensities are produced by increasing or decreasing the number of open nozzles; 15 nozzles for 60 mm/hr and 30 nozzles for 130 mm/hr. Because of the simple design and portability of the simulator and because two plots are covered during one run, many plots can be evaluated in a relatively short time. The general procedure included rainfall simulation in the spring and fall on at least two replications of 3 or 4 treatments on more than 1 soil type in each ecosystem studied.

Three rainfall simulation runs were made on each plot pair in the following sequence: dry run - initial 60-min rainfall on dry soil conditions; wet run - 30-min rainfall about 24 hr after the dry run and; very wet run - 30-min rainfall 30-min after the completion of the wet run. Rainfall application rate was measured with a recording raingage and rainfall distribution on each plot was measured with 4 non-recording raingages. Plot runoff was measured volumetrically or by specially designed flumes (4 l/sec maximum capacity) equipped with FW-1 water level recorders that measure instantaneous discharge.

Plot sediment yield was calculated from periodic sediment samples taken throughout the hydrograph. Sampling intervals were dependent on changes in the runoff rate with more frequent sampling when discharge was rapidly changing (Simanton and Renard 1982). During a run, time of runoff initiation, sediment samples, and end of runoff were recorded on field notes for later comparisons to recorder charts. Sediment samples were analyzed for total concentration and particle size distribution and all rainfall, runoff, and sediment data were used in computer programs developed especially for our simulator studies.

Study Sites and Treatments

Rangeland study sites and their major soil, vegetation, and precipitation characteristics are listed and shown in Table 1 and Figure 1.

Arizona Plots:

The Arizona rainfall simulator plots are located on the Walnut

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*EI = Erosivity (MJ • mm ha^{-1} • h^{-1}): R= summation of EI for individual storms in any year.

Table 1. Descriptions of rainfall simulation-soil loss study sites.

Site designation	Annual precipitation (mm)	Soil description	Predominant vegetation
Arizona Plots, Walnut Gulch:			
Bernardino	300	Thermic, *Ustollic Haplargid*	Blackgrama *(Bouteloua eriopoda),* Sideoats grama *(Bouteloua curtipendula),* Snakeweed *(Gutierrezia Sarothrae).*
Cave	300	Thermic, shallow *Typic Paleorthid*	Creosote bush *(Larrea tridentata),* whitethorn *(Acacia constricta).*
Hathaway	300	Thermic *Aridic Calciustoll*	*False mesquite (Calliandra eriophylla),* creosote bush, snake weed, blue grama *(Bouteloua gracilis),* black grama.
Reynolds Creek:			
Flats	250	Nannyton: Fine, loamy, mixed, mesic typic haplargids	Shadscale *(Atriplex confertifolia),* Cheatgrass *(Bromus tectorum),* Bottlebrush squirreltail *(Sitanion hystrix).*
Nancy	300	Ruclick-Babbington: Fine, montmorillonitic, mesic xerollic duragrid	Big sagebrush *(Artemisia tridentata* subsp. *wyomingensis),* Sandberg bluegrass *(Poa sandbergii),* Cheatgrass, Bottlebrush squirreltail.
Lower Sheep	380	Searla: Fine, montmorillonitic frigid pachic agrixeroll	Low sagebrush *(Artemisia arbuscula),* Sandberg bluegrass, Bottlebrush squirreltail.
New Mexico Plots:			
Los Alamos	470	Clayey, mixed, mesic *Lithic Aridic Haplustal*	Pinyon pine *(Pinus edulis),* one-seeded juniper *(Juniperus monosperma),* blue grama, sand dropseed *(Sporobolus cryptandrus).*
Nevada Test Site:			
Mercury	150	Shallow, mixed thermic, *Typic durorthid*	Spiney menodora *(Menodora spinescens),* creosote bush, shadscale
Area 11	150	Shallow, mixed thermic, *Typic durorthid*	*Boxthorn (Lycium andersonii),* Indian ricegrass *(Oryzopsis hymenoides),* shadescale.
North Central NV:			
Saval Ranch	350	Very fine, montmorillonitic frigid, abruptic aridic durixeroll	Alkali sagebrush *(Artemisia longiloba),* Sandberg bluegrass, Bottlebrush squirreltail.

Gulch Experimental Rangeland Watershed in southeastern Arizona. The watershed is representative of millions of hectares of brush and grass rangeland found throughout the semiarid Southwest, and is considered a transition zone between the Chihuahuan and Sonoran Deserts. Average annual precipitation on the watershed is about 300 mm, and is bimodally distributed with 70 percent occurring during the summer thunderstorm season of July to mid-September. Soils are generally well drained, calcareous, gravelly loams with large percentages of rock and gravel on the soil surface. Three soil series selected were: Bernardino (thermic *Ustollic Haplargid),* Cave (thermic, shallow *Typic Paleorthid),* and Hathaway (thermic *Aridic Calciustoll*). These soils comprise nearly 45 percent of the Walnut Gulch Watershed area (Gelderman 1970), and are USDA-SCS benchmark soils for Arizona. The Bernardino series is a deep, well-drained, fine-textured soil formed in old calcareous alluvium. The soil can have up to 50 percent, by volume, gravel and cobbles in the surface 10 cm and usually less than 35 percent gravel in the remaining profile. Percent sand, silt, clay, and organic matter in the surface 5 cm are 84, 10, 6, and 0.8, respectively. The Cave series is a shallow, well-drained, medium-textured soil with indurated lime hardpans that have developed at less than 45 cm in old gravelly and cobbly calcareous alluvium. This soil can have up to 60 percent, by volume, gravel and cobbles

Figure 1. *Location map of rangeland erosion rainfall simulator plots.*

in the surface 10 cm, and usually less than 40 percent gravel in the remaining profile. Sand, silt, clay, and organic matter in the surface 5 cm are 66, 26, 8, and 1.8 percent, respectively. The Hathaway series is a deep, well-drained, gravelly medium and moderately coarse-textured soil over very gravelly, coarse-textured materials of moderate depths. This soil was formed from gravelly or very gravelly calcareous old alluvium, and can have up to 70 percent, by volume, gravel and occasional cobbles in the surface 10 cm, and usually less than 50 percent in the remainder of the profile. Percent sand, silt, clay, and organic matter in the surface 5 cm are 74, 17, 9, and 1.5 respectively.

Treatments on the Arizona plots were initially imposed in the spring of 1981, and then reapplied, except for the tilled treatment, prior to each season's rainfall simulations. These treatments were: natural cover or no treatment (both grass and shrub), clipped (vegetation clipped at the soil surface and then controlled with a systemic herbicide), bare (vegetation clipped and controlled with systemic herbicide and all surface rock fragments greater than 5 mm removed), and tilled (up and down slope moldboard plowing and disking). The tilled treatment was intended to represent the standard USLE treatment for determination of the soil erodibility factor (K). The clipped treatment was used to determine vegetation effects on erosion and the bare plot was to define the role of rock fragments (erosion pavement) on soil erosion. A pinpoint meter was used to describe plot surface and canopy characteristics before and after initial treatment. The meter is 3.05 m long, with pin holes spaced every 60 mm. The meter was placed perpendicular to the plot slope and rested on the metal plot border at 10 positions evenly spaced along the plot. At each position, 49 pin-point surface and canopy measurements were made by dropping a pin through each pin hole. Characteristics measured were bare soil (particles < 2 mm), gravel (particles 2 to 20 mm), rock (particles$>$20 mm), litter, vegetative basal cover and crown cover.

Southwest Idaho and North-Central Nevada Plots:

The rainfall simulation plots representative of extensive sagebrush rangelands in the northwest United States were located at 3 sites on the Reynolds Creek Experimental Watershed in southwest Idaho, and at 1 site on the Saval Ranch in north-central Nevada. Season precipitation distributions in the area show a winter maximum and summer minimum, and increases with increasing elevation. Most erosion is associated with snowmelt or rain-on-snow runoff. Detailed soil texture, organic matter, structure, permeability, and erodibility data from plot samples and nearby pits were reported by Johnson et al. (1984).

Treatments on the simulation plots were: (1) tilled - vegetation and coarse roots were removed before rototilling to about 15 cm depth, an approximation of the USLE fallow condition, (2) clipped - all vegetation was cut at the ground surface and removed without serious disturbance of roots and cryptogams, (3) partial clipping -only herbaceous plants were clipped and removed from 2 plots on the Saval Ranch to simulate vegetation removal by cattle grazing, (4) grazed - plots were grazed naturally by cattle a month or two before simulation runs, and (5) ungrazed - cattle were excluded from grazing for about 10 years before simulation runs.

Canopy and ground cover, including vegetation, litter, and rock, were measured by use of a vertical point frame. A total of 160 points were recorded on tilled plots and 520 points on other plots. Partly decomposed plant material and rock/gravel greater than about 2 mm diameter were included as ground cover.

New Mexico Plots:

The rainfall simulator plots in northern New Mexico were established in June, 1982, and are located at the Los Alamos National Laboratory Engineered Test Facility in Los Alamos, New Mexico. This area is typic Pinyon-Juniper ecosystem, and has interspatial grassy areas. Average annual precipitation is about 470 mm, with about 60 percent occurring during the summer months of June through September. Thunderstorms dominate the summer rainy period, and rain and snow occur during the winter months. Two natural cover plots were installed on the Hackroy soil series, which consists of very shallow to shallow, well-drained soils that formed in material weathered from tuff on mesa tops. The soil is commonly observed as the Hackroy sandy loam (Nyhan et al. 1978) and classified as a *Lithic Aridic Haplustal* (clayey, mixed, mesic family). The surface layer of the Hackroy soils is brown sandy loam or loam, about 10 cm thick. The subsoil is a reddish brown clay, gravelly clay or clay loam about 20 cm thick. The depth to tuff bedrock and the effective rooting depth are 20 to 50 cm. The soils exhibit low permeability, low available water capacities, medium runoff and moderate water erosion hazard. Additional study area description from a companion study investigating the hydrology and erosion of shallow land burial trench caps can be found in Nyhan et al. (1984).

Nevada Test Site Plots:

The Nevada Test Site (NTS) plots were established in April of 1983 at Area 11 (plots 1-6), which is located in the transition zone between the Great Basin and Mojave Desert, and near Mercury, Nevada (plots 7-12), in the northern Mojave Desert. Annual precipitation generally varies from 125 to 175 mm of which about 75% occurs between mid-September and late-March and the remaining comes during the summer season as scattered thunderstorms. The two study sites are about 35 air-km apart on soils that have not been given official series names. Both soils are *Typic Durothid* (shallow, mixed thermic). The primary differences between the two soils are in textural class and in parent material. Area 11 soil is coarse-loamy, and formed in material weathered from tuff, basalt, and limestone. Mercury soil is loamy, with randomly dispersed clay pockets, and formed in material weathered from limestone, quartz, and tuff. Both study sites are underlain by silica-lime hardpan; the soils are well drained with medium to rapid runoff, and both have moderate permeability. The Mercury soil has higher water holding capacity primarily as the result of higher clay content and less coarse sand through the profile. Percent coarse sand, fine sand, silt and clay in the surface 5-cm are 15.2, 69.6, 14.5, and 0.7, respectively for the Area 11 soil, and 20.4, 58.8, 14.8 and 6.0, respectively, for the Mercury soil. Plot treatments were the same as the Arizona plots, except that the tilled treatment was not made. Also, the NTS plots had soil moisture measurements made using psychrometric transducers and resistance cells. Other than these two differences, all aspects of the study were identical to the Arizona erosion plot study.

Results and Discussion

Arizona Plots:

Four years, or 8 seasonal rainfall simulations, have been made on the 24 Arizona erosion plots at Walnut Gulch. Data from these simulations and plot surface and vegetation characteristics are given in Appendix A. Summaries of runoff and erosion rates are given in Tables 2 and 3. Light wind and filter plugging problems caused deviations from the planned 60 mm application rate. Runoff and subsequent erosion from the tilled plots were practically nonexistent except for the very wet runs. Because of the unexpected response from the tilled plots, only one replication on each soil was retilled after the first year of runs. This deviation from the original plan was designed so that the recovery rate and response of the tilled plot could be determined. The tilled plot data have not been summarized because of complications involved with sequences of retreatment and invasion of vegetation.

Seasonal Differences: Seasonal (spring-fall) runoff and erosion rate (per EI unit) differences were found throughout the 4-year study period. The magnitude of these differences appears to be treatment and soil variable, but the trend was toward more runoff and consequent erosion from the fall simulations, except for the

Table 2. Average spring (Sp) and fall (Fa) runoff rate (mm/EI)[1] Arizona plots.

		Natural		Clipped		Bare	
Soil	Surface	Sp	Fa	Sp	Fa	Sp	Fa
Bernardino	dry	0.017	0.012	0.021	0.038	0.052	0.066
	wet	0.016	0.018	0.029	0.052	0.055	0.060
	very wet	0.025	0.026	0.040	0.057	0.060	0.068
Cave	dry	0.022	0.043	0.028	0.062	0.053	0.069
	wet	0.025	0.044	0.044	0.062	0.055	0.068
	very wet	0.033	0.049	0.052	0.070	0.059	0.076
Hathaway	dry	0.020	0.046	0.028	0.060	0.042	0.064
	wet	0.018	0.035	0.032	0.056	0.039	0.059
	very wet	0.024	0.042	0.040	0.066	0.056	0.069

[1] EI = erosivity (MJ • mm ha^{-1} • h^{-1})

Table 3. Average spring (Sp) and fall (Fa) erosion rates (kg/ha/EI)[1], Arizona plots.

		Natural		Clipped		Bare	
Soil	Surface	Sp	Fa	Sp	Fa	Sp	Fa
Bernardino	dry	0.248	0.067	0.379	0.592	9.717	8.468
	wet	0.194	0.102	0.433	0.741	10.489	8.986
	very wet	0.266	0.125	0.669	0.830	10.061	8.612
Cave	dry	0.367	0.486	1.013	1.737	9.547	11.074
	wet	0.414	0.436	1.253	1.543	8.099	9.316
	very wet	0.449	0.437	1.637	1.684	7.371	8.985
Hathaway	dry	0.347	0.389	0.743	1.273	9.882	10.948
	wet	0.244	0.299	0.685	1.260	8.387	9.147
	very wet	0.331	0.360	0.884	1.464	9.705	10.112

[1] EI = erosivity (MJ • mm ha^{-1} • h^{-1})

Table 4. Average runoff and soil loss by treatments, Reynolds Creek and Saval Ranch plots.

	Runoff (mm)			Soil loss (gm)		
Treatment	Dry run	Wet run	Very wet run	Dry run	Wet run	Very wet run
Tilled	37.5	24.1	23.5	22225	15580	13194
Clipped	10.2	9.4	13.3	1309	1133	1406
Part. Clipped	5.4	7.4	11.2	495	488	685
Grazed	6.1	6.5	9.8	681	492	613
Ungrazed	0.3	0.6	2.8	45	41	75

Table 5. Data for rainfall simulator on natural cover plots at Los Alamos, New Mexico (June, 1982).

Plot No.	Treatment	Precipitation (mm)	Erosion Index[1] (MJ • mm • ha^{-1} • ha^{-1})	Runoff (mm)	Sediment (gm)
			Dry Surface		
1	NAT	56.06	663	17.97	1866
2	NAT	54.96	638	11.02	1088
			Wet Surface		
1	NAT	20.90	184	7.19	626
2	NAT	22.43	212	4.81	310
			Very Wet Surface		
1	NAT	28.30	338	20.92	2860
2	NAT	29.16	359	16.47	1637

[1] EI corrected for rainfall simulator and natural rainfall energy differences.

natural plots. The natural cover plots had less erosion in the fall, probably because of the increased vegetative cover produced during the summer growing season. Also, the clipped and bare plots would still be influenced by the soil surface compacting effects produced by the summer thunderstorm rainfall, an effect dissipated by the winter freeze-thaw process that tends to loosen the soil surface before the spring simulator runs.

Soil Differences: Runoff rates among the three soils did not vary as greatly as the erosion rates. The Bernardino soil had lower erosion rates than either the Cave or Hathaway, regardless of the plot treatment. Erosion rate differences between the Cave and Hathaway soils were very small, except for the clipped treatment under which the Cave soil had higher erosion rates (possibly showing a higher soil erodibility and/or more exposed surface soil.

Antecedent Moisture Effects: Runoff rates increased as soil moisture increased (dry surface to wet to very wet) on all soils, treatments and both seasons. Generally, erosion rates were lowest from the wet surface condition.

Treatments: Runoff rates varied between treatments and were affected by both soil and season. The bare plot always had the greatest runoff and erosion rates, regardless of the soil or season, but the magnitude of these rates was greatest in the fall. The natural cover plot had the lowest runoff rate, and again, the fall rates showed the larger treatment differences. Treatment effects on erosion rates were very obvious, with the bare treatment on the Bernardino soil having an erosion rate nearly 90 times greater than the natural cover treatment. The bare treatment erosion rate of the other two soils was nearly 30 times greater than the natural cover treatment. The clipped treatment erosion rate on the Bernardino soil was nearly 8 times greater than that of natural cover treatment. The erosion rate of the clipped treatment on the other two soils was about 4 times greater than the natural cover treatment erosion rate.

Surface and Vegetative Characteristics Effects: Results from the treatment comparisons of erosion rates indicated the effects of various surface and canopy characteristics. Vegetative canopy does affect erosion rates of rangeland soils but not as dominantly as does rock and gravel cover (erosion pavement). Analysis of the erosion pavement effect (rock and gravel particles > 5 mm) on erosion rates indicates that the relationship was exponential and, based on data from the three soils for all runs over the four year period, had an exponent of –0.044 (Fig. 2). These results are very similar to those reported by Simanton et al. (1984), who used only one year of simulator data to develop the erosion pavement-erosion rate relationship. Vegetative canopy, during the first two seasons' runs, did not seem to affect erosion rates. However, as vegetative cover became more dominant on the ungrazed, natural cover plots, the erosion rate difference between the vegetated and clipped plots began to increase until there was an almost tenfold difference in erosion rates between the two conditions. Vegetation type differences did not significantly affect erosion rates; similar rates were found for both grass, grass/shrub, and shrub-dominated canopies.

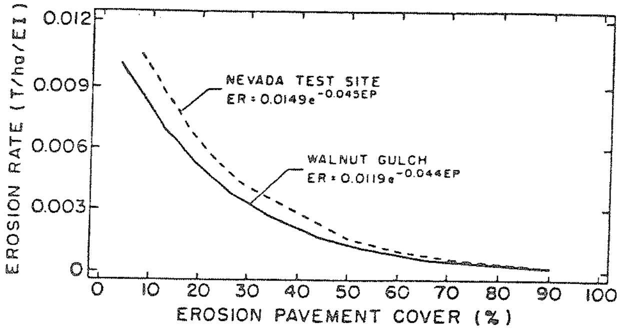

Figure 2. *Relation between erosion rate (ER) and erosion pavement (EP) for the Arizona and Nevada Test Site rainfall simulator erosion plots.*

USLE Parameter Values — K-Factor, C-Factor: Assuming the bare plot represented the USLE "unit plot" (corrected for LS) condition as the most erodible condition possible (C=1), the K factor (t • ha • ha/ha • MJ • mm) value from the simulator results were 0.009, 0.011, and 0.011 for the Bernardino, Cave, and Hathaway soils, respectively. These measured K values are 44, 33, and 43 percent of the K values derived from the soil erodibility nomograph developed by Wischmeier et al. (1971). Measured K values, as reflected in the erosion rate from the bare plots, did not vary between spring and fall simulations but did change over the 4-year study period (see Simanton and Renard in these proceedings). If the measured K values from the bare plot are used to calculate C in the USLE, C factor evaluation can be made from measured erosion and related to surface and vegetation characteristics of the erosion plots. Additional data are being collected to develop rangeland C value tables for different combinations of vegetation and surface conditions.

Southwest Idaho and North-Central Nevada Plots:

Data from rainfall simulation and surface and canopy characteristics of 38 plots from the summer of 1982 are listed in Appendix B. Light wind and slight simulator filter plugging caused some variation in applied rainfall. Runoff from the plots ranged from 0 on a few ungrazed plots to over 90 percent of applied rainfall on some tilled plots. Soil losses also ranged widely, with greatest losses from tilled plots on 9-percent slopes.

Data summaries by treatment show minimal values of runoff and erosion from ungrazed plots, consistently high values on tilled plots, and intermediate values on clipped and grazed plots (Table 4).

USLE soil erodibility factor (K) values, determined from rainfall simulation on tilled plots and by the soil erodibility nomograph (Wischmeier and Smith 1978) using plot soil samples, were compared, and the nomograph K values were slightly higher than measured K values on most of the plots (Johnson et al. 1984). Much of this difference is probably caused by the lack of a true fallow soil surface. Soil erodibility values by rainfall simulation varied widely between dry, wet, and very wet runs, and among sites; however, for practical application, nomograph erodibility values caused only a slight over-prediction of soil loss.

Cover-management factor values for ungrazed plots with rainfall simulation were consistently less than estimated by the subfactor method (Dissmeyer and Foster 1981), probably because higher infiltration capacity was not accounted for as a subfactor. Additional detailed analysis has been made by Johnson et al. (1984).

Soil loss predictions, based on USLE cover factors for rangelands, do not fully account for the complexity of surface roughness, root and cryptogam effects, and diversity of plant cover, both in time and space. However, average cover-management factor values, for grazed plots by the subfactor procedure, were in reasonable agreement with rainfall simulation results.

New Mexico Plots:

Data summaries from 1 season rainfall simulations at the Los Alamos National Laboratories (LANL) natural erosion plots are given in Table 5, and plot surface and vegetation characteristics are presented in Table 6. Both runoff and erosion rates increased with increasing soil moisture as represented by the wet and very wet runs. Though there was a relatively small increase in rates between the dry and wet runs, the very wet run had nearly a threefold increase in erosion rate associated with nearly a twofold increase in runoff rate. Vegetation canopy appears to reduce both runoff and erosion, but the data are limited, and analysis is difficult.

Nevada Plots:

Two years, or 4 seasonal, rainfall simulations have been made on the NTS erosion plots. Data from these simulations and plot surface and vegetation characteristics are given in Appendix C. Data summaries of the runoff and erosion rates are given in Tables 7 and 8.

Seasonal Differences: As with the Arizona plots, seasonal (spring-fall runoff and erosion rate (per EI unit) differences were found throughout the 2 year study period. Fall runoff rates were higher than the spring regardless of the soil. However, on the Mercury soil, the season of higher runoff rates (fall) was not the season of higher erosion rates (spring), indicating that some factor, other than runoff, was controlling erosion.

Soil Differences: The Mercury soil had higher runoff and erosion rates than the Area-11 soil, regardless of the plot treatment.

Antecedent Moisture Effects: Runoff rates increased as soil moisture increased (dry surface to wet to very wet) on both soils under all treatments. Erosion rates were more variable, and decreased on the wet surface runs under the natural treatment. These runoff and erosion responses were very similar to those from the Arizona plots.

Treatments: Runoff rates varied among treatments, and were affected by both soil and season. The bare plot always had the greatest runoff rate, regardless of the soil or season, but the runoff rate was greater in the fall. The natural cover plot had the lowest runoff rate, and again, the fall rates showed the larger treatment differences. Bare treatment erosion rates on the Mercury soil were about 20 times greater than the rates from the natural treatment and 10 times greater than the clipped treatment. The Area 11 bare treatment erosion rates were about 45 times greater than the natural treatment, and about 25 times greater than the clipped treatment. These erosion rate differences between treatments are not as great as found on the Arizona plots, but the general trend of treatment effect is the same, again indicating the importance of erosion pavement on the erosion process.

Surface and Vegetative Characteristics Effects: Erosion pavement appears to be an important factor in the erosion process, but not as dominant as was found on the Arizona plots. Vegetation was more effective in reducing erosion rates on the NTS than on the Arizona plots. Analysis of the effect of erosion pavement (rock and gravel particles > 5 mm) on erosion rates indicated that the relationship was exponential, similar to the Arizona relationship, and based on data from the two soils for all runs over the two year period, had an exponent of -0.045 (Fig. 2).

USLE Parameter Values - K-Factor, C-Factor: Assuming the bare plot represented the USLE "unit plot" (corrected for LS) condition as the most erodible condition possible (C=1) (t • ha • ha/ha • MJ • mm), the K factor value from the simulator results were 0.016, and 0.010 for the Mercury and Area 11 soils, respectively. These measured K values are 38 and 16 percent of the K values derived from the soil erodibility nomograph developed by Wischmeier et al. (1971). The measured K values from the bare plot

Table 6. Plot characteristic data for rainfall simulator on natural cover plots at Los Alamos, New Mexico (June, 1982).

Plot No	Treatment	Slope (%)	Biomass ($gm\ m^{-2}$) Cactus	Grass	Shrub	Leaf area index (x100) Cactus	Grass	Shrub	Canopy cover (%)
1	NAT	5.2	63.2	1.0	7.0	2.4	1.1	1.6	63
2	NAT	5.2	25.0	5.0	31.0	1.3	1.7	18.1	78

NOTE: Biomass calculations based on oven dry-weight basis.

Table 7. Average spring (Sp) and fall (Fa) runoff rate (mm/EI)[1], Nevada Test Site.

Soil	Surface	Natural Sp	Natural Fa	Clipped Sp	Clipped Fa	Bare Sp	Bare Fa
Mercury	dry	0.027	0.048	0.048	0.065	0.062	0.078
	wet	0.037	0.049	0.059	0.075	0.068	0.076
	very wet	0.045	0.060	0.066	0.088	0.077	0.094
Area 11	dry	0.003	0.018	0.001	0.026	0.021	0.057
	wet	0.011	0.016	0.011	0.026	0.043	0.053
	very wet	0.022	0.033	0.026	0.038	0.054	0.062

[1] EI = erosivity (MJ • mm ha^{-1} • h^{-1})

Table 8. Average spring (Sp) and fall (Fa) erosion rate (kg/ha/EI)[1], Nevada Test Site.

Soil	Surface	Natural Sp	Natural Fa	Clipped Sp	Clipped Fa	Bare Sp	Bare Fa
Mercury	dry	0.514	0.518	1.003	0.871	11.943	9.642
	wet	0.471	0.445	1.069	0.984	14.125	9.708
	very wet	0.581	0.575	1.218	1.341	12.197	11.180
Area 11	dry	0.050	0.167	0.038	0.678	3.531	10.031
	wet	0.189	0.125	0.249	0.302	8.060	10.017
	very wet	0.400	0.211	0.484	0.420	10.682	11.336

[1] EI = erosivity (MJ • mm ha^{-1} • h^{-1})

were used with the measured soil loss from the natural and clipped plots to estimate C values for rangeland conditions at the NTS. Time related changes in the C factor were found, and, when more data become available (the simulator studies are continuing at the NTS), results will be more definitive.

Conclusions

Rainfall simulator studies on erosion plots have been made on rangelands in Arizona, Idaho, New Mexico, and Nevada. An extensive data base has been developed for various ecosystems in these western states, and because the same simulator and similar experimental design were used for all the studies, results can be easily transferred across ecosystems. Results from these studies have been related to USLE parameters and to effects of various surface and canopy characteristics. The importance of erosion pavement on the erosion process of western rangelands has been demonstrated, and appears to be more dominant than vegetation canopy.

Rangeland rainfall simulation erosion studies are a relatively new research area, and the results from our studies have only begun to answer some of the basic questions regarding erosion estimating techniques on rangelands. Additional studies, research approaches, and analyses are still needed to fully understand the rangeland upland erosion processes.

References

Dissmeyer, G.E., and G.R. Foster. 1981. Estimating the cover-management factors (C) in the Universal Soil Loss Equation for forest conditions. J. Soil Water Cons. 36(4):235-240.

Gelderman, F.W. 1970. Soil survey, Walnut Gulch experimental watershed, Ariz. Spec. Rept., USDA-SCS, 55 p.

Johnson, C.W., M.R. Savabi, and S.A. Loomis. 1984. Rangeland erosion measurements for the USLE. Trans. ASAE 27(5):1313-1320.

Neff, E.L., editor. 1979. Rainfall simulator workshop, Tucson, Ariz. ARM-W-10, USDA-SEA, 184 p.

Nyhan, J.W., L.W. Hacker, T.E. Calhoun, and D.L. Young. 1978. Soil survey of Los Alamos County, New Mexico. Los Alamos Sci. Lab. Rept. LA-6779-MS, Los Alamos, NM, 102 p.

Nyhan, J.W., G.L. Depoorter, B.J. Drennon, J.R. Simanton, and G.R. Foster. 1984. Erosion of earth covers used in shallow land burial at Los Alamos, New Mexico, J. Environ. Qual. 13:361-366.

Simanton, J.R., and K.G. Renard. 1982. Seasonal change in infiltration and erosion from USLE. *In:* Hydrol. and Water Resour. in Arizona and the Southwest, Office of Arid Land Studies, Univ. of Arizona, Tucson 12:37-46.

Simanton, J.R., E. Rawitz, and E.D. Shirley. 1984. Effects of rock fragments on erosion of semiarid rangeland soils. *In:* Erosion and Productivity of Soils Containing Rock Fragments. Spec. Pub. No. 13, Soil Sci. Soc. Am., Madison, WI, pp. 65-72.

Swanson, N.P. 1965. Rotating-boom rainfall simulator. Trans. ASAE 8(1):71-72.

Wischmeier, W.H., and J.V. Mannering. 1969. Relation of soil properties to its erodibility. Soil Sci. Soc. Am. Proc. 33:131-137.

Wischmeier, W.H., C.B. Johnson, and B.V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil Water Conserv. 26:189-192.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses - a guide to conservation planning. U.S. Dept. Agric., Agric. Handbook No. 537, 58 p.

Time Related Changes in Rangeland Erosion

J.R. Simanton and K.G. Renard

Key Words: rainfall simulation, USLE, runoff

Abstract

Rainfall simulation studies on semiarid rangeland plots in southeastern Arizona have indicated that erosion rates per unit rainfall energy changed with time during a four-year study. Erosion rates changes corresponded to observed changes in runoff rate and were also reflected in changes in USLE erosion parameters. The study showed that at least two years of seasonal simulations are needed before erosion and runoff rates reach equilibrium with energy input.

Introduction

Erosion studies in cropland areas have indicated that erosion rates vary in time for various cover-management situations, and that these changes are often related to soil erodibility changes (Dissmeyer and Foster 1981, Van Doren et al. 1984). Most currently-used models assume soil erodibility is time invariant. Thus, some of the cover-management parameter temporal changes observed in field data are possibly reflecting soil erodibility changes. Very little information is currently available concerning erosion rate change within natural conditions on rangelands.

One method of estimating rangeland erosion is through the use of the Universal Soil Loss Equation, USLE (Wischmeier and Smith 1978). The equation has been used with various degrees of success to estimate rangeland erosion from small semiarid watersheds (Simanton et al. 1980, Renard and Foster 1985). Because of the relatively small amount of USLE compatible data available from rangelands, and the need for quantification of rangeland USLE factor values, rainfall simulation studies were conducted on rangeland sites at the Walnut Gulch Experimental Watershed in southeastern Arizona, during the spring and fall, for 4 years (see Simanton et al. in these proceedings for detailed description). Though the main objective of the rainfall simulations was to quantify USLE factors for rangelands, this paper reports interesting time dependent changes found to be occurring during the 4-year study.

The USLE estimates average annual soil loss using the equation:

$$A = RKLSCP$$

where A = estimated soil loss (tons/ha/yr),
R = rainfall erosivity factor (EI units/yr) (EI = MJ • mm/ha • h),
K = soil erodibility factor (tons/ha/EI unit) (t • ha • h/ha • MJ • mm),
LS = slope steepness-length factor,
C = cover and management factor, and
P = erosion control practice factor.

Of the five factors in the USLE (LS is usually considered one term), the rainfall factor is the only one that can be expected to significantly change naturally from one year to another on rangeland. This is also the factor over which man has no control. The cover-management factor may also change naturally from year to year, but not as drastically as that for the rainfall factor. Actual perennial vegetation cover changes are difficult to perceive on a year to year basis, and tend to leave the impression that a static cover condition exists on rangeland.

Rainfall simulator experiments, to evaluate the terms of the USLE, were initiated in the spring of 1981 on three soils at the Walnut Gulch Experimental Watershed (Simanton and Renard 1982). The experimental design included using a rotating boom rainfall simulator (Swanson 1965) on 10.7 m by 3.05 m plots, with two replications of natural, clipped, bare, and tilled treatments. Grazing was excluded from the plots throughout the study period. The clipped treatment consisted of clipping the vegetation at the ground surface, removing the clippings, and controlling any vegetation regrowth with a systemic herbicide. The bare treatment included vegetation clipping and removal, herbicide control, and removing all rock fragments larger than 5 mm in diameter from the soil surface that were not partially embedded in the soil. The tilled treatment was the standard up-and-down slope cultivation like that used to evaluate K-factor values for agricultural soils (Wischmeier and Smith 1978). This treatment was assumed to be the one standard that could be used for direct comparison to other rainfall simulation studies. The initial treatments were made prior to the rainfall simulations in the spring of 1981. Retreatments were made before each successive seasonal rainfall simulation (simulations were made in the spring and fall of each year). The tilled treatment was not repeated on one of the replications after the first year of the study, and then not repeated on the remaining replication after the second year of the study.

Research Location and Description

The Walnut Gulch Experimental Watershed is located in southeastern Arizona. The area is representative of millions of hectares of brush and grass rangeland found throughout the semiarid Southwest, and is considered a transition zone between the Chihuahuan and Sonoran Deserts (Hastings and Turner 1965). Average annual precipitation on the watershed is about 300 mm, and is bimodally distributed, with 70% occurring during the summer thunderstorm season of July to mid September. Soils are generally well drained, calcareous, gravelly loams with large percentages of rock and gravel on the soil surface. The three soil series selected were: Bernardino (a thermic *Ustollic Haplargid),* Cave (thermic, shallow *Typic Paleorthid),* and Hathaway (thermic *Aridic Calciustoll).* These soils comprise nearly 45% of the Walnut Gulch Watershed area (Gelderman 1970), and are USDA-SCS benchmark soils for Arizona. The Bernardino series is a deep, well-drained, fine textured soil formed in old calcareous alluvium. Although this soil may have 50%, by volume, gravel and cobbles in the surface 10 cm, the remainder of the profile is usually less than 35% gravel. The Cave series is a shallow, well-drained, medium textured soil with indurated lime hardpans that have developed at less than 45 cm in old gravelly and cobbly calcareous alluvium. This soil can have up to 60%, by volume, gravel and cobbles in the surface 10 cm, and usually less than 40% gravel in the remaining profile. The Hathaway series is a deep, well-drained, gravelly medium and moderately coarse-textured soil over very gravelly,

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coarse-textured materials of moderate depths. This soil was formed from gravelly, or very gravelly, calcareous old alluvium, and can have up to 70%, by volume, gravel and occasional cobbles in the surface 10 cm, and usually less than 50% in the remainder of the profile. Vegetation of the area includes: creosote bush *(Larrea tridentata)*, white-thorn *(Acacia constricta)*, tarbush *(Flourensia cernua)*, snakeweed *(Gutierrezia sarothrae)*, burroweed *(Aplopappus tenuisectus)*, black grama *(Bouteloua eriopoda)*, blue grama *(B. gracilis)*, sideoats grama *(B. curtipendula)*, and bush muhly *(Muhlenbergia porteri)*. Typically, plant canopy averages 50% and plant basal area averages 2%.

Results and Discussion

The concept of using a tilled fallow plot as the reference for the simulator studies on rangeland was abandoned after a short time because: (1) tillage is not a common practice on semiarid rangelands; (2) the tilled rangeland plots did not yield appreciable runoff and subsequent erosion in contrast to that treatment's yield in agronomic cropped areas; and (3) the tilled plots remained artificially rough with tremendous surface depression storage because of the large amount of boulders, cobbles, and gravel material brought to the soil surface. Thus, after two seasons, only the clipped and bare treatments were left to compare to the natural plots.

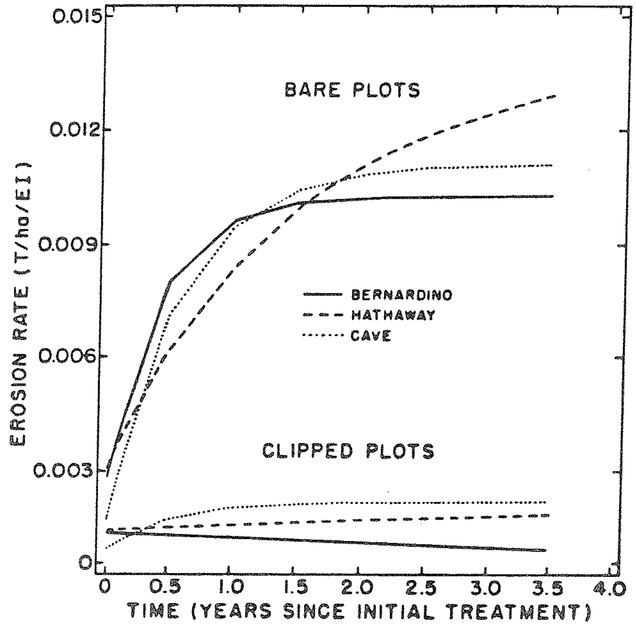

Figure 1. *Computer fitted function of actual erosion and time data for the 2 replication average for spring and fall runs with time zero equal to spring 1981 for the Walnut Gulch bare and clipped plots.*

The bare soil treatment produced the largest erosion rates (tons/-ha/EI) of all treatments, and the rates increased with time for about 2 years before reaching an "equilibrium" with the energy input for both the Bernardino and Cave soils (Fig. 1). After 4 years, the Hathaway soil erosion rate still had an upward trend. The erosion rate increase for this treatment closely emulated runoff changes (Fig. 2) which may be attributed to the decrease in root and residue material in the soil, which in turn decreased the soil macropore structure (Dixon 1975). Furthermore, the formation of a rill network that was observed to develop after the vegetation and rock fragments were removed would also cause the runoff and erosion to increase, as well as shorten the runoff response time to the simulated rainfall. Most likely, the increase in erosion rate is a combination of these and other factors. If the erosion rate increase was a function of plant and litter removal, the effect should be found in the clipped plot results.

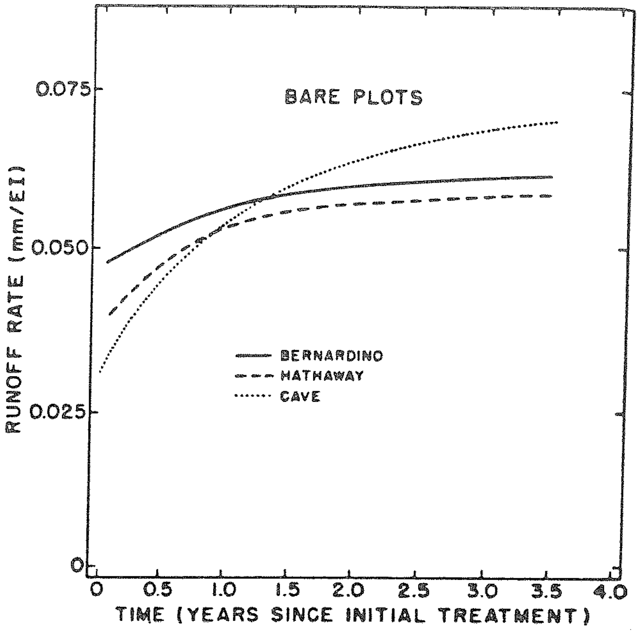

Figure 2. *Computer fitted function of actual runoff and time data for the 2 replication average for spring and fall runs with time zero equal to spring 1981 for the Walnut Gulch bare plots.*

The clipped plot's erosion rate indicated a small change with time (Fig. 1), and, as with the bare plot, the change was associated with the change in runoff rate (Fig. 3). This suggests a small influence of plant and litter cover removal on erosion rate, and that the rill network formation was probably dominating the process. In addition, the erosion pavement may be effective in maintaining a high infiltration capacity by preventing soil surface crusting or sealing, and also reducing overland flow velocity.

Erosion and runoff rates of the natural plots showed a downward trend for the Bernardino and Hathaway soils and an upward

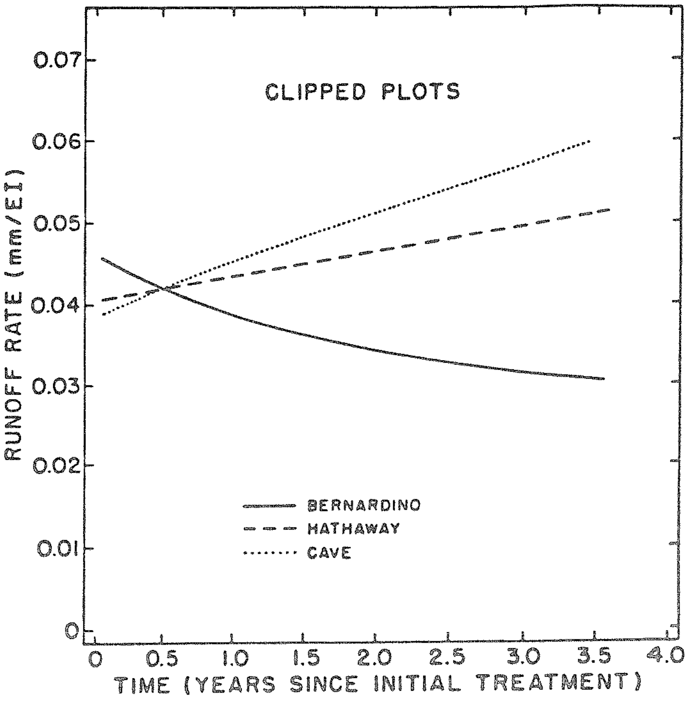

Figure 3. *Computer fitted function of actual runoff rate and time data for the 2 replication average for spring and fall runs with time zero equal to spring 1981 for the Walnut Gulch clipped plots.*

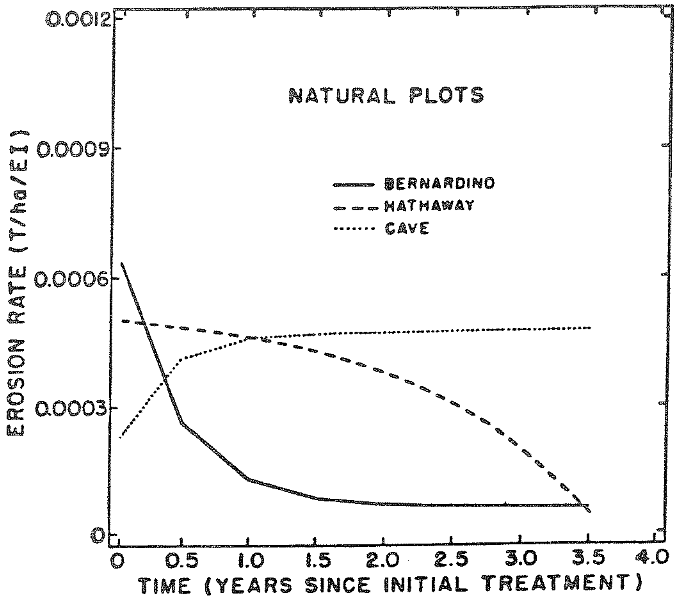

Figure 4. *Computer fitted function of actual erosion rate and time data for the 2 replication average for spring and fall runs with time zero equal to spring 1981 for the Walnut Gulch natural plots.*

trend on the Cave soil for about the first 2 years (Fig. 4 and 5). The shapes of the erosion and runoff rate curves are probably reflecting vegetation differences. The Bernardino natural plots were dominated by perennial grasses; the Cave natural plots were shrub and forb dominated; and the Hathaway natural plots had both grass and shrub canopy cover (see Simanton et al. in these proceedings).

Results from these four years of simulation indicate the importance of multi-year simulations in that erosion rates do change in time. If the data are to be used in models estimating long term management effects on erosion, the data base needs to extend for more than 1 year.

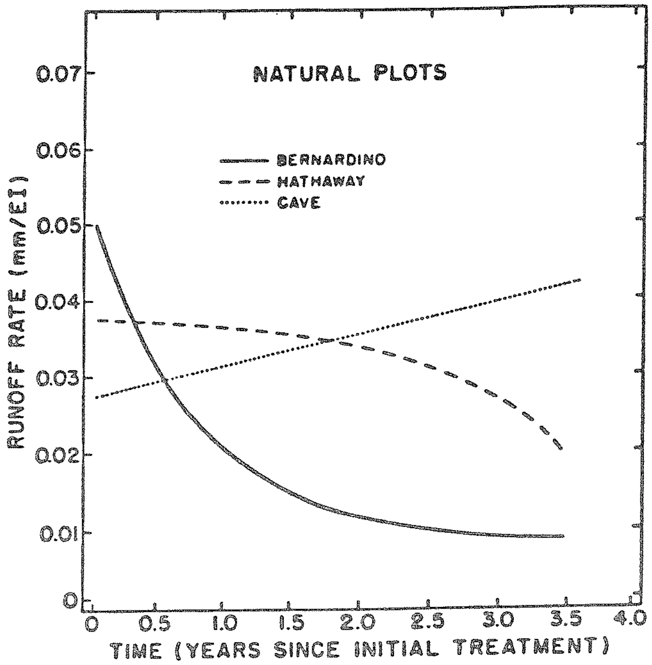

Figure 5. *Computer fitted function of actual runoff rate and time data for the 2 replication average for spring and fall runs with time zero equal to spring 1981 for the Walnut Gulch natural plots.*

Because the tilled plot did not have significant runoff or erosion, the bare plot was used as the rangeland "standard plot" to determine K values (t • ha • h/ha • MJ • mm) for the three soils used in the study (assume C equaled 1 for the bare condition). Soil K values increased with time and, for the Bernardino and Cave soils, leveled out after about 2 years (Fig. 6). The calculation to determine K from actual soil loss for the bare plot on each soil is,

$$K = A/RCLSP$$

where:

A = actual soil loss from the bare plot,
R = rainfall energy to produce the soil loss,
LS = slope and length correction for each plot,
P = 1 for rangeland conditions, and
C = 1 for the bare plot.

When C = 1 for the bare plot, the simulator derived K values were 0.009, 0.012, and 0.011 (t • ha • h/ha • MJ • mm) for the Bernardino, Hathaway, and Cave soils, respectively. The nomograph values (derived from soil characteristics as described by Wischmeier et al., 1971) for these same three soils were 0.021, 0.028, and 0.036 (t • ha • h/ha • MJ • mm), respectively. If the bare plot C value is assumed to be 0.45, as given in Table 10 of Agricultural Handbook 537 (Wischmeier and Smith 1978), and used to calculate K from the simulator bare plot data, K values would be 0.020, 0.027, and 0.024 (t • ha • h/ha • MJ • mm), respectively. These are fairly consistant with the nomograph K values for the three soils. However, the 0.45 maximum C value in Table 10 of Handbook 537 was determined from an agricultural soil, and represents the ratio of soil loss from a 7-year reconsolidated tilled soil to the 2-year average soil loss just after tillage (i.e., soil loss from the tilled soil was 2.2 times greater than the soil loss from the same soil 7 years after its last tillage). Results from our rangeland tilled treatment indicated that both runoff and erosion were reduced just after tillage, as compared to the natural condition, and that erosion increased with time as the soil reconsolidated, vegetation invaded, and rock fragments worked to the soil surface.

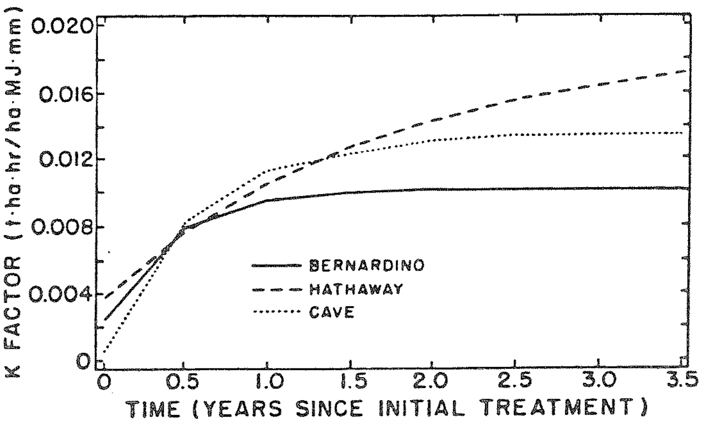

Figure 6. *Computer fitted function of USLE K factor change with time for the Walnut Gulch bare plots. Time zero equals spring 1981 and C was assumed 1 for the bare surface condition.*

Assuming that a complete series of runs (each season) represented a year's total natural R (average R for Walnut Gulch is about 1020, and a season's simulated rainfall R is about 1150), then each season's simulation represented a year, and time-related changes in erosion rates could be made. The third and fourth year average soil loss was 71, 84, and 56% of the average soil loss during the first and second year after tillage for the Bernardino, Hathaway, and Cave soils, respectively.

Vegetation effects on erosion rates were determined from erosion rate differences between the clipped and natural treatments on all soils. By the end of the 4 year study, the clipped plots had an average equilibrium erosion rate almost 5 times greater than the average erosion rate of the natural plots. However, the bare plots had an average equilibrium erosion rate of more than 25 times the average rate of natural plots. Even though the clipped plots did not have vegetation after the first year of treatment, the erosion rate changed very little with time, suggesting that the erosion reducing effect of vegetation was not as significant as the effect of surface rock fragments, as shown by Simanton et al. in these proceedings.

Canopy cover of the natural plots tripled on the Bernardino and Hathaway plots, and nearly doubled on the Cave plots over the 4-year study (Fig. 7). This increase is, undoubtedly, a result of the increased water applied, but also may be reflecting response to no livestock grazing. Litter cover on the natural plot's soil surface decreased with increasing vegetation canopy but the amount of bare soil more than doubled over the 4-year study period (Fig. 8). This increase in surface soil on the natural plots could be caused by vegetation trapping of wind blown soil or, as evidenced by the almost complete lack of litter cover, termite activity. Termites bring soil to the surface, and use it to coat litter particles so they can utilize the litter daylong out of the direct rays of the sun (Whitford et al. 1982). With weathering, these termite casts break down, and the soil remains on the surface. Protected by the vegetation canopy, the soil brought to the surface is not eroded from the natural plot as rapidly as from a plot without vegetation.

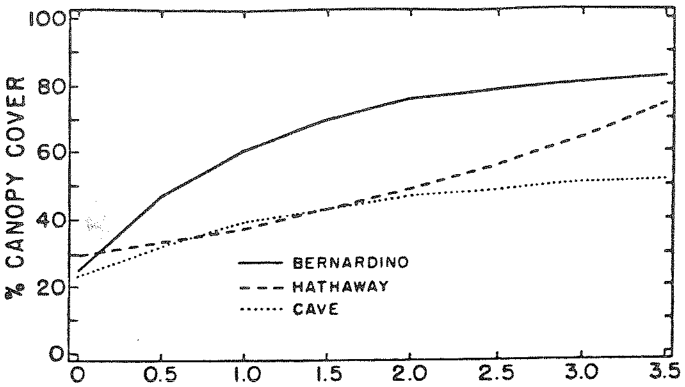

Figure 7. Computer fitted function of percent canopy cover and time where time zero equals spring 1981 for the Walnut Gulch natural plots.

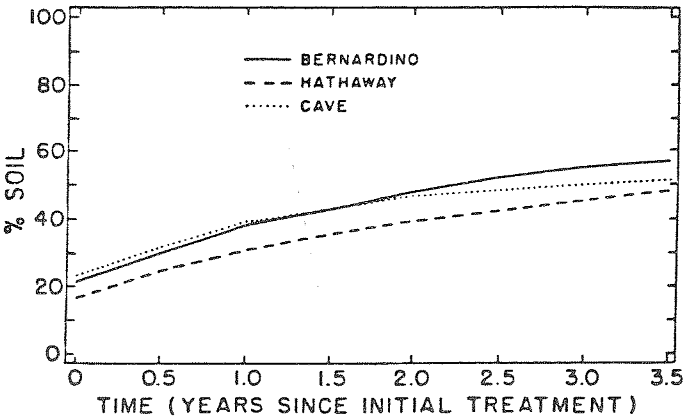

Figure 8. *Computer fitted function of percent bare soil and time where time zero equals spring 1981 for the Walnut Gulch natural plots.*

The USLE C factor, or cover-management factor, was calculated for the natural plots assuming that the bare plot C value was unity, and that the calculated K, or soil erodibility factor, of the bare plot was valid for each of the soils. Because of the method of calculation, the C and K factors are not independent, and a decrease in one will produce an increase in the other. The C value decreased with time, but at different rates for each soil-vegetation complex (Fig. 9). The rate of decrease for C on the Bernardino soil natural plot (grass vegetation) was over 2 times the increasing rate of the K value during the first year of the study. The decrease in the C value of the Hathaway soil natural plot (shrub and grass vegetation) was about the same as the increase in the K value. The Cave soil natural plot (shrub and forbs) had a C value change that was 6 times less than the corresponding increase in the K value during the first year of study. The C value of the Bernardino and Cave soils reached equilibrium around 2 years after the start of the simulation study, whereas the Hathaway soil natural plot still had a slight downward trend after 4 years. The differences in C factor response reflect the effect of vegetation canopy types, with the grass canopy being more important in erosion control than a shrub canopy. However, the effect of the vegetation type also influences runoff, which is interrelated with erosion.

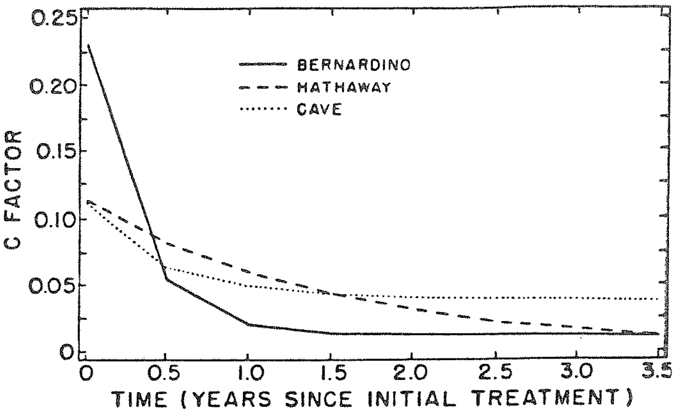

Figure 9. *Computer fitted function of USLE C factor change with time where time zero equals spring 1981 for the Walnut Gulch natural plots. The C factor was calculated using the simulator derived K value from the bare plots whose C value was assumed to be 1.*

Summary

Four years of seasonal rainfall simulation studies on rangeland USLE-type plots have indicated that erosion and runoff rates per unit of EI change with time for the first one to two years, and then tend to reach an equilibrium rate. Associated with these changes, were rate changes in the USLE K (bare treatment) and C factors, vegetation canopy, and amount of bare soil accumulation on the plot surface (natural plot). This study indicates tht at least two years of spring and fall rainfall simulation runs are necessary to adequately define relatively long-term responses of rangeland runoff and erosion.

References

Dissmeyer, G.E., and G.R. Foster. 1981. Estimating the cover-management factor (C) in the universal soil loss equation for forest conditions. J. Soil and Water Cons. 36:235-240.

Dixon, R.M. 1975. Infiltration control through soil surface management. Proc. ASCE Symposium on Watershed Management, Irrig. & Drain. Div., Logan, UT., 543-567.

Gelderman, F.W. 1970. Soil Survey, Walnut Gulch Experimental Watershed, Arizona. Special Report USDA-SCS, 55 p.

Hastings, J.R., and R.M. Turner. 1965. The changing mile. Univ. of Ariz. Press, Tucson, AZ, 317 p.

Renard, K.G., and G.R. Foster. 1985. Managing rangeland soil resources: The universal soil loss equation. Rangelands 7:118-122.

Simanton, J.R., and K.G. Renard. 1982. Seasonal change in infiltration and erosion from USLE plots in southeastern Arizona. Hydrology and Water Res. in Arizona and the Southwest, Office of Arid Land Studies, Univ. of Arizona, Tucson 12:37-46.

Simanton, J.R., H.B. Osborn, and K.G. Renard. 1980. Application of the USLE to southwestern rangelands. Hydrology and Water Res. in Arizona and the Southwest, Office of Arid Land Studies, Univ. of Arizona, Tucson, X;213-220.

Swanson, N.P. 1965. Rotating-boom rainfall simulator. Trans. Amer. Soc. Agr. Engr. 8:71-72.

Van Doren, D.M., W.C. Moldenhauer, and G.B. Triplett, Jr. 1984. Influence of long-term tillage and crop rotation on water erosion. Soil Sci. Soc. Am. J. 48:636-640.

Whitford, W.G., Y. Steinberger, and G. Ettershank. 1982. Contributions of Subterranean termites to the "economy" of Chihuahuan desert ecosystems. Ecologia 55:298-302

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains—Guide to conservation planning. USDA Agr. Handbook No. 537, 58 p.

Rainfall Simulation on Long Slopes of a Phosphate Mine Embankment

George E. Hart, Robert S. Johnston, and Cyril Whitson

Keywords: rainfall simulation, erosion, slope length, mining embankment.

Abstract

Eight rainfall simulator runs were made on a revegetated embankment whose surface was about 54% rock and gravel. Two runs were made on 15.2, 30.5, 45.7 and 61.0 meter plots at intensities between 32 and 42 mm/hr. Erosion per unit area was just slightly greater on the longer plots than on the shortest, but nearly as much as postulated by the length factor in the Universal Soil Loss Equation.

Introduction

Simulated rainfall tests of erosion were made in 1984 on plots of various lengths on a phosphate mine embankment northeast of Soda Springs, Idaho. The objective of these tests was to determine the effect of slope length on erosion and to evaluate the effectiveness of midslope drainage structures for erosion control. Plot lengths were 15.2, 30.5, 45.7, and 61.0 meters; each plot was 3.7 meters wide. The profile of the slope was quite uniform, and the average gradient of the slope was 27%.

Seldom have rainfall simulators been used on such long plots as these and some evaluation of our field methods may help prospective users. A Colorado State University type of sprinkling simulator was used on paired plots with three lines of risers running down the embankment from a pump and water storage bags on the top. Pairs of plots were installed between the three riser lines. Operational characteristics of this simulator have been described by Neff (1979). Overall, the equipment performed satisfactorily and provided usable data from eight runs. But three difficulties should be noted:

1. Rainfall intensities were not as high as desired. We planned for about 50 mm/hr, but the measured intensity on the plots ranged from 32 to 42 mm/hr., which is roughly the 20-yr rainfall intensity recurrence interval for this location. Wind drift may account for some of the reduction in intensity, but we observed that pressure at the risers could not be raised by adjusting the pressure regulators beyond 1.4 kg/cm^2 (20 psi) even though pump pressure was 2.73 kg/cm^2 (39 psi). This loss in pressure probably was due to large frictional losses in the lines and pressure regulators. Our pump was rated at 1135 l/min (300 gal/min) and we suggest that a larger pump be used to provide higher pressures and intensities when long lines of risers are used.

Even though runs were made during relatively calm periods, winds of 6 to 13 km/hr were recorded during the runs. About 15 wedge type plastic rain gages were distributed over each plot and a coefficient of variation from 22 to 34% was observed for rainfall distribution.

2. Sections of sheet aluminum, formed into an inverted V, were laid on the surface along the sides and ends of the plot to create a border. Soil was backfilled and packed against the border and then sealed with a soil tackifier to prevent runoff from leaking under the border. This worked well on the side borders; but during two runs the border at the bottom of the plot failed when the backfill material became saturated midway in the run. A trough, imbedded and sealed into the surface, rather than a flume, would be a better collecting device because runoff would not concentrate and saturate the backfilled soil near the flume.

3. Water supply often is limiting with large rainfall simulators. In our tests, we used three water bags made of rubber-nylon mesh, each with 17 m^3 (4500 gal.) storage, but filled only to about 15 m^3 for safety. During two runs, the bags did not completely drain and runs were terminated early. Sufficient water storage should be available to insure that comparable runoff times, in our case at least 40 minutes, occur on all lengths of plots.

Results

Values of runoff, rainfall, and erosion (calculated as the product of discharge rate and suspended sediment concentration) are given in Table 1. These data represent total values, regardless of the time of each run, and valid comparisons between plot lengths therefore cannot be made from this table. They are presented to illustrate the variability in hydrologic data from plots of differing lengths when runoff time is not carefully controlled. As noted previously, failure of our runoff collection system and running out of water were the main reasons why runoff times varied between plots.

More surface runoff per unit area was generated from the 15.2 meter plots than from the longer ones. Runoff averaged 19 mm. from the shortest plot which was about twice the average amount (10, 8, 9 mm) from the 30.5, 45.7, and 61 meter plots, respectively. Average rainfall was about the same on each set of plots and the difference in runoff volumes suggests that the hydrologic efficiency of the longer plots was not as high as that on the short plot.

Soil losses ranged from .09 to .50 metric tonnes/ha (.04 to .22 tons/ac) from simulated rainfall events which averaged 37 mm/hr. The annual rainfall erosivity (R), in the Universal Soil Loss Equation (USLE), is estimated to be 16 units for this area (Isrealsen et al. 1980). We calculated the erosivity of our simulated storms to be about 4 units. Using a factor of 4 to convert from per-storm erosion to annual erosion, soil loss rates from .4 to 2.0 metric tonnes/ha (.2 to .9 tons/ac) are estimated from our plot data.

These low erosion rates reflect the resistance to erosion of these mine embankments which have been revegetated with grass for three seasons. Cover estimates, made from grid analysis of vertical photographs, show that gravel (<75 mm diameter) occupied 50% of the surface, stone greater than 75 mm was 4%, live vegetation (grasses) covered 10%, and litter amounted to 28% of the area. Only 8% of the surface area was bare soil. Topsoil is generally not used in the revegetation of phosphate mine embankments in this area. Erosion rates when the embankment was newly-constructed and more soil was exposed probably were much greater than we observed in the third year of rehabilitation.

In order to present a better comparison of the effect of plot length on erosion, the data have been tabulated in Table 2 to show accumulated rainfall, runoff, and sediment yields in the first 11

Watershed Science Unit, Utah State University, Logan 84322, and USDA Intermountain Forest and Range Experiment Station, Logan, UT 84321. Use of water delivery trucks by Conda Mining Company is gratefully acknowledged.

Table 1. Runoff and erosion for entire run.

Plot	Length (m.)	Moist. (%)	Runoff Time (min.)	P (mm.)	P (mm/hr)	Q (mm.)	Q/P (%)	Erosion (tonnes/ha)
1	15.2	10	41	22	32	19	86	.40
2	15.2	11	42	24	36	19	79	.31
3	30.5	7	16 (a)	23	40	5	22	.17
4	30.5	8	37	24	42	15	62	.37
5	45.7	12	42	20	32	5	25	.09
6	45.7	4	33	21	42	10	48	.50
7	61.0	11	42	24	38	10	42	.36
8	61.0	7	11 (a)	17	34	5	29	.23

(a) Short runs due leakage under border near flume.

Table 2. Runoff and erosion during first 11 minutes of runoff.

Plot	Length	Discharge at 11 min. (l/sec)	Max. Conc. (ppm)	Erosion Plot (tonnes/ha.)	Erosion Avg. (tonnes/ha.)	Rill Density (m/m²)
1	15.2	.51	4570	.137	.098	.07
2	15.2	.45	2530	.058		.36
3	30.5	.82	8640	.087	.109	.39
4	30.5	1.19	2630	.131		.23
5	45.7	.23	2170	.009	.094	.03
6	45.7	1.47	6610	.178		.23
7	61.0	1.39	5600	.112	.122	.20
8	61.0	1.39	6610	.132		.33

minutes of runoff from each plot. In this comparison we find no greater increase in erosion per unit area with increasing plot length. Average erosion during the first 11 minutes of runoff was .098, .109, .094, and .122 metric tonnes/ha from the 15.2, 30.5, 45.7 and 61 meter lengths, respectively. Runoff values from plot 5 are suspect because they are exceptionally low when compared to other plots, and this may result in an underestimate of erosion from that plot. The factor, L, in the USLE postulates a relationship of $(L/22.1)^m$ between slope length, L, and unit area erosion, where m = .5 on slopes greater than 5% (Wischmeier and Smith, 1978). Our limited data suggest that a value of about m = .15 is more appropriate on these older mine embankments and we suggest this as an area for further research and experimentation.

We believe there are two reasons why these embankments have low erosion rates at this stage of rehabilitation and do not respond more closely to the slope length relationship in the USLE. First, the surface conditions with over 50% cover of gravel and stone are similar to an erosion pavement from which most of the erodible soil has been removed by previous surface runoff. This condition probably has greater surface roughness and opportunities for detention of sediments than would occur on agricultural croplands. Secondly, rills appear to be the dominant pathway for water movement rather than interrill surface runoff. Rills are not deeply incised, but rather are shallow, stone-armoured depressions. A rapid rise in suspended sediment concentrations was observed within three to five minutes after runoff started; concentrations declined notably in the later portions of the run. This suggests an initial flushing of existing sediments, produced by natural weathering, by freeze-thaw action, or deposition of windblown sediment, from the rills.

An interesting, but unexplained, observation is that, on seven of eight runs, there was an inverse relationship between rill density and unit erosion; plots with higher rill density appeared to have lower sediment yield. This suggests to us that the processes of rill erosion on these stoney embankments may be considerably different than rill erosion processes on croplands.

Summary

In this preliminary study a large sprinkling-type rainfall simulator was used on plots up to 61 meters in length. Two operational problems limited the duration of runoff and restricted direct comparison of erosion from plots of different length. Problems of leakage of runoff under borders at the bottom of the plot and insufficient water supply for long runs can be minimized by improved field methods. Firm conclusions cannot be made at this time because of limited observations. But it appears that erosion rates after three years of grass rehabilitation are low, and are estimated to be .4 to 2.0 metric tonnes/ha/yr. Erosion per unit area did not increase much on the longer plots. Using the first 11 minutes of runoff as a common comparison, erosion averaged .10, .11, .09 and .12 tonnes/ha from the 15.2, 30.5, 45.7 and 61 meter plots, respectively.

Literature Cited

Isrealsen, C.E., C.G. Clyde, J.E. Fletcher, E.K. Isrealsen, F.W. Haws, P.E. Packer, and E.E. Farmer. 1980. Erosion control during highway construction. National Cooperative Highway Research Program Report 221. Transportation Research Board, Washington, D.C.

Neff, E.L. 1979. Editor. Rainfall simulator workshop, Tucson, Ariz., ARM-W-10, USDA-SEA, 184 p.

Wischmeier, Walter H., and Dwight D. Smith. 1978. Predicting rainfall erosion losses. USDA. Agriculture Handbook No. 537.

Shrub Use of Water from Simulated Rainfall in the Mojave Desert

E.M. Romney, R.B. Hunter, and A. Wallace

Key Words: water balance, soil moisture stress, growth response, timing and intensity of precipitation

Abstract

Rainfall simulation experiments provided an opportunity to investigate the recharge of water into northern Mojave Desert soil and its subsequent use by woody shrubs after similar timing and intensity of precipitation. Applications of about 100 mm of water per treatment were made in May and September 1983, and May and October 1984. From 50 to 80 percent of the water remaining on treated plots after runoff was lost to the system by evaporation, transpiration, diffusion, etc., within the first week after simulated rainfall. From 30 to 50 percent of the water retained after runoff had recharged into the soil profile to a depth of 40-cm by one week after treatment. Shrubs growing on the treated plots experienced low moisture stress for a period of 4 to 6 weeks before the depletion of recharge water once again placed them under high moisture stress. Shrubs responded to water applied in May by extending their period of active growth for 4 to 6 weeks before undergoing summer dormancy. The growth response from water applied in September and October was masked by impact from grazing jackrabbits and burrowing pocket gophers that were attracted to the study plots.

Woody shrubs have remarkable adaptations to survive the high degree of variability in soil water that occurs in shrub-desert ecosystems where the recharge of soil water is determined by the timing and intensity of precipitation, permeability of the soil profile, antecedent moisture content, and temperature and wind conditions. Wallace et al. (1980) called attention to the complexities of vegetation response to water in the northern Mojave Desert as the result of these interacting abiotic factors. Investigations disclosed that the position of an ecosystem relative to patterns of water run-on and run-off in the landscape and the soil water storage capacity of the system largely determines potential primary productivity. Because patterns of precipitation in the northern Mojave Desert are highly varied from year to year (Romney et al. 1973, Beatley 1974a b, Ackerman et al. 1980, Hunter et al. 1980, Lane et al. 1984), the potential effectiveness of precipitation in providing water input to shrub-desert areas is not easy to predict. Rainfall simulation studies conducted at the Nevada Test Site by participants from USDA/ARS-Tucson, Los Alamos National Laboratory and UCLA provided an opportunity to investigate the recharge of soil water and its subsequent utilization by shrubs from similar rainfall timing and intensity events. Findings are presented from rainfall simulator applications in May 1983, September 1983, May 1984 and October 1984.

Materials and Methods

Descriptions of the rotating-boom rainfall simulator, procedures used for treatments, and examples of application have been reported (Swanson 1965, Swanson 1979, Simanton and Renard 1982, Nyhan et al. 1984). Studies at the Nevada Test Site were conducted on plots in Area 11, which is located in the transition zone between the Great Basin and Mojave Desert, and near Mercury, Nevada, in the northern Mojave Desert. Simulated rainfall was applied to duplicate, randomized plots with 1) all vegetation cover removed, 2) all vegetation plus erosion pavement (rock and gravel >2 mm) removed, and 3) natural vegetation cover intact (control). Water potential measurements were made for each plot at 15 and 30-cm depths on about weekly intervals in order to determine the antecedent moisture content before treatment and to monitor the soil moisture loss during the period following simulated rainfall until the next natural precipitation event rewet the soil. Two different kinds of moisture sensors were used: dew point thermocouple-psychrometers (for tracking high water stress condition) and fiberglass soil moisture cells (for tracking low water stress conditions). Additional fiberglass cells were emplaced at 5-cm depth just before the October 1984 rainfall application in order to monitor near-surface water loss during the period immediately following treatment.

Ecological characteristics of the mixed species shrub population at each study site were determined from non-destructive dimensional measurements and from shrub biomass parameters developed by Romney et al. (1973). Soil profile characteristics and particle size distributions were determined by standard soil survey methods (Soil Survey Staff 1975, Day 1965). Data for soil water involved in this study were obtained primarily from natural vegetation control plots on which vegetation cover determinations were made just before each simulated rainfall application by the pin point meter method described by Simanton and Renard (1982).

Results and Discussion

Study Site Characteristics

Descriptions and characteristics of soil profiles near the study plots are given in Table 1. At each site the soil pedon was relatively shallow and underlain by massive hardpan and parent material. Soil water holding capacity was higher at Mercury than at Area 11, primarily as the result of higher clay content and less coarse sand throughout the soil profile (Table 2). Listed in Table 3 are some characteristics of the standing vegetation surrounding the study plots. The mixed species shrub population was more complex at Area 11 with the presence of shrubs native to the Great Basin Desert and the Mojave Desert. Nevertheless, the density, cover, and standing biomass was similar for both locations.

Soil Water Recharge from Simulated Rainfall

Figure 1 illustrates an example of the soil moisture potentials measured with dew point thermocouple-psychrometers in plots with different surface cover treatments following the simulated rainfall application in May 1983. This same kind of soil moisture depletion pattern developed during the period after each simulated rainfall application until the next natural rainfall event rewet the

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Table 1. Soil profile characteristics at Area 11 (Pedon ARS4) and at Mercury (Pedon ARS1)

Pedon ARS4:

Typic Durorthid, coarse-loamy, mixed, thermic.

East-facing alluvial fan, 4 to 8 percent slope gradients, elevation, 1,250 meters.

Well drained, medium runoff, moderate permeability above duripan.

Soil formed in material weathered from tuff, basalt and limestone.

Profile

A2 0-5 cm. Pale brown (10YR 6/3) loamy sand; dark greyish brown (10YR 4/2) moist; weak fine platy structure; soft, friable, slightly sticky and plastic; fine and medium roots; slightly effervescent, moderately alkaline (pH 8.2).

C1 5-14 cm. light grey (10YR 7/2) gravelly, sandy sand; brown (10YR 4/3) moist; weak, fine subangular blocky structure; soft, friable nonsticky or plastic; many fine and medium roots; violently effervescent, moderately alkaline (pH 8.4).

C2 14-27 cm. Very pale brown (10YR 7/3) gravelly sand; brown (10YR 4/3) moist; medium subangular blocky structure; soft, friable, slightly sticky and plastic; few fine and medium roots; violently effervescent, moderately alkaline (pH 8.4).

C3 cam 27⁺ cm. Silica-lime hardpan.

Pedon ARS1:

Typic Durorthid, loamy, mixed, thermic, with randomly dispersed clay pockets under shrub clumps.

South-facing crest of dissected alluvial fan, 5 to 10 percent slope gradients, elevation 1150 meters.

Well drained, medium to rapid runoff; moderate permeability above duripan; moderate erosion.

Soil formed in material weathered from limestone, quartz and tuff.

Profile

A2 0-6 cm. Light grey (10YR 7/2) gravelley loamy sand, brown (10YR 5/3) moist; weak, fine, platy structure; soft, friable, non-sticky; violently effervescent (ph 8.5), few roots (unique, random clay pockets around roots and large rocks).

C1 6-25 cm. Very pale brown (10YR 7/3) gravelley loamy sand, brown (10YR 5/3) moist; weak, fine subangular blocky structure; soft, friable, non-sticky; violently effervescent (pH 8.5); fine and medium roots.

C2 cam 25⁺ cm. Silica-lime hardpan

Table 2. Soil particle size distribution (<2 mm fraction) in soil profiles

Profile Sample	Coarse Sand %	Fine Sand %	Silt %	Clay %
Area 11 - Pedon ARS4				
A_2 (0-5 cm)	15.2	69.6	14.5	0.7
C_1 (5-14 cm)	20.7	73.2	5.7	0.4
C_2 (14-27 cm)	59.7	38.6	1.5	0.2
Mercury - Pedon ARS1				
A_2 (0-6 cm)	20.4	58.8	14.8	6.0
C_1 (6-15 cm)	20.1	59.8	13.4	6.7

Table 3. Characteristics of native vegetation at simulated rainfall study sites.

Species	Density No/ha	Rel. Dom. %	Cover M²/ha	Biomass kg/ha
		AREA 11		
Acamptopappus shockleyi	400	1.2	29.1	25.3
Atriplex confertifolia	2600	21.8	556.1	1163.5
Chrysothamnus viscidiflorus	200	1.1	27.3	22.0
Ceretoides lanata	100	1.4	37.7	26.4
Ephedra nevadensis	6100	16.8	428.3	418.1
Grayia spinosa	800	11.4	290.3	421.9
Lycium andersonii	1300	27.0	686.9	727.2
Menodora spinescens	100	0.5	14.1	23.5
Oryzopsis hymenoides	1900	0.7	19.6	10.5
Tetradymia axillaris	100	1.3	31.8	51.5
Artemisia spinescens	5600	16.4	417.2	703.5
Total	19200		2538.4	3593.4
		MERCURY		
Atriplex canescens	100	1.4	38.5	32.0
Atriplex confertifolia	5300	26.3	730.9	1128.5
Ephedra nevadensis	1300	5.6	157.1	114.5
Larrea tridentata	300	10.2	283.9	239.2
Menodora spinescens	7600	52.2	1447.5	2059.7
Sphaeralcea ambigua	100	0.1	0.2	0.1
Lepidium fremontii	800	4.2	117.1	164.0
Total	15500		2775.2	3738.0

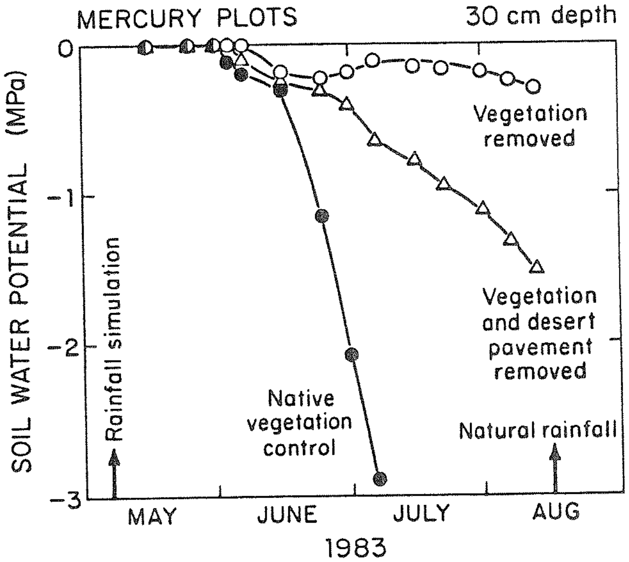

Figure 1. *An example of the change in soil moisture potential under different ground cover conditions after simulated rainfall in May 1983. Data points are single readings from dew point thermocouple-phychrometers at 30-cm depth.*

soil profile. High soil moisture stress began to occur about 6-weeks after simulated rainfall and, while this moisture stress developed more rapidly and intensively on the control plots with natural vegetation cover, there was also continued loss of soil moisture from the denuded plots. We attribute this moisture loss primarily to evapotranspiration from the shrub-covered plots and to evaporation from the denuded plots, although we must assume that some lateral diffusion and robbery of water by invading roots also occurred.

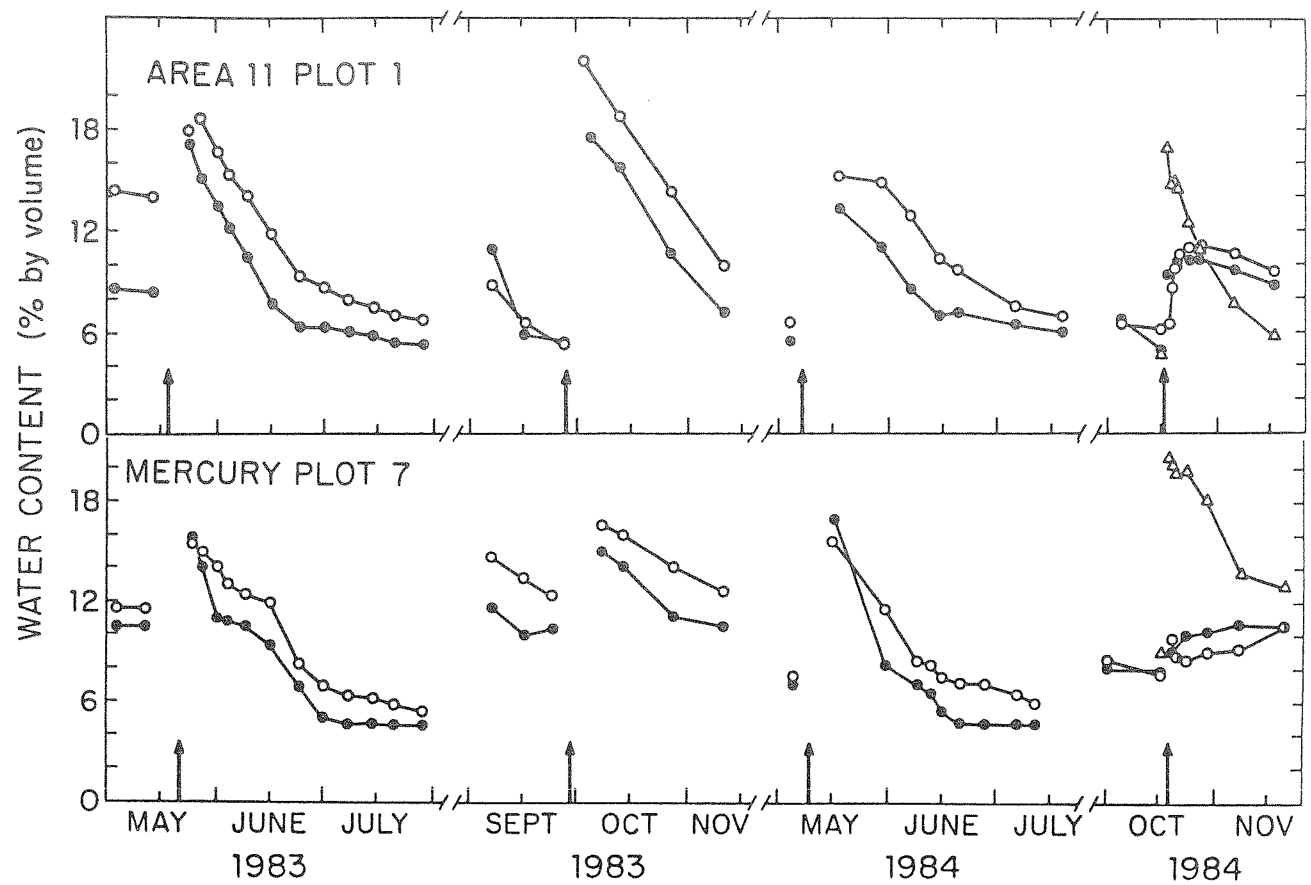

Figure 2. *An example of the water content in control plots with natural shrub cover at Area 11 and Mercury during the periods after simulated rainfall (vertical arrows) until natural precipitation again rewet the soil. (Δ = 5 cm, o = 15 cm, ● = 30 cm depth)*

We recognized early on that the array of soil moisture sensors emplaced at 15 and 30-cm depths would provide only crude estimates of water balance and that the impact from native vegetation surrounding the study plots could not be measured without extensive instrumentation. Moreover, we did not wish to further disturb the study plots or the native vegetation surrounding them since this study was of secondary interest to the main experiment. We did, however, collect soil samples at 5-cm depth from areas between the study plots for gravimetric measurement of near surface moisture loss after the simulated rainfall application in May 1983. Results of samplings at 3 to 5-day intervals varied considerably but they indicated both rapid and extensive loss of water from the soil surface, especially during the first few days after treatment. We

Table 4. Fate of simulated rainfall on selected control plots from similar time and intensity of application.

Time and location	Rainfall applied[1]	Water runoff[2]	Available water[3]	Recharge water[4]	Loss to system[5]
	mm	mm	mm	mm	mm (%)
May 1983					
Area 11-1	109.5	20.5	89.0	32.0	57.0 (64)
Mercury-7	114.8	55.1	59.7	18.9	40.8 (68)
September 1983					
Area 11-1	106.9	32.3	74.6	35.2	39.4 (53)
Mercury-7	111.5	76.4	35.1	17.6	17.5 (50)
May 1984					
Area 11-1	107.2	24.8	82.4	23.0	59.4 (70)
Mercury-7	113.0	45.8	67.2	36.2	31.0 (46)
October 1984					
Area 11-1	101.9	43.0	58.9	18.7	40.2 (68)
Mercury-7	108.4	64.7	43.7	7.4	36.3 (83)

[1] Simulated rainfall 60 min on day 1; 30 min 24 hrs later plus 30 min after 30 min delay.
[2] Runoff water from plots during simulated rainfall application.
[3] Difference between applied water and runoff water.
[4] Estimated water content in soil (5 to 40-cm depth) one week after treatment.
[5] Water loss by evaporation, transpiration, diffusion, etc. during the first week after simulated rainfall.

discontinued gravimetric sampling on later runs and installed fiberglas soil moisture cells at 5-cm depth for the simulated rainfall application in October 1984.

Data in Table 4 include estimates of the recharge water content in the soil profile one week after simulated rainfall for an example shrub-covered control plot at Area 11 and at Mercury. These estimates assumed that the moisture sensor readings at 15-cm were representative of the soil water status from 5 to 20-cm depth and that readings at 30-cm represented the water status from 20 to 40-cm depth. We assumed no recharge below 40-cm which was reasonable for the amount of water remaining on the study plots after runoff. Soil moisture potential readings were converted to water contents on the basis of laboratory-measured soil moisture characteristics for Area 11 and Mercury soils. The results showed that runoff from simulated rainfall on the shrub-covered control plots was higher at Mercury (40 to 70 percent) than at Area 11 (20 to 40 percent). The amounts of water that recharged into the soil profile generally ranged from 30 to 50 percent of the available water that remained on plots after runoff. Differences between the recharge water estimates and the available water inputs indicate that from 50 to 80 percent of the simulated rainfall remaining after initial runoff was lost to the system through evapotranspiration and other processes mentioned above within the first week after application.

Water Utilization by Shrubs from Simulated Rainfall

A similar pattern of depletion of recharge water by shrubs after each simulated rainfall event was evident from soil water content curves calculated from readings of the combined soil moisture sensors emplaced at 15 and 30-cm depths in the soil profile. Figure 2 shows an example of the change in soil water under a shrub-covered control plot at Area 11 and at Mercury during the period after each simulated rainfall until the next natural rainfall rewet the soil. The soil water recharge and depletion pattern was essentially the same for the first three simulated rainfall events at both study sites. For the October 1984 event we had emplaced soil moisture sensors at 5-cm depth and were able to see the rapid loss of water near the soil surface (last event, Figure 2). Note, however, the lower recharge of water at greater depths for the October 1984 application than had occurred on previous events. We attribute this to a high water loss by sublimation and evaporation resulting from freezing at the soil surface and high wind conditions that persisted during the first week after treatment. We speculate that this freezing temperature effect of inhibiting deep infiltration of recharge water might be even more pronounced during the winter season when most of the natural rainfall occurs in the northern Mojave Desert.

An observation of great interest was the repeatedly rapid loss of water from near surface soil within the first week after simulated rainfall treatments and the similarity of the draw-down stress at different points within the soil profile. The results are that woody shrubs have only a short period of time in which to respond to added water before high moisture stress conditions once again occur during out-of-season rainfall periods. This is probably the main reason why shrubs show little response to single, out-of-season rainstorms and only respond significantly, as the result of their genetic makeup, to the winter and spring multiple-rainstorm patterns in the Mojave Desert.

Data in Table 5 are measurements of canopy cover on the natural shrub-covered control plots made on the day before each simulated rainfall application by the pin point meter method (Simanton and Renard 1982). The study plots were protected from cattle grazing but they were exposed to the natural wildlife population; therefore, the canopy cover values might not represent the true measure of shrub growth response to added water. We concluded from the evidence of many clipped branches and the presence of above-normal amounts of fecal pellets that jackrabbits *(Lepus californicus)* sought out the wetter study sites and grazed heavily upon the more succulent vegetation. This was especially evident at Area 11 where grazing by jackrabbits probably accounts for the regression in canopy cover that was measured just before the plots were treated in October 1984.

Table 5. Canopy cover of native vegetation on the control study plots.

Simulate rainfall application	Area 11		Mercury	
	Plot 1	Plot 4	Plot 7	Plot 11
	percent of plot area			
May 1983	19.6	18.5	18.3	17.3
September 1983	23.0	29.0	23.0	25.2
May 1984	20.0	22.0	21.0	23.0
October 1984	18.6	18.6	22.4	25.4

Results from simulated rainfall treatments showed that shrubs responded positively, but not aggressively, to water added out-of-season. This supports previous observations by Romney et al. (1978) and Hunter et al. (1980) that woody shrubs in the northern Mojave Desert are capable of only limited growth response to water received during periods of the year that also experience high soil and air temperatures. In this study the shrubs responded to water applied in May by extending their period of active growth before undergoing summer dormancy. Any growth response that occurred from water applied in September and October was masked by the grazing impact from jackrabbits. As an additional point of interest, the added water treatments also attracted and enhanced the activity of pocket gophers *(Thomomys bottae)*.

Conclusions

The following conclusions are reached from applications of simulated rainfall on study plots located in the northern Mojave Desert.

1. Irrespective of time of treatment in spring and fall seasons of the year, from 50 to 80 percent of the applied water remaining after runoff was lost to the system by evaporation, transpiration and diffusion processes within the first week after applications of simulated rainfall.
2. From 30 to 50 percent of the applied water (after runoff) had recharged into the soil profile by one week after treatment.
3. Shrubs growing on treated plots experienced low moisture stress for a period of 4 to 6 weeks before their rapid draw-down of recharge water again placed them under high moisture stress conditions.
4. Shrubs responded to water applied in May by extending their period of active growth for 4 to 6 weeks before undergoing high temperature-induced summer dormancy. Growth responses from added water in September or October were masked by grazing impact from jackrabbits and pocket gophers attracted to the simulated rainfall study plots.

Literature Cited

Ackerman, T.L., E.M. Romney, A. Wallace, and J.E. Kinnear. 1980. Phenology of desert shrubs in southern Nye County, Nevada. Great Basin Natur. Mem. 4:4-23.

Beatley, Janice E. 1974a. Effects of rainfall and temperature on the distribution and behavior of *Larrea tridentata* (Creosotebush) in the Mojave Desert of Nevada. Ecology 55:245-261.

Beatley, Janice C. 1974b. Phenological events and their environmental triggers in Mojave Desert ecosystems. Ecology 55:856-863.

Day, P.R. 1965. Particle fractionation and particle-size analysis. pp. 545-567 *In* Part 1, Methods of soil analysis, C.A. Black (ed.). Amer. Soc. Agron., Madison, Wis.

Hunter, R.B., E.M. Romney, A. Wallace, and J.E. Kinnear. 1980. Residual effects of supplemental moisture on the plant population of plots in the northern Mojave Desert. Great Basin Natur. Mem. 4:24-30.

Lane, L.J., E.M. Romney, and T.E. Hakonson. 1984. Water balance calculations and net production of perennial vegetation in the northern Mojave Desert. J. Range Manage. 37:12-18.

Nyhan, J.W., G.L. DePoorter, B.J. Drennon, J.R. Simanton, and G.R. Foster. 1984. Erosion of earth covers used in shallow land burial at Los Alamos, New Mexico. J. Environ. Qual. 13:361-366.

Romney, E.M., V.Q. Hale, A. Wallace, J. Childress and T.L. Ackerman. 1973. Some characteristics of soil and perennial vegetation in northern Mojave Desert areas of the Nevada Test Site. University of California, Los Angeles, Laboratory of Nuclear Medicine and Radiation Biology Report, UCLA 12-916.

Romney, E.M., A. Wallace, and R.B. Hunter. 1978. Plant response to nitrogen fertilization in the northern Mojave Desert and its relationship to water manipulation. pp. 232-243 *In* Nitrogen in desert ecosystems, N.E. West and J. Skujins (eds.). Dowden, Hutchinson & Ross, Inc., Stroudsburg, PA.

Simanton, J.R., and K.G. Renard. 1982. Seasonal changes in infiltration and erosion from USLE plots in southeastern Arizona. Hydrol. and Water Res. in Ariz. and the Southwest 12:37-46.

Swanson, N.P. 1965. Rotating-boom rainfall simulator. Trans. Amer. Soc. Agr. Eng. 8:71-72.

Swanson, N.P. 1979. Field plot rainfall simulation (rotating-boom rainfall simulator), Lincoln, Nebraska. pp. 166-179 *In* Proc. rainfall simulator workshop, USDA, March 7-9, Tucson, AZ.

Soil Survey Staff. 1975. Soil Taxonomy. USDA agriculture handbook No. 436.

Wallace, A., E.M. Romney, and R.B. Hunter. 1980. The challenge of a desert: revegetation of disturbed desert land. Great Basin Natur. Mem. 4:216-225.

Desert Water Balance Using a Combination of Psychrometric and Resistance Sensors

Richard Hunter and Paul D. Greger

Key words: water potentials, transpiration, evaporation

Abstract

A combination of psychrometric and electrical resistance soil moisture instruments was used to determine water contents on irrigated plots in the northern Mojave Desert. The combination allowed determination of moisture contents between essentially saturation (~ 30%) and a dryness below plant availability (4<%). The technique was well suited to determination of the near-surface moisture dynamics which involved roughly two-thirds of the applied water. Preliminary results with the technique demonstrated that vegetation removal reduced soil drying rates, but removal of surface rocks had little effect.

Introduction

Though water is the primary growth-limiting resource in warm deserts (Noy-Meir 1973), there is very little published information on actual desert soil water contents and potentials (Cable 1977a, Hunter et al. 1975, 1976). Among the reasons are that soil moisture status varies rapidly and widely and no single instrument is well suited to determining water content (needed to calculate inputs, fluxes, and losses) and also water potentials (needed to estimate availability to plants). Confounding problems involving between point variability in soils and instrument calibration render interpretation of readings difficult.

Techniques attempted in semiarid and arid regions to date are gravimetry, (Miller et al. 1982, Branson et al. 1976, Sharma 1976) gypsum blocks (Whitford 1973), thermocouple psychrometers (Hunter et al. 1975, Moore and Caldwell 1972), and neutron probes (Cable 1977, Sharma 1976). While a neutron probe is reasonably well suited to balance studies, its cost, spatial insensitivity, difficulty of installation, and the inability to relate its measurements to plant availability limit its usefulness. Neutron probes are particularly unsuitable in the Mojave Desert, where soil-water interactions are largely within 30 cm of the surface. Gravimetry is too destructive and time-consuming to be employed frequently on small areas and rocky soils. Gypsum blocks have been short-lived and difficult to calibrate. Soil psychrometers are fairly well suited to measuring water potentials during the plant growing season, but are sensitive over a relatively small range of water contents.

Electrical resistance moisture-temperature cells (Colman and Hendrix 1949) are adequately sensitive in wet soil, but lose sensitivity well before desert plants are water stressed.

We have attempted to combine psychrometric and resistance sensors to measure soil moisture and thus to compute a water balance. With experimental plant and surface rock removal we have estimated transpiration and mulching effects on soil water content following irrigation.

Study Sites

Two sites on the Nevada Test Site were studied. The first was near Mercury, Nevada, at 1150 m elevation, latitude 36° 40′ N and longitude 116° 0′ W. Slope was 8–10%, with aspects of east to southeast. Shrub canopies covered 25% of the soil, the major species being *Menodora spinescens* (10.3%), *Atriplex confertifolia* (6.6%) and *Larrea tridentata* (4.1%). Soil on a nearby site was typic durorthid, coarse-loamy, thermic, with randomly dispersed perched clay pockets. Bulk density was 1.6 g/cc, and density of fines (<2 mm) was 1 g/cc.

The second site was near the Mojave Desert - Great Basin transition zones, latitude 36° 58′ N, longitude 115° 58′ W elevation 1250 m. It is a valley, Area 11, known locally as "Plutonium Valley." Slopes are 6 to 9%, with an eastern aspect. Soil was typic durorthid, coarse-loamy, mixed, thermic, of shallow location. Shrub cover was 24%, with major species being *Atriplex confertifolia* (6.4%); *Lycium andersonii* (5.2%); *Artemesia spinescens* (5.0%) and *Ceratoides lanata* (3.2%). Bulk density was 1.4, and the density of the fines was 1 g/cc.

Methods

At each site, six metal bordered plots (3.05 × 10.7 m) were situated with the long axis parallel to the slope. Two replicates of three treatments were used: Control, Vegetation removed, and Vegetation and Rocks (>7 mm) removed. Soil psychrometers and soil moisture resistance cells were buried together at 15 and 30 cm in the central portion of each, and the surfaces were allowed to weather naturally for six to eight weeks. For final treatments (October 1984) resistance cells were added at 5 cm. All were then watered (115 to 130 mm) with a rainfall simulator at the rate of 60 mm/h, and runoff was measured as described by Simanton and Renard (1982). Sensors were read at intervals of three to seven days until significant precipitation rewet the soil. This procedure was repeated four times within two years.

Potential and resistance sensors were calibrated in the laboratory against percent water by weight for sieved samples of the two soils. Soils of known water content were enclosed with sensors in air-tight jars and sensors read until readings were constant. Equilibration took four to six weeks at low water contents. Fitted power curves (Table 1) were used to calculate soil moisture contents for each plot.

Bulk and fine densities were measured by excavation: hole volume was determined by refilling rubber lined holes with measured volumes of water, and excavated soils were dried, sieved and weighed.

Results

Curves of resistance and water potentials for the two soils (Figure 1) were similar in shape but varied considerably with respect to

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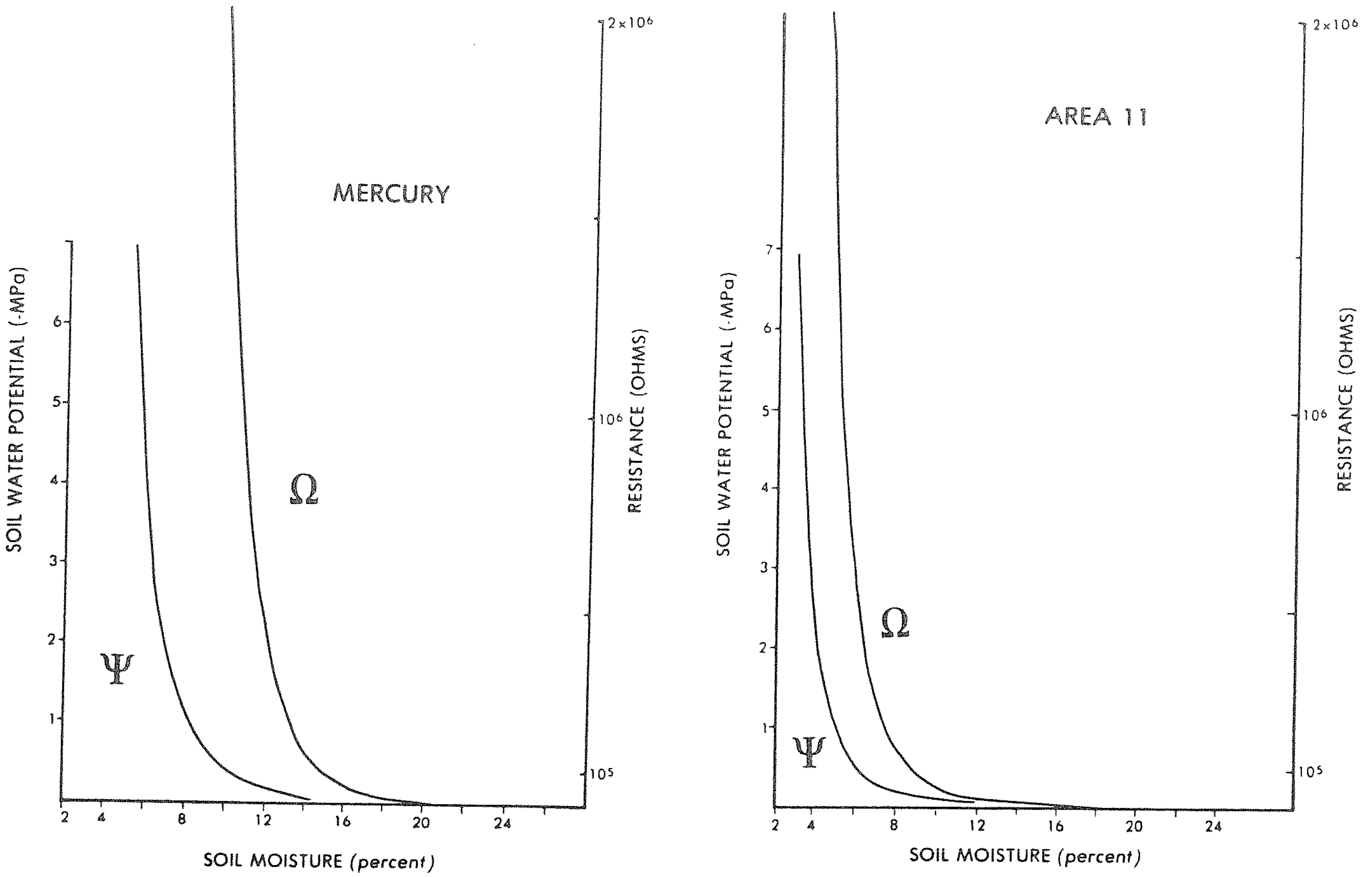

Figure 1. *Calibration curves and correlation coefficients for volumetric water content vs. resistance (Ω) and water potential Ψ in Mercury (a) and Area 11 (b).*

volumetric water content (Θ) in the two soils. The two sensor types were quite complementary in the Mercury soil. The resistance cells were sensitive in the range from Θ of 29% ($10^3\ \Omega$) to 12% ($0.5 \times 10^6\ \Omega$); and the psychrometers covered the range from 11% (-0.3 MPa) to 5.5% (-4.5 MPa). In Area 11, though the ranges were complementary, the psychrometric range of 6.5% (-0.3 MPa) to 3.5% (-4.5 MPa) was of little consequence, because the majority of water was lost before the psychrometers were useful.

Reliability of both sensors was good. During two years of use not one of 24 resistance cells failed, while one of 24 psychrometers failed.

In the lab we have found 20 psychrometers to have a standard error of less than 0.1 MPa over solutions at 0, 3, 11, and 22 MPa. At -4.5 MPa they had a similar variability, but with a mean of only -4.2 MPa. In the field resistance cells placed in pairs 2 to 4 cm apart varied in readings as much as 8% of soil moisture content by volume in control plots, but to a maximum of 2% in plots with vegetation removed. Two groups of ten psychrometers buried touching each other in the field had standard errors of <0.1 MPa up to 2 MPa while several groups of five buried individually at 30 cm approximately 1 m apart had standard errors of <0.3 MPa under 1 MPA, up to 0.9 MPa at 2.0 to 3.0 MPa.

Table 1. Soil moisture (g/gdw soil) vs. resistance (Ω) and water potential (-bars) curves.

Location	Equation	r
Area 11	$\% = 92.1\ (\Omega)^{-.207}$	-.88
	$\% = 5.01\ (\mathrm{Mpa})^{-.261}$	-.99
Mercury	$\% = 70.6\ (\Omega)^{-.138}$	-.99
	$\% = 8.05\ (\mathrm{Mpa})^{-.238}$	-.98

Figure 2 demonstrates the combination of results from the two

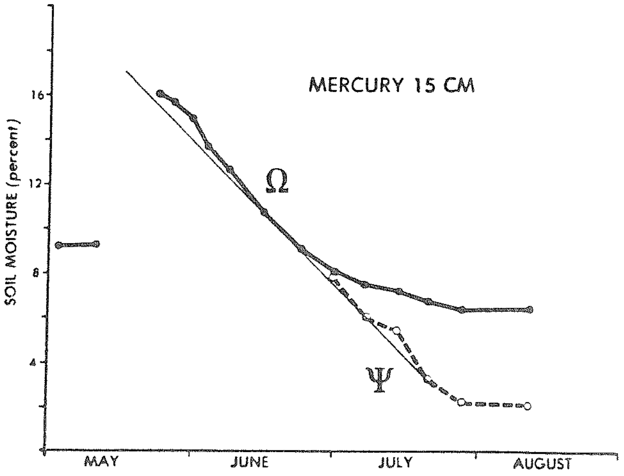

Figure 2. *Water content changes at one location with time as indicated by resistance (Ω) and psychrometric (Ψ) sensors.*

sensors. As the resistance sensors approached their limit the apparent drying curve leveled out. At roughly the same time the psychrometric sensors became sensitive, extending the curve downward until they in turn became nonfunctional. The line drawn through the points shows a surprising constancy of drying rate over the ten week period which was consistent with drying patterns in deep plant-free containers in the glasshouse (unpublished data). The curves in Figure 2 suggest that with resistance cells alone soils would have appeared to stop drying at Θ = 6%. The psychrometric sensors extended the observed drying curve to near the limit of their operability. It was reasonable, but not independently confirmed, that drying rates declined in August as indicated by the psychrometric sensors.

Sensitivity of psychrometers to vegetation and rock removal is demonstrated for Area 11, in Figure 3. The sensors were nonoperative for four to six weeks following a May 19 irrigation. The vegetated plots dried out first and fastest, followed by plots with rock and vegetation removed, and then by plots with only vegetation removed.

A different picture was given by the combined sensors, upon conversion to Θ (Figure 4a). The difference in Θ was established in the first two weeks following treatment, after which time the changes were roughly parallel.

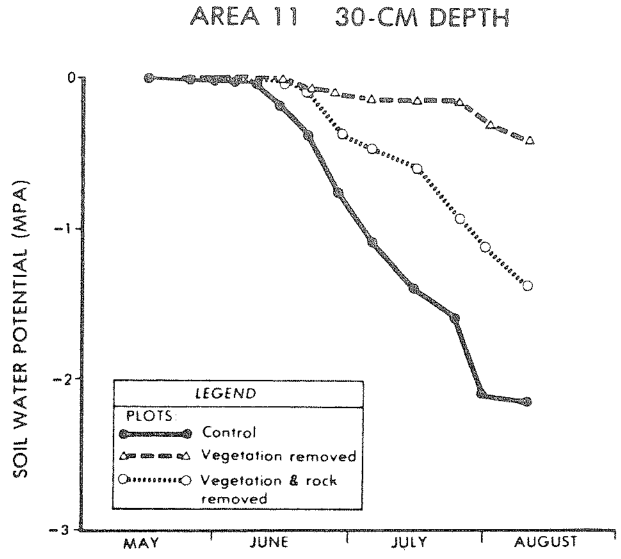

Figure 3. *Water potential changes as affected by removal of vegetation and surface rocks.*

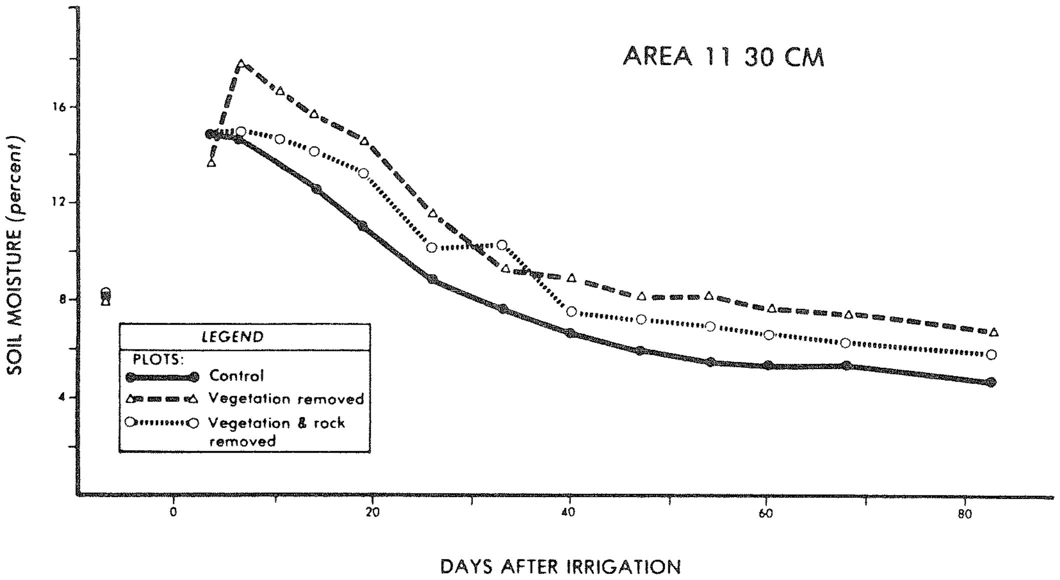

Figure 4a

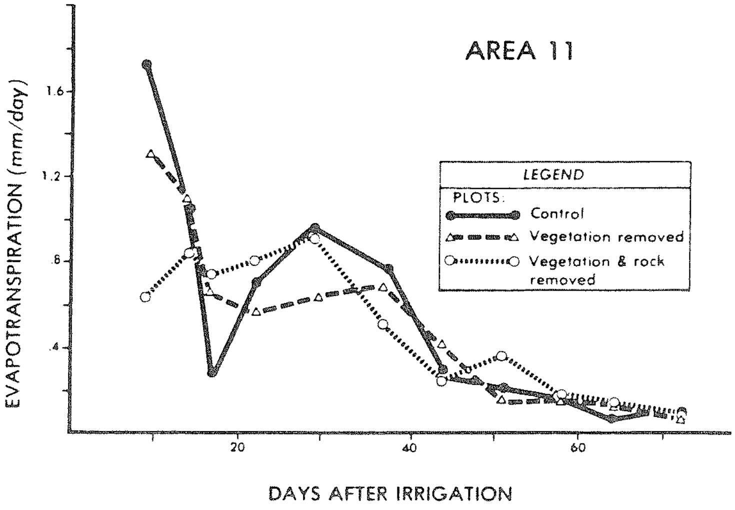

Figure 4b

Figure 4. *Estimated volumetric soil moisture (a) and drying rates (b) in Area 11.*

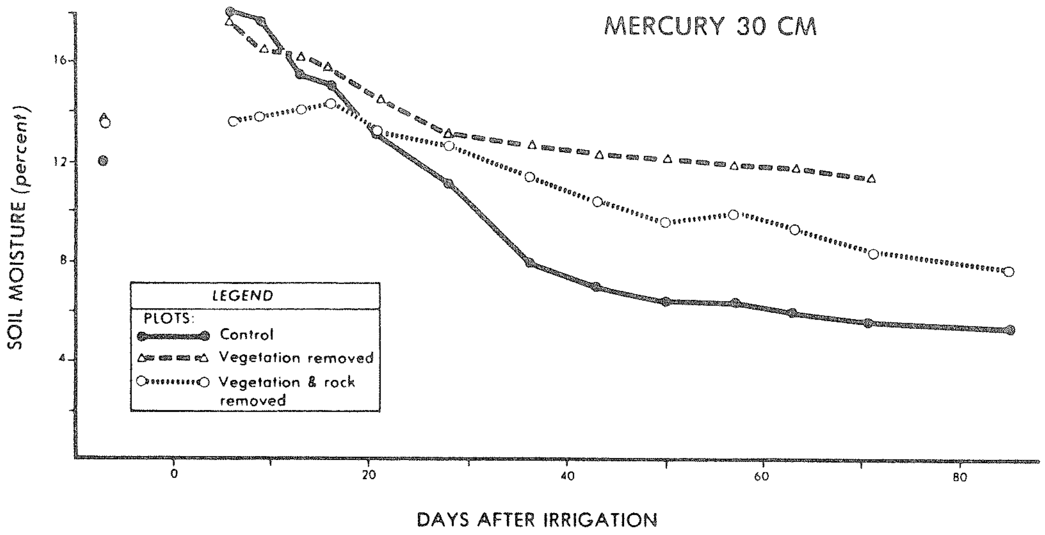

Figure 5a

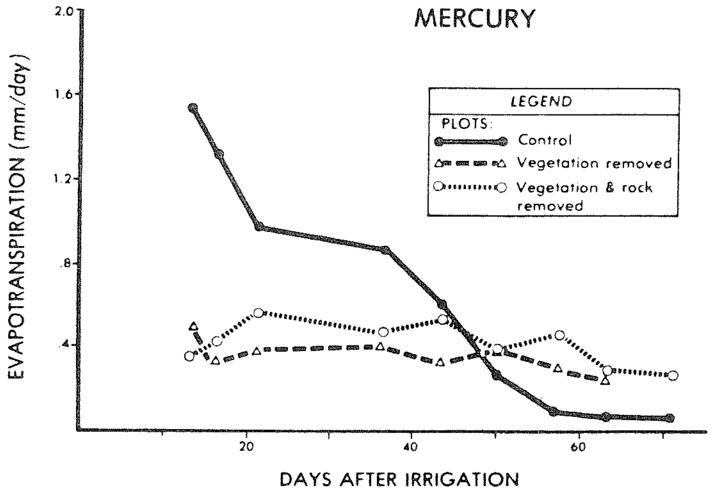

Figure 5b

Figure 5. Estimated volumetric soil moisture (a) and drying rates (b) in Mercury.

When an estimate of total water content is made from these data, an estimate of evapotranspiration (change in soil water per day) can be made (Figure 4b). The rates of evapotranspiration were very similar after the first two weeks. It appeared then that for Area 11, plant cover had little effect on evapotranspiration rate, at least from the top 30 cm of soil.

The situation was considerably different in Mercury. Figures 5a and 5b show that the rate of loss was much greater for the vegetated plot until the soil was essentially depleted.

While soil drying was relatively slow, wetting was rapid. Figure 6 shows results from wetting and subsequent drying at these depths following calculated infiltration (water applied minus runoff) of 35 mm of water in October 1984. The 5 cm depth wet from 4.5 to 16% within 24 hours. The 15 cm depth changed from 6 to 7% the first day, but continued to increase (to 8.5%) for three more days. Wetting at 30 cm of about 1.5% took one to two weeks.

A surprising initial finding was that a large proportion of the water applied could not be accounted for when comparing soil infiltration calculated from input runoff data (Table 2). For the last trial, in October 1984, readings were taken immediately before and one day following treatment, in order to allow as little time for surface evaporation as possible. Using that technique, the water in Mercury was reasonably well accounted for, while in Area 11, only 33% was measured. The days of treatment and the subsequent three days were very cold, with strong winds, and we feel much of the applied water froze near the surface and was lost by sublimation.

Table 2. Water balance estimates for Area 11 plots with sensors read immediately prior to and succeeding treatment, October, 1984. "Input" was measured as the difference between precipitation and runoff (Simanton and Renard 1982).

	Control		Vegetation Removed		Vegetation & Rock Removed	
	Plot 1	Plot 4	Plot 2	Plot 5	Plot 3	Plot 6
Water Input, mm	59	82	58	68	35	35
Measured Soil Change, mm	23	16	23	24	12	13
Unmeasured, water, mm	36	66	35	44	23	22
Unmeasured water, (%)	61	80	60	65	66	63

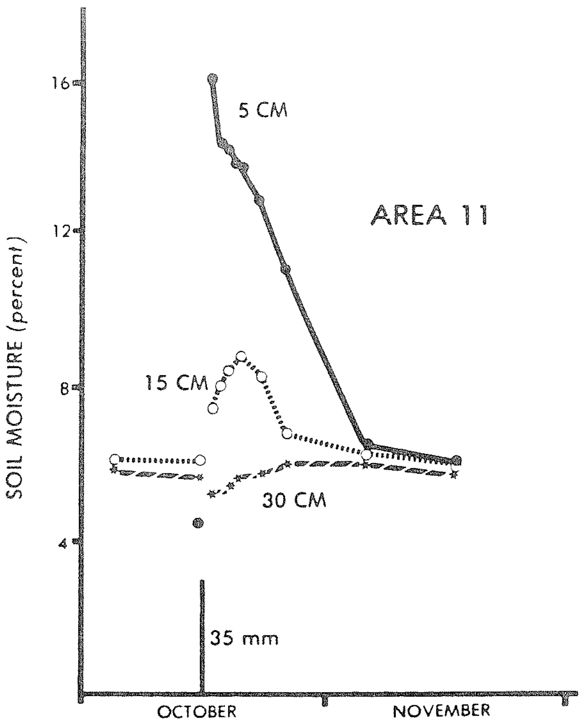

Figure 6. *Soil wetting and drying at three depths following calculated "infiltration" of 35 mm of water in October, 1984.*

Discussion

There are both advantages and disadvantages to the proposed technique. Some of the advantages are particularly important in deserts. First, because the sensors measure moisture at discrete points, they are suited to indicating soil moisture in shallow and narrow soil zones. For example, we have detected moisture at 1 cm from a 1 mm rainfall which had no effect at 5 cm. Similarly, in October 1984, calculated input of 35 mm thoroughly wet 5 cm, but not 15 cm (Figure 6), providing relatively independent evidence of significant surface evaporation losses. The point nature of the moisture determinations thus allows us to evaluate not only water balance, but also some of the dynamics of wetting and drying.

Second, the wide range of soil moisture contents measured is important. Desert soils wet to field capacity for only a short period after rainfall (hours, but not days), then dry within a few weeks to essentially air-dry. The combination of instruments allows measurement of all but the final 1 to 2% of moisture loss.

In addition there are significant advantages in the relatively low cost, ease of reading, and reliability of the instruments.

The two most significant disadvantages were that point determinations required extrapolation of moisture conditions between sensors, and that calibration was difficult.

Our limited experience suggests quite significant small scale variability in soil moisture frequently occurs as soils wet and dry. This was particularly true near the surface and at the wetting front. Nevertheless, we have in general found consistent trends in drying that make extrapolation between sensors reasonable. For example, soils at 30 cm dried at roughly the same rates as those at 15 cm (data not presented), but were 1 to 3% wetter. The gradients at the wetting and drying fronts become less steep with time, and of course they could have been measured by appropriate location of sensors.

Our calibration technique differed from those recommended by Colman and Hendrix (1949) for resistance sensors and by Wescor for psychrometers. We used soils in closed containers and waited weeks for equilibration to occur. Dry soils required stirring to hasten equilibration. Ovens produced temperature gradients which prevented equilibration. Qashu (1969) used field calibration (presumably gravimetric) which was later confirmed by neutron probe. Remson and Fox (1955) found poor calibration curves of the resistance sensors. In practice there are factors in the desert which reduce the significance of calibration errors. The wide range of moisture contents encountered, the use of different sensors for different ranges, and fairly specific endpoints (too wet, too dry) for the different sensors all limit the seriousness of small calibration errors.

To summarize, we have attempted the use of a combination of psychrometric and electrical resistance instruments to determine soil water balance, evaporation and transpiration in the Mojave Desert. Initial trials suggest the technique has considerable promise, obviating many of the difficulties of other techniques.

References

Branson, F.A., Reuben F. Miller, and I.S. McQueen. 1976. Moisture relationships in twelve northern desert shrub communities near Grand Junction, Colorado. Ecology 57:1104-1124.

Cable, Dwight R. 1977a. Seasonal use of soil water by mature velvet mesquite. J. Range Manage. 30:4-11.

Cable, Dwight R. 1977b. Soil water changes in creosotebush and bur-sage during a dry period in southern Arizona. J. Ariz. Nev. Acad. Sci. 12:15-20.

Colman, E.A., and T.M. Hendrix. 1949. The fiberglass electrical soil-moisture instrument. Soil Sci. 67:425-438.

Hunter, R.B., E.M. Romney, J.D. Childress, and J.E. Kinnear. 1975. Responses and interactions in desert plants as influenced by irrigation and nitrogen applications. US/IBP Desert Biome Res. Memo 75-13. Utah State Univ., Logan. 14 pp.

Hunter, R.B., E.M. Romney, A. Wallace, H.O. Hill, T.A. Ackerman, and J.E. Kinnear. 1976. Responses and interactions in desert plants as influenced by irrigation and nitrogen applications. US/IBP Desert Biome Res. Memo. 76-14. Utah State Univ., Logan. 7 pp.

Miller, R.F., F.A. Branson, I.S. McQueen, and C.T. Snyder. 1982. Water relations in soils as related to plant communities in Ruby Valley, Nevada. J. Range Manage. 35:462-468.

Moore, R.T., and M.M. Caldwell. 1972. The field use of thermocouple psychrometers in desert soils. In R.W. Brown and B.P. Van Hareren (eds.) *Psychrometry in Water Relations Research.* Utah Agr. Exp. Sta., Logan, UT pp. 165-169.

Remson, J., and G.S. Fox. 1955. The displacement of calibration curves for electrical soil-moisture units. Amer. Geophys. Union, Trans. 36:821-826.

Sharma, M.L. 1976. Soil water regimes and water extraction patterns under two semi-arid shrub (Atriplex Spp.) communities. Aust. J. Ecol. 1:249-258.

Simanton, J.R., and K.G. Renard. 1982. Seasonal changes in infiltration and erosion from USLE plots in southeastern Arizona. Hydrology and Water Resources in Arizona and the Southwest. 12:37-46.

Whitford, W.G. 1973. Jornada validation site report. US/IBP Desert Biome Res. Memo. 73-4. 332 pp.

Mobilization of ^{137}Cs During Rainfall Simulation Studies at the Nevada Test Site

E.H. Essington and E.M. Romney

Key Words: **erosion, sediment, fallout, radionuclide**

Abstract

Fallout ^{137}Cs mobilized with runoff sediments during a rainfall simulation test at the Nevada Test Site was measured in order to estimate the magnitude of its mobilization and its distribution among particle size fractions of the sediment. The concentration of ^{137}Cs was found to be higher in the fine materials (<50 micron) than in the coarse materials in both the sediment and in the uneroded (reference) soil surrounding the test plots. The distribution of ^{137}Cs among particle size fractions of sediments from the natural plots was the same as that of the reference soil. However, in the plots treated by removal of the vegetative or rock mulch cover, the ^{137}Cs concentrations were higher in the fraction greater than 500 micron compared to those of the reference soil. A portion of the ^{137}Cs appeared to be associated with low density organic matter (partially decomposed plant litter), which was flushed from the plots during the rainfall episode.

Introduction

Rainfall simulation studies have been conducted at the Nevada Test Site (NTS) since 1983 in order to extend the data base necessary for modeling erosion and sediment transport in arid regions. An added objective of conducting such studies at NTS involves the need to describe and predict the rates of erosion and movement of surface radioactive contamination.

A study was conducted during a simulated rainfall event in order to provide information on the magnitude of water resuspension and removal of radioactive contamination in an area of NTS subject to erosive storm events. The radionuclides removed from such a source of contamination will be transported to stream channels and ultimately to areas of deposition and accumulation sometimes quite distant from the source location. The impact of that redistribution can affect land use and occupational exposures as well as create additional areas of contamination.

The objective of this study was to provide information on the magnitude of fallout ^{137}Cs mobilization in several particle size fractions of sediment as a result of a calibrated rainfall simulation in an area of the NTS representative of a nearby highly contaminated area. Although the radioactive material of concern in that area contains plutonium, it was thought that fallout ^{137}Cs might offer valuable preliminary data and would allow calibration of the site with respect to soil erosion and contaminant transport rates.

History

During the past three decades investigators have attempted to evaluate the effects of erosion on the mobilization and deposition of fallout radionuclides. Menzel (1960) reported that the concentration of fallout ^{90}Sr was about 10 times higher in soil carried by runoff than in soil from the supplying plow layer. Using small test plots dosed with ^{137}Cs, Rogowski and Tamura (1965, 1970) reported that loss of ^{137}Cs was logarithmically related to loss of soil. They reported that after a 200-day period the loss of ^{137}Cs was seven times higher from bare plots than from plots with a good meadow cover.

Tamura (1975) investigated the distribution of plutonium among particle size fractions of soils from a contaminated site on NTS in southern Nevada. His data suggest that plutonium accumulated in the clay size fraction and concluded that that enrichment was probably due to the transport of highly contaminated clay size particles from a nearby contaminated area.

Ritchie et al. (1972) reported that fallout ^{137}Cs had concentrated in reservoir sediments by factors of 2 to 12 relative to ^{137}Cs concentrations in the supplying watershed. The higher values were in the more arid climates.

Efforts were made to describe the conditions under which the fallout ^{137}Cs was eroded. Ritchie et al. (1970, 1972) determined that much of the fallout ^{137}Cs had accumulated in the surface organic matter (plant litter) or in the top few centimeters of mineral soil. McHenry and Ritchie (1977) attempted to determine what soil factors would correlate with the degree of erosion of ^{137}Cs. Their regression analysis showed that predictive models useful for estimating the distribution of ^{137}Cs in surface soils and in sediments of arid watersheds must include estimates of the areal concentrations of fallout ^{137}Cs, the size of the watershed, and an expression of the chemical activity of the surface soil (e.g., CEC). Other factors, e.g., annual and seasonal precipitation, soil nutrient status, and soil texture are less important.

More recently investigators have attempted to use fallout ^{137}Cs as a tracer for estimating the degree of soil erosion (McHenry et al. 1973, Ritchie et al. 1974, Ritchie et al. 1975, Brown et al. 1981, Brown et al. 1981, and Longmore et al. 1983). Their attempts have, for the most part, been successful in estimating areas of depletion and deposition and for estimating sediment losses to streams and reservoirs in selected watersheds.

None of the investigations designed to evaluate the redistribution of fallout radionuclides or those designed to use ^{137}Cs as an erosion tracer have measured the distribution of the ^{137}Cs among particle size fractions in the sediments. Yet that information will be of value in assessing the need and methods for decontamination. That information will also be of value in assessing the impact of redistribution of radionuclides on the ecosystem of the area.

Materials and Methods

A rainfall simulation study was initiated at Plutonium Valley, Area 11, on the NTS in May 1983. Sediment generated during the first of a series of semi-annual simulated rainfall episodes was collected and analyzed for ^{137}Cs content. The study area is located

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on an east-facing alluvial fan of 4 to 8% slope. Soils of the area were generally described by Leavitt (1974), but a more complete description of the plot site was made for the simulation studies; a summary of that description is listed in Table 1. Details of the experimental rainfall simulations are listed in Table 2 and consist of 3 duplicate surface treatments distributed randomly among 6 plots and 3 rainfall treatments.

Table 1. Typical Characteristics of Soils of the Erosion Plots in Area 11 (Plutonium Valley), Nevada Test Site

SOIL: Aridisol, Typic Durorthid, coarse-loamy, mixed, thermic. Well drained, medium runoff, moderate permeability, underlain by silica-lime hardpan at 27 cm.

PARENT MATERIAL: volcanic tuff, basalt, and limestone

ASPECT: east-facing alluvial fan

SLOPE: 4 - 8%

ELEVATION: 1250 m (MSL)

PRECIPITATION: 150 - 200 mm (6 - 8 in)

PARTICLE SIZE DISTRIBUTION: (percent in 0 - 5 cm)

Coarse sand = 15.2
Fine sand = 69.6
Silt = 14.5
Clay = 0.7

Table 2. Plot and Rainfall Treatments for which ^{137}Cs Concentrations in Sediment were Determined

SURFACE TREATMENTS (duplicate)
Natural Plots 1 and 4 (Control)
Clipped Plots 3 and 6 (Vegetation removed)
Bare Plots 2 and 5 (Vegetation and rock mulch removed).

RAINFALL TREATMENTS
Dry - 51 mm/hr^{-1} for 1 hr
Wet - 24 hrs later, 51 mm hr^{-1} for 1/2 hr
Very wet - 1/2 hr later, 51 mm hr^{-1} for 1/2 hr

A series of 8 soil samples 900 cm^2 by 5 cm deep was collected from just outside each plot pair before any rainfall was applied. The 5-cm deep soil sample was chosen because of its use as a standard surface soil sample in other ecosystem studies at NTS. The collection pattern is shown with plot dimensions in Fig. 1. Those soil samples were air dried and sieved to obtain 4 particle size fractions: >2000, 2000-500, 500-50, and <50 micron. Those samples were collected to provide a reference to which concentrations of ^{137}Cs in sediment could be compared.

Sediment samples were collected from the runoff plots during the full term of the first simulation runs (May, 1983) except during the time in which small sediment load samples were being collected by other investigators. Collection of the runoff was accomplished by diverting the total outflow from the recording flume to a 0.22-m^3 (55-gal) steel drum (Fig. 2) through a 3.8-cm id. PVC hose. This configuration was used so that sediment load samples could be collected without interference; the hose and plastic bottle collector could be temporarily moved aside to allow positioning of the sediment load sample bottle in the flume outflow. Outflow fluids were collected from each plot during each portion of the simulation schedule (Table 2). Those samples were allowed to settle for 48 to 72 hrs after which the fluids and floating material were decanted and discarded. The remaining sediments were transferred to a smaller container and were wet sieved in the laboratory to the same size fractions as the reference soil.

Ten-gram aliquots of all of the sieved fractions were radioassayed for ^{137}Cs using a solid state gamma spectrometer system. Only 1 sediment sample from each treatment was collected and analyzed and except for treatment duplicates no other replication was attempted. For that reason the results were used only to express trends but not to provide statistically defensible tests of hypotheses.

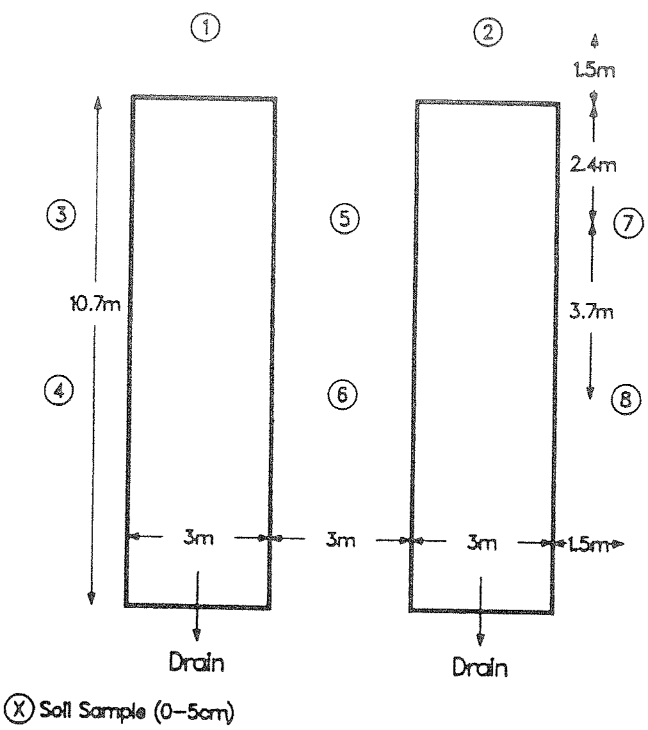

Fig. 1. *Schematic diagram of the rainfall simulation plot pairs showing the reference soil sample locations.*

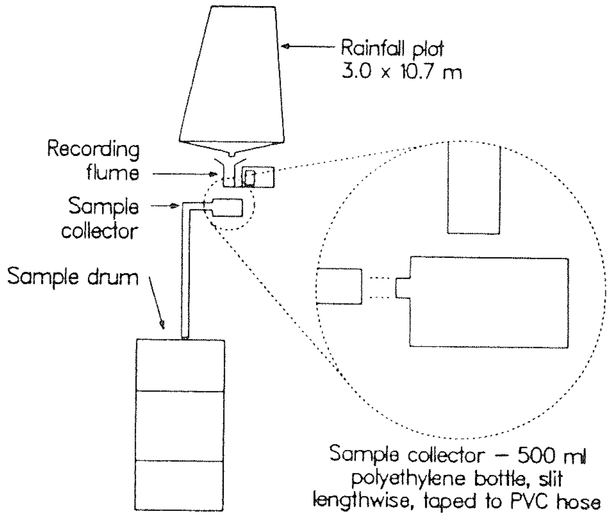

Fig. 2. *Schematic of runoff collection system.*

Results and Discussion

The average ^{137}Cs concentrations among particle fractions of the reference soils are listed in Table 3. Those data indicate a trend toward ^{137}Cs concentrations in the finer fractions. They also indicated the degree of variability in ^{137}Cs concentrations between plot pairs; there appears to be no significant difference between plot

Table 3. Average Concentrations of ^{137}Cs in Particle Size Fractions of Reference Soils

Plot	^{137}Cs concentration[1] (mBq g^{-1})[2] 2000-500μ	500-50μ	<50μ
1,2	39 (0.44)	46 (0.27)	100 (0.21)
3,4	45 (0.57)	44 (0.28)	92 (0.30)
5,6	21 (0.35)	42 (0.33)	76 (0.35)

[1] Values in parentheses are C.V. (n=8)
[2] 1 mBq g^{-1} is equivalent to 0.027 pCi g^{-1}

pairs. Concentrations of ^{137}Cs in sediment particle fractions are listed in Table 4. Although differences in ^{137}Cs concentrations between particle fractions exist, no strong trends are noted for samples from the natural plots. A trend is suggested, however, for the treatments where the ground cover was removed, i.e., higher ^{137}Cs concentrations in the large and small fractions. The higher concentrations in the <50-micron fractions is consistent with observations that ^{137}Cs tends to concentrate by sorption in the clay fractions of soils.

Table 4. Concentrations of ^{137}Cs in Particle Size Fractions of Sediment Collected from the Various Plots during the Various Rainfall Treatments

Plot	Rainfall Treatment	^{137}Cs concentration[1] (mBq g^{-1})[2] 2000-500μ	500-50μ	<50μ
Natural				
1	Dry	<68	87 (15)	80 (5)
	Wet	28 (4)	52 (5)	77 (5)
	Very wet	70 (5)	83 (5)	63 (5)
4	Very Wet	42 (16)	35 (6)	72 (27)
Clipped				
3	Wet	120 (8)	85 (5)	120 (6)
	Very Wet	120 (6)	53 (5)	140 (6)
6	Very Wet	82 (5)	62 (5)	100 (6)
Bare				
2	Dry	78 (5)	70 (5)	130 (6)
	Wet	65 (5)	57 (5)	120 (6)
	Very wet	48 (5)	53 (5)	110 (6)
5	Dry	130 (6)	92 (5)	130 (6)
	Wet	83 (5)	90 (5)	120 (6)
	Very wet	100 (6)	92 (5)	120 (6)

[1] Values in parentheses are SD of the counting results (n=1)
[2] 1 mBq g^{-1} is equivalent to 0.027 pCi g^{-1}

The ^{137}Cs concentrations are distributed differently in the sediment than in the reference soil. To better visualize that difference the ratios of ^{137}Cs in the sediment to the ^{137}Cs in the reference soil were calculated for each particle fraction and are shown in Table 5. For this comparison the ^{137}Cs concentrations of the 3 rainfall treatments were averaged before the ratios were calculated. Note that almost all of the ratios are greater than unity. Cesium-137 deposited from fallout has been shown to accumulate in the uppermost increments of soil and tends toward an exponential decrease in concentration with depth. Cesium-137 in the reference soil may, therefore, be somewhat diluted with soil material of lesser ^{137}Cs concentration. Also the eroded ^{137}Cs probably originates from the top few millimeters of surface soil that contains the highest concentration of fallout ^{137}Cs.

Table 5. Ratios of ^{137}Cs concentrations in Particle Fractions of Sediment Relative to Reference Soils

Plot	^{137}Cs in sediment/^{137}Cs in reference 2000-500μ	500-50μ	<50μ
Natural			
1	1.3	1.6	0.7
4	1.1	1.2	1.4
Clipped			
3	2.6	1.6	1.5
6	3.9	1.4	1.3
Bare			
2	1.6	1.3	1.2
5	5.1	2.2	1.7

The ratios for the natural plots are quite similar. However, there is strong evidence that the 2000- to 500-micron fraction of the sediment from the disturbed plots contains elevated levels of ^{137}Cs. After allowing the sediment to settle in the steel drum it was observed that a considerable amount of partially decomposed plant litter was present. It was also noted that the material in the 2000- to 500-micron fraction was considerably less dense than material from the other size fractions suggesting that that material contained considerable amounts of organic matter.

Cesium has been reported in the literature to be enriched in the organic litter at the soil surface. A similar enrichment of ^{137}Cs in the organic litter fraction of the mobilized sediment may also be inferred by comparing the results in Tables 5 and 6. Sediments from Plot 5 (bare) were considerably higher in organic matter than were the reference soils surrounding Plot 5 for all size fractions (Table 6); the greater the size fraction, the greater the enhancement. Thus, organic matter tends to be more mobile than mineral particles of similar sizes. The larger size fractions of the sediment from the treated plots were also highly enriched in ^{137}Cs compared to the reference soils; the factors ranged from 1.6 to 5.1 as seen in Table 5. From the evidence that both ^{137}Cs and organic litter were enriched in the mobilized sediments compared to the surrounding reference soil and that ^{137}Cs is known to be enriched in organic litter at the soil surface it is concluded that much of the mobile ^{137}Cs was associated with the partially decomposed organic litter. The greater mobility of the organic litter compared to mineral particles can be attributed to its lower density for similar size fractions; ^{137}Cs, because of its association with the organic litter, should also be more mobile in those cases where the soil has been disturbed.

Table 6. Organic Matter Content of Reference Soil and Sediment Removed from Plot 5 (Bare)

Case	Organic matter[1] (mg/g) 2000-500μ	500-50μ	<50μ
Reference	3.0 (0.1)	1.9 (0.04)	5.2 (0.1)
Plot 5	150 (11)	58 (4)	27 (3)

[1] Values in parentheses are SD of triplicate analyses; values based on determination of COD.

A calculation was made to estimate the total ^{137}Cs removed during the rainfall simulation event. For this estimation the ^{137}Cs concentration in the sediment was adjusted using the sediment load data listed in Table 7. The percent removed was that ^{137}Cs in the total sediment load divided by the ^{137}Cs predicted to be in the plot based on the ^{137}Cs in he reference soil; the estimation is presented in Table 8. Less than 0.3% was removed from the natural plots and similarly from the clipped plots where only vegetation was removed. On the other hand, better than 3% or 10 times as much ^{137}Cs was removed from the bare plots where vegetation and rock mulch was removed. That degree of ^{137}Cs removal is consistent with values reported in the literature although care should be exercised in making that comparison since the conditions of the various experiments were different.

Table 7 Measured Sediment Load from Rainfall Simulator Plots[1]

Plot	Rainfall Treatment	Sediment removed (g)
Natural		
1	Dry	83
	Wet	390
	Very wet	660
4	Dry	0
	Wet	0
	Very wet	140
Clipped		
3	Dry	75
	Wet	160
	Very wet	340
6	Dry	0
	Wet	370
	Very wet	710
Bare		
2	Dry	2500
	Wet	4400
	Very wet	7200
5	Dry	2900
	Wet	2300
	Very wet	4400

[1] Data from R. Simanton, USDA-ARS, Tucson, AZ.

Table 8. Percentage Removal of ^{137}Cs as a Result of Rainfall Simulation. Values Based on Total ^{137}Cs Removed in Three Rainfall Treatments Divided by ^{137}Cs in Reference Soil.

Plot	Plot treatment	^{137}Cs removed (%)
1,4	Natural	0.3, 0.02
3,5	Clipped	0.1, 0.3
2,5	Bare	3.0, 3.4

Summary

The results generated in this study suggest that radioactive contaminants residing on or near the surface of arid rangeland soils are subject to mobilization by the forces of rainfall and runoff. The degree of mobilization is strongly exacerbated by disturbances or removal of the rock mulch (desert pavement). Higher concentrations of mobile ^{137}Cs seem to be associated with a mobile organic fraction possibly of partially decomposed plant litter. That information is important input to designing cleanup or containment scenarios as any disturbance of the natural surface may cause the contamination to become more mobile than if the areas were left alone.

This study also tested a simplistic method of collecting runoff sediments in bulk. The method caused minimal impact on collection of sediment load samples and proved to be efficient in collection of bulk samples for subsequent analysis.

Literature Cited

Brown, R.B., N.H. Cutshall, and G.F. Kling. 1981. Agricultural erosion indicated by ^{137}Cs redistribution: I. Levels and distribution of ^{137}Cs activity in soils. Soil Sci. Soc. Am. J. 45:1184-1190.

Brown, R.B., G.F. Kling, and N.H. Cutshall. 1981. Agricultural erosion indicated by ^{137}Cs redistribution: II. Estimates of erosion rates. Soil Sci. Soc. Am. J. 45:1191-1197

Leavitt, V.D. 1974. Soil surveys of five plutonium contaminated areas on the test range complex in Nevada. NERC-LV-539-28

Longmore (McCallan), M.E., B.M. O'Leary, C.W. Rose, and A.L. Chandica. 1983. Mapping soil erosion and accumulation with the fallout isotope caesium-137. Aust. J. Soil Res. 21:373-385

McHenry, J. Roger, Jerry C. Ritchie, and Angela C. Gill. 1973. Accumulation of fallout cesium-137 in soils and sediments in selected watersheds. Water Resources Research 9:676-686

McHenry, J. Roger, and Jerry C. Ritchie. 1977. Physical and chemical parameters affecting transport of ^{137}Cs in arid watersheds. Water Resources Research 13:923-927

Menzel, Ronald G. 1960. Transport of strontium-90 in runoff. Science 131:499-500

Ritchie, J.C., E.E.C. Clebsch, and W.K. Rudolph. 1970. Distribution of fallout and natural gramma radionuclides in litter, humus and surface mineral soil layers under natural vegetation in the Great Smokey Mountains, North Carolina-Tennessee. Health Physics 18:479-489

Ritchie, Jerry C., J. Roger McHenry, and Angela C. Gill. 1972. The distribution of ^{137}Cs in the litter and upper 10 cm of soil under different cover types in northern Mississippi. Health Physics 22:197-198

Ritchie, Jerry C., J. Roger McHenry, Angela C. Gill, and Paul H. Hawks. 1972. Fallout ^{137}Cs in reservoir sediment. Health Physics 22:96-98

Ritchie, Jerry C., James A. Spraberry, and J. Roger McHenry. 1974. Estimating soil erosion from the redistribution of fallout ^{137}Cs. Soil Sci. Soc. Amer. Proc. 38:137-139

Ritchie, Jerry C., Paul H. Hawks, and J. Roger McHenry. 1975. Deposition rates in valleys determined using fallout cesium-137. Geol. Soc. of Amer. Bull. 86:1128-1130

Rogowski, A.S., and Tsuneo Tamura. 1965. Movement of ^{137}Cs by runoff, erosion and infiltration on the alluvial Captina Silt Loam. Health Physics 11:1333-1340

Rogowski, A.S., and Tsuneo Tamura. 1970. Erosional behavior of cesium-137. Health Physics 18:467-477

Tamura, Tsuneo. 1974. Characterization of plutonium in surface soils from Area 13 of the NTS. PP. 27-41. *In:* M.G. White and P.B. Dunaway (ed.) The radioecology of plutonium and other transuranics in desert environments. NVO-153, USDOE

Rainfall Simulator Studies of Earth Covers Used in Shallow Land Burial at Los Alamos, New Mexico

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Key words: erosion, experimental plots, infiltration, waste management

Abstract

Ten 3.05 by 10.7 m experimental plots were established and subjected to simulated rainfall in a study of erosion of trench caps similar to those used for disposal of low-level radioactive wastes at Los Alamos, NM. Treatments included natural, tilled, bare soil, gravel mulch, vegetated, and vegetated plus gravel mulch plots. Measured soil loss data were used to estimate soil erodibility and cover-management factors for the Universal Soil Loss Equation (USLE).

Introduction

A conservative estimate (U.S. Department of Energy 1982) of the annual volume of low-level radioactive wastes produced in the United States is 16 million cubic meters by the year 2020. Disposal of this amount of waste material is a major concern, because new burial sites will be required. These new burial sites will be selected in many different locations with widely varying environmental conditions.

Currently, the most common method of disposing of low-level wastes is shallow land burial (SLB). Trenches are excavated, filled with wastes, and then closed. Management practices range from simple backfilling of the trench to cover the buried waste, to installation of multilayered trench caps and revegetation of the sites. When the burial site receives its final cover, it is subject to natural processes such as erosion, which can modify the configuration of the surface cover and threaten the integrity of the trench cap.

The purpose of our research was to study erosion rates and processes affecting the integrity of earth covers used in shallow land burial at Los Alamos, New Mexico. We used a rainfall simulator (see Swanson 1965 and Simanton and Renard 1982 for descriptions) to study runoff and erosion on simulated trench caps designed to closely match actual trench caps used for shallow land burial at Los Alamos (see Warren 1980 for descriptions).

Methods

Erosion plots (3.05 by 10.7 m) were subjected to simulated rainfall from a rotating boom simulator using materials and experimental design described by Simanton and Renard (1982) and Nyhan et al. (1984). Briefly, a simulated trench cap (15 by 63 m) was constructed with a profile consisting of 15 cm of topsoil (Hackroy sandy loam) over 90 cm of backfill (crushed Bandelier tuff). The downhill slope of both layers was installed at 7%, and 8 experimental plots were installed in paired-plots configuration. Three treatments imposed in 1982 were cultivated up and down slope and disked, bare soil, and vegetated. In addition, two natural and undisturbed plots were subjected to the same simulated rainfall sequences as the eight treated plots. In 1983, the treatments were changed to include the following plots: cultivated, bare soil, bare soil with a gravel (<13 mm diameter) mulch cover at an application rate 13 kg/m^2 and vegetated with the same gravel application rate. Rainfall simulator runs on all plots were in the following sequence. A dry run for 60 min, a wet run for 30 min 24 h later, and a very wet run for 30 min after a 30 min delay following the wet run. All application rates were constant and at a rate of about 60 mm/h. Rainfall rates were measured with a recording raingage, and rainfall amounts were measured with 8 nonrecording raingages on the plots. Runoff rates were measured with a small flume at the downstream end of the plots, and sediment concentration was determined by analyzing runoff/sediment samples collected from the flume outflow at several times during the duration of runoff.

Results

Primary methods of comparing runoff, sediment concentration, and soil loss or sediment yield used here include direct comparisons and comparison of parameters or factors used in mathematical models representing the processes. Because the experimental design was slightly modified from 1982 to 1983, the results will be described by experimental year.

The 1982 Studies

As expected, runoff and sediment yield from the two natural plots were quite different than runoff and sediment yield from the treated plots. Runoff during the dry run on the natural plots gradually increased from zero to about 30 mm/h, while sediment concentration remained relatively constant at 3.5 to 4.1 g/l. In the successive wet and very wet runs, runoff occurred much sooner after the initiation of rainfall than on the dry runs, and peak discharge rates of about 20 mm/h and about 40/mm/h were observed on the wet and very wet runs, respectively. This reflects decreased infiltration rates into increasingly wet soil profiles. The peak sediment concentrations of 4.0 to 5.4 g/l, during the very wet runs, also reflect the influence of antecedent moisture and increased runoff.

Equilibrium sediment concentrations from the cultivated plots generally ranged from under 50 to just over 100 g/l, which represent an increase of about 10 to 30 times the concentration from the natural plots. Instantaneous sediment concentration values exhibited even larger differences between the cultivated and natural plots.

Equilibrium runoff rates from the bare soil, barley vegetated, and cultivated treatments were similar, but sediment concentrations were quite different. Maximum sediment concentrations from the smooth, bare soil plots were about 60 g/l, compared with 108 g/l from the cultivated plots. Maximum sediment concentrations from the vegetated plots (barley cover) were lower, and ranged from about 15 to 26 g/l. Hydrograph and sedigraph data from each simulator run were integrated over the time runoff occurred, and the resulting average runoff and soil loss amounts for each surface treatment are shown in Table 1. Average soil losses from the bare soil and barley plots were 64 to 67% and 29 to 38%,

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Table 1. Average runoff and soil loss for rain simulator runs on dry, wet, and very wet soil surfaces on erosion plots as a function of surface treatment[1] (1982 data).

Treatment (No. of plots)	Average runoff (mm)			Average soil loss (kg)		
	Dry surface	Wet surface	Very wet surface	Dry surface	Wet surface	Very wet surface
Natural cover (2)	14.5	6.0	18.7	1.47	0.46	2.24
Cultivated (2)	44.1	25.0	27.2	104.93	65.37	66.09
Bare soil (2)	46.7	26.8	28.4	70.55	41.88	44.58
Barley cover (4)	37.9	26.5	27.6	30.56	23.43	24.84

[1] Represents an initial 60-min rainfall simulation (dry surface), a 30-min run 24 h later (wet surface), and another 30-min run after a 30-min delay (very wet surface), all performed at a nominal target rate of about 60 mm h^{-1}.

respectively, of losses from the cultivated plots. The influence of antecedent soil moisture erosion was significant for all plots. Overall, average soil loss rates increased by 19 to 53% between the dry and wet runs, and increased by 1 to 7% between the wet and very wet runs (Table 1).

We used the soil loss data to estimate values for the soil erodibility, K, and soil loss ratios for the cover-management, C, factors of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). Values for K were calculated from the measured soil losses from the cultivated plots and the energy and intensity of the simulated rainfall applied to these plots. Soil losses from the three rainfall simulator runs on the cultivated plots were summed and adjusted for soil loss from the standard unit plot (22.1 m length, 9% slope) according to USDA Agricultural Handbook 537 (Wischmeier and Smith 1978), using the recommended conversion to metric units (Foster et al. 1981). The simulated rainfall EI factor (storm erosivity factor) for the three simulated rainstorms was calculated (Meyer and McCune, 1958) as the product of the energy of the rainfall (MJ ha^{-1}) and the simulated rain intensity (mm h^{-1}). The average K factor, for all three simulator runs on both tilled plots, was then calculated by dividing the total unit-plot adjusted soil loss for the three simulator runs by the estimated total EI factor. This gave a K value of 0.085 Mg ha h ha^{-1} MJ^{-1} mm^{-1}, with a C.V. of 15% (n = 6). This K value agrees quite well with the estimate of 0.079 Mg ha ha ha^{-1} MJ^{-1} mm^{-1} that we determined from the soil erodibility nomograph (Wischmeier et al. 1971).

Table 2. Soil loss, cover management factor (C), and plant cover estimates for the trench cap plots with barley cover, and for the natural plots (1982 data).

Plot number	Total soil loss[1] (Mg ha^{-1})	C factor[2]	Plant cover (%)
Trench cap plots with barley cover			
2	45	0.43	62
4	28	0.27	84
5	28	0.27	78
7	39	0.37	62
Natural plots			
N1	2.4	0.023	63
N2	1.3	0.013	78

[1] Sum of soil losses from plot during dry, wet, and very wet soil surface rain simulator runs, adjusted for losses from a standard USLE unit plot.

[2] Total soil loss from the vegetated plot/average total soil loss from the cultivated erosion plots.

The cover management factor in the USLE is an average soil loss ratio, which in conjunction with the distribution of erosivity throughout the year is weighted according to the distribution of the soil loss ratio throughout the year. This factor reflects the ratio of the soil loss at a specific crop stage to the corresponding loss from the clean-tilled, unprotected soil of a unit plot. Thus, we calculated soil loss ratios for the barley cover and natural cover treatments by dividing the total soil loss from all three simulator runs for these treatments, adjusted for soil loss from the standard unit plot (Wischmeier and Smith 1978) by the corresponding soil loss from the tilled plots (Table 2). Soil loss ratios ranged from 0.27 to 0.3 for the barley plots, and from 0.013 to 0.023 for the plots with natural vegetative cover. These soil loss ratios agreed quite well with standard soil loss ratios for barley cover at crop stages 1 and 2 having soil loss ratio values of 0.31 to 0.60, and for the natural vegetation in local rangelands having soil loss ratio values of 0.01 to 0.08.

Soil loss ratios are obviously more than just a function of vegetative cover, as evidenced by the large difference between soil loss ratios for the barley on the trench cap and the cover on the natural plots (Table 2). Plant cover on the barley plots increased from 62 to 84% as soil loss decreased from 44.9 to 28.4 Mg ha^{-1}. The plant cover on the natural plots, which included some additional protection due to litter, etc. also ranged from 63 to 78% cover, yet much smaller soil losses were observed on these plots than on the barley plots.

Table 3. Average runoff and soil loss for rain simulator runs on dry, wet, and very wet soil surfaces on erosion plots as a function of surface treatment[1] (1983 data).

Treatment (No. of plots)	Average runoff (mm)			Average soil loss (kg)		
	Dry surface	Wet surface	Very wet surface	Dry surface	Wet surface	Very wet surface
Cultivated (2)	60.4	28.0	30.7	96.17	53.22	59.70
Bare soil (2)	51.1	23.6	27.2	60.23	26.69	33.27
Gravel (2)	46.2	23.3	28.3	5.08	1.92	2.37
Gravel plus wheatgrass (2)	47.2	25.8	29.0	3.91	1.55	1.21

[1] Represents an initial 60-min rainfall simulation (dry surface), a 30-min run 24 h later (wet surface), and another 30-min run after a 30-min delay (very wet surface), all performed at a nominal target rainfall rate of about 60 mm h^{-1}.

Several subfactors of the cover-management factor (C factor) should be considered in making a comparison of the soil loss ratios in the plots with natural cover and the barley plots on the trench cap. The C factor is directly influenced by variations in subfactors involving not only plant and canopy cover, but also residual mulch, incorporated plant residues, plant roots, and changes in soil structure, density, biological activity, and many other properties (Wischmeier and Smith, 1978). Shallow land burial site preparation, such as those that occurred on our trench cap plots, removes vegetation, the root zone of the soil, residual effects of prior vegetation, and partial covers of mulch and vegetation, all of which substantially increase soil erosion. Another observed difference was the large amount of dark green lichens and algae (cryptogams) growing in erosion-resistant pedestals throughout the natural plots. An additional contributing factor was the difference in the texture of the surface soils in the two plots: the fine-textured subsoil in the natural soil series was mixed into the soil surface layer of the trench cap plots compared with the undisturbed and sandier topsoil found on the natural plots. These factors influenced the infiltration/runoff relationships on these two types of soils and surfaces (Table 1).

In time, plant succession and soil formation processes will make the erosional and hydrologic properties of the disturbed soil surfaces at the SLB site more similar to those of the undisturbed natural plots. Thus, the time required for the revegetated trench cap surfaces to reduce soil erosion as effectively as the natural systems has major implications in waste management decisions at these sites. Clearly, more research is needed to investigate how the cover-management and the soil erodibility factors change with time on the trench cap to ensure successful, long-term management of infiltration and soil erosion processes in a wide range of trench cap environments.

The 1983 Studies

Four treatments were imposed on the eight erosion plots by the end of July, 1983. As in 1982, two plots received a new up- and downslope disking (cultivated treatment). Both standard tilled plots were thus again comparable to the standard USLE plot used to determine the erodibility factor. A second year's data were collected on the two plots that were not tilled and had no vegetative cover (bare soil treatment). To determine the influence of partial gravel cover on soil erosion, two plots were prepared as the bare soil treatment, and they then received a gravel (<13 mm diameter) mulch cover at an application rate of 13 kg/m^2 (gravel cover treatment). The influence of partial gravel cover plus vegetation on soil erosion was determined on two plots that were first seeded with Western Wheatgrass (*Agropyron smithii* Rydb.) at a seeding rate of 13 g/m^2 and received a simultaneous surface application of 18-24-6 (N-P-K) fertilizer at a rate of 13.5 g/m^2. Both plots then received the same gravel application rate as the gravel cover treatment (gravel and plant cover treatment).

Runoff rates and maximum sediment concentrations (63.6 to 75.5 g/l) from the cultivated plots were similar to the data collected on the same plots in 1982. Maximum sediment concentrations of 30 to 50 g/l from the bare plots were also similar to the corresponding values from the 1982 experiments. However, the plots with gravel cover exhibited maximum sediment concentrations and sediment loss rates some 13 to 24 times smaller than those from the cultivated plots (Table 3).

Runoff hydrographs and sedigraphs were integrated throughout the duration of runoff for each run. The average runoff and soil loss for each treatment are shown in Table 3. The influence of the gravel was to reduce the amount of soil loss and increase the amount of infiltration with respect to the bare soil plots.

Values of the soil erodibility factor, K, in the USLE, were calculated from the measured soil losses from the cultivated plots, and the energy and intensity of the simulated rainstorms applied to these plots, as previously described for the 1982 simulator runs. The average K factor for all three simulator runs on both tilled plots in 1983 was 0.069 Mg ha h ha^{-1} MJ^{-1} mm^{-1}, with a C.V. of 11% (n = 6). There is no significant difference between this K value and the 1982 estimate, both of which agree with the K estimate from the soil erodibility nomograph (Wischmeier et al. 1971).

We calculated estimates of the USLE cover management factor which reflect the soil loss ratio from a plot with a certain amounts of gravel and/or plant cover to the corresponding loss from the clean-tilled, unprotected soil of a unit plot (as shown in Table 4).

Table 4. Soil loss, cover management factor (C), and gravel cover estimates for the trench cap plots with gravel and gravel plus wheatgrass covers (1983 data).

Plot number	Total soil loss[1] (Mg ha^{-1})	C factor[2]	Gravel cover (%)	Plant cover (%)
Trench cap plots with gravel cover				
2	3.71	0.040	75	0.0
7	4.66	0.050	71	0.0
Trench cap plots with gravel plus wheatgrass cover				
4	4.55	0.048	70	[3]29(20)
5	1.47	0.016	70	32(23)

[1] Sum of soil losses from plot during dry, wet, and very wet soil surface rain simulator runs, adjusted for losses from a standard USLE plot.

[2] Total soil loss from the vegetated plot/average total soil loss from the cultivated erosion plots.

[3] Numbers in parenthesis represent percentages of cover where gravel and wheatgrass were both present in the field, i.e., for plot 4, 29% of the 385 field locations had wheatgrass present, but 20% of the 385 field locations also had gravel present.

Soil loss ratios ranged from 0.040 to 0.050 for the trench cap plots with gravel cover, and from 0.016 to 0.048 for the plots with a cover if gravel plus wheatgrass.

The gravel and plant cover estimates responsible for these reductions in soil loss are also presented in Table 4. Gravel cover estimates ranged from 70 to 75%, with the young, small wheatgrass plants contributing very little additional cover in the two plots with gravel plus wheatgrass cover.

These soil loss ratio values are generally slightly lower than standard soil loss ratios observed in other field studies for gravel and mulch covers with this amount of ground cover. Data from Wischmeier and Smith (1978) indicate that soil loss ratios equal to about 0.10 to 0.15 would be expected for the amount of ground cover we observed (Table 4). A similar study of stone mulches on construction sites in Indiana also resulted in high soil loss ratio values relative to this amount of plant cover (Meyer et al. 1972). However, the explanation for our small soil loss ratio values lies in the fact that, even with the low landslope (7%) on our erosion plots relative to much larger landscape values on erosion plots in other field studies, our unprotected, highly erosive trench cap soil had larger soil loss rates than unprotected soil surfaces in other studies. Thus, any amount of plant or gravel cover would reduce the amount of soil loss from our trench cap plots even more than from less erodible soils in other field studies.

Discussion

After the determination of the K and C factors with the use of the rainfall simulator, the major purpose of the resulting soil loss prediction procedure is to supply specific and reliable guides for selecting adequate erosion control practices for the SLB site. This process is also used to estimate the upland erosion phase of sediment yield to predict stream loading rates.

The USLE is most successfully used to predict long-term average soil losses from upland shallow land burial sites, but not for specific rainstorms. The average soil losses are predicted for a sufficient number of similar events or time intervals to cancel out the effects of short-time fluctuations in uncontrolled variables. The USLE-estimated soil losses will be the most accurate for medium-textured soils, slope lengths of less than 400 ft, gradients of 3 to 18%, and cover-management systems that have been used in erosion plot studies. As these limits are exceeded, the probability of extrapolation error will be increased.

If this degree of accuracy of the USLE is inadequate, and if estimates of soil loss from specific storms, sediment yield from complex areas within the SLB site, and characteristics of eroded and transported sediment are required, more detailed models such as CREAMS (Knisel 1980) must be used. CREAMS, a field scale model for Chemical, Runoff, and Erosion from Agricultural Management Systems, was first applied to SLB of low-level radioactive wastes at Los Alamos (Lane and Nyhan 1981, Nyhan and Lane 1982, Hakonson et al. 1984). Although several USLE factors are used in CREAMS, the water balance component of CREAMS, unlike the USLE, addresses the influence of antecedent soil water content on sediment, nutrient, and pesticide losses on a storm-by-storm basis.

However, researchers and users should not see either the USLE or the CREAMS model as a final representation of erosion prediction technology. Both of these models are but continuing steps in our efforts to develop improved models to estimate erosion and sediment yield for applications such as improved shallow land burial design criteria.

Literature Cited

Foster, G.R., D.K. McCool, K.G. Rcnard, and W.C Moldenhauer. 1981. Conversion of the Universal Soil Loss Equation to SI metric units. J. Soil Water Cons. 36:355-359.

Hakonson, T.E., G.R. Foster, L.J. Lane, and J.W. Nyhan. 1984. The application of an agricultural water balance and erosion model in environmental science - a user perspective. *In:* Symposium on prediction of agricultural non-point source pollution: model selection and application, Venice, Italy.

Knisel, W.G. 1980. CREAMS: a field-scale model for chemicals, runoff, and erosion from agricultural management systems. USDA Cons. Res. Rep. 26, U.S. Government Printing Office, Washington, D.C.

Lane, L.J., and J.W. Nyhan. 1981. Cover integrity in shallow land burial of low-level wastes: hydrology and erosion. Oak Ridge Nat. Lab. Rep. ORNL/NFW-81/34:419-430.

Meyer, L.D., and D.L. McCune. 1958. Rainfall simulator for runoff plots. Trans. Amer. Soc. Agri. Engrs. 39:644-648.

Meyer, L.D., C.B. Johnson, and G.R. Foster. 1972. Stone and woodchip mulches for erosion control on construction sites. J. Soil Water Cons. 27:264-269.

Nyhan, J.W., and L.J. Lane. 1982. Use of a state-of-the-art model in generic designs of shallow land repositories for low-level wastes. *In:* R.G. Post and M.E. Wacks (eds.) Waste management '82. University of Arizona, Tucson.

Nyhan, J.W., G.L. DePoorter, B.J. Drennon, J.R. Simanton, and G.R. Foster. 1984. Erosion of earth covers used in shallow land burial at Los Alamos, New Mexico. J. Environ. Qual. 13:361-366.

Simanton, J.R., and K.G. Renard. 1982. Seasonal changes in infiltration and erosion from USLE plots in southeastern Arizona. Hydrology and Water Resources in Arizona and the Southwest, Office of Aridland Studies, Univ. Arizona, Tucson 12:37-46.

Swanson, N.P. 1965. Rotating-boom rainfall simulator. Trans. ASAE 8:71-72. U.S. Department of Energy, Office of Nuclear Energy. 1982. Spent fuel and radioactive waste inventories, projections, and characteristics. U.S. Dept. Energy Rep. No. DOE/NE-0017-1.

Warren, J.L. 1980. Shallow land burial: experience and developments at Los Alamos. *In:* Underground disposal of radioactive wastes. International Atomic Energy Agency, Vienna, Austria.

Wischmeier, W.H., C.B. Johnson, and B.V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil Water Cons. 26:189-192.

Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall erosion losses—a guide to conservation planning. USDA Handb. No. 537, U.S. Government Printing Office, Washington, D.C.

APPENDICES: A, B, C: Rainfall Simulation on Rangeland Erosion Plots

Data presented in the following appendices are from rainfall simulation studies conducted in Arizona, Idaho, New Mexico and Nevada, which are described by Simanton, Johnson, Nyhan, and Romney in these proceedings. The EI value presented in these appendices has been corrected for the difference between the rotating boom simulator rainfall energy and that of natural rainfall (i.e., actual measured × 0.77 = EI reported).

APPENDIX — A

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE DRY RUN SPRING 1981

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	59.69	793.81	0.00	0.00
4	BARE	57.15	755.35	45.68	8539.50
5	CLIP	59.69	659.01	30.06	1179.90
6	NAT	60.71	671.95	39.34	1275.40
7	NAT	59.44	617.66	28.85	1691.60
8	BARE	53.85	551.96	29.90	5352.50
9	CLIP	57.15	669.74	25.70	1277.90
10	TILL	57.40	673.14	0.42	166.60
11	BARE	54.61	645.23	25.04	7534.00
12	NAT	52.32	611.19	17.82	1095.40
13	TILL	59.94	829.38	3.67	418.80
14	CLIP	53.34	726.24	17.76	1161.80
15	NAT	57.40	771.18	18.22	889.10
16	BARE	57.15	767.26	31.34	5437.60
17	CLIP	58.17	780.37	22.95	1457.30
18	TILL	51.82	680.63	7.37	810.30
19	CLIP	60.45	811.51	20.05	1499.00
20	BARE	56.90	757.39	20.45	3293.60
21	NAT	55.63	726.24	11.51	741.70
22	TILL	62.23	825.30	1.55	344.40
23	BARE	56.39	689.65	15.08	2290.90
24	TILL	62.99	782.41	0.00	0.00
25	CLIP	55.88	653.06	3.26	117.30
26	NAT	59.94	707.35	1.78	180.80

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE WET RUN SPRING 1981

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	30.73	350.78	0.74	96.00
4	BARE	30.73	347.38	15.33	3015.90
5	CLIP	30.23	392.82	16.64	429.80
6	NAT	29.97	388.91	18.52	600.70
7	NAT	28.96	361.68	12.73	700.00
8	BARE	30.48	383.46	15.81	2923.30
9	CLIP	28.96	324.57	15.03	639.30
10	TILL	29.46	331.04	3.75	291.60
11	BARE	32.00	453.92	12.19	4379.20
12	NAT	27.43	380.74	8.43	432.20
13	TILL	26.42	339.72	10.95	2317.70
14	CLIP	26.42	339.72	9.65	417.70
15	NAT	32.51	451.37	8.06	427.60
16	BARE	28.19	383.80	12.67	2266.80
17	CLIP	29.21	387.21	10.51	486.00
18	TILL	27.94	367.97	14.72	1447.30
19	CLIP	30.99	427.37	12.13	840.60
20	BARE	30.48	419.54	12.59	1994.00
21	NAT	29.46	403.54	6.16	314.80
22	TILL	32.51	451.37	6.74	806.20
23	BARE	31.50	435.37	15.93	3583.40
24	TILL	32.00	443.37	0.50	67.10
25	CLIP	32.51	380.91	6.53	218.80
26	NAT	32.51	380.91	3.45	311.90

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE VERY WET RUN
SPRING 1981

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	30.48	370.53	1.30	140.30
4	BARE	31.50	380.91	18.68	4386.20
5	CLIP	30.48	403.20	18.39	542.20
6	NAT	29.97	395.37	22.23	813.00
7	NAT	28.45	333.25	14.54	678.40
8	BARE	29.21	343.29	16.56	3355.90
9	CLIP	28.19	299.89	16.85	975.40
10	TILL	29.46	315.38	10.22	729.70
11	BARE	30.99	410.69	16.68	5649.80
12	NAT	25.91	334.95	9.83	485.70
13	TILL	25.91	313.17	12.79	3507.30
14	CLIP	27.94	341.25	14.07	651.60
15	NAT	30.23	376.48	11.63	542.10
16	BARE	25.65	312.32	15.14	2982.90
17	CLIP	30.99	427.37	16.74	644.30
18	TILL	28.45	387.72	18.66	1724.00
19	CLIP	29.46	375.29	16.22	867.00
20	BARE	28.96	367.80	15.58	2340.10
21	NAT	30.99	444.22	10.30	421.30
22	TILL	30.48	435.88	15.79	1515.30
23	BARE	32.00	429.41	19.33	4427.50
24	TILL	32.51	437.24	5.74	389.40
25	CLIP	31.50	346.87	10.03	328.30
26	NAT	30.99	340.57	4.75	304.70

APPENDIX—A (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH
SPRING 1981

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
3	TILL	12.1	5.9	22.2	66.5	5.3	0.0	0.0	0.0	0.0
4	BARE	12.2	2.0	16.3	60.4	21.2	0.0	0.0	0.0	0.0
5	CLIP	10.8	17.8	31.4	28.8	22.0	0.0	0.0	0.0	0.0
6	NAT	11.1	28.8	33.5	30.4	5.1	14.0	6.0	0.6	20.6
7	NAT	11.5	23.9	41.6	25.7	7.6	9.0	10.0	0.6	19.6
8	BARE	11.7	1.2	15.1	67.1	16.5	0.0	0.0	0.0	0.0
9	CLIP	10.4	19.6	25.3	36.5	18.6	0.0	0.0	0.0	0.0
10	TILL	10.4	12.6	21.4	58.4	7.6	0.0	0.0	0.0	0.0
11	BARE	9.9	3.7	5.5	61.2	29.6	0.0	0.0	0.0	0.0
12	NAT	10.2	15.9	33.1	19.0	30.0	8.0	11.0	2.0	21.0
13	TILL	10.6	10.8	9.6	72.9	6.7	0.0	0.0	0.0	0.0
14	CLIP	12.1	15.3	36.5	14.7	33.5	0.0	0.0	0.0	0.0
15	NAT	10.4	14.1	33.1	20.6	30.0	8.0	9.0	4.0	21.0
16	BARE	9.7	4.7	8.0	49.8	37.5	0.0	0.0	0.0	0.0
17	CLIP	9.0	11.2	35.9	20.0	32.2	0.0	0.0	0.0	0.0
18	TILL	7.5	14.7	15.1	64.5	5.7	0.0	0.0	0.0	0.0
19	CLIP	10.4	9.4	31.0	37.1	22.5	0.0	0.0	0.0	0.0
20	BARE	10.8	3.3	9.0	62.7	24.3	0.0	0.0	0.0	0.0
21	NAT	9.9	9.0	24.9	36.9	25.5	3.0	18.0	1.0	22.0
22	TILL	10.5	19.8	13.3	58.0	9.0	0.0	0.0	0.0	0.0
23	BARE	9.1	4.1	5.5	64.9	25.5	0.0	0.0	0.0	0.0
24	TILL	8.8	37.1	7.8	46.7	8.4	0.0	0.0	0.0	0.0
25	CLIP	10.2	9.6	17.5	21.4	51.4	0.0	0.0	0.0	0.0
26	NAT	10.1	13.5	17.4	21.4	45.1	5.0	21.0	0.0	26.0

PLOTS	SOIL SERIES
3-10	BERNARDINO
11-18	HATHAWAY
19-26	CAVE

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE DRY RUN
FALL 1981

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	54.10	612.04	0.00	86.28
4	BARE	56.39	668.72	36.92	8583.84
5	CLIP	57.15	692.71	34.30	1366.88
6	NAT	57.40	699.18	14.01	308.99
7	NAT	55.37	650.16	18.26	401.85
8	BARE	54.86	637.40	32.12	7425.76
9	CLIP	53.85	645.91	29.89	3677.23
10	TILL	56.90	726.58	0.54	192.20
11	BARE	52.83	581.74	40.49	13014.82
12	NAT	59.18	741.56	34.17	1488.69
13	TILL	54.10	612.55	9.66	2152.08
14	CLIP	57.40	691.52	36.69	1977.21
15	NAT	55.37	644.38	30.55	778.64
16	BARE	56.90	682.84	38.89	13139.07
17	CLIP	56.64	684.37	31.92	3374.31
18	TILL	56.39	677.74	12.80	1604.75
19	CLIP	56.39	672.46	41.13	5069.68
20	BARE	59.18	745.65	33.23	14744.12
21	NAT	50.55	532.56	25.01	1029.99
22	TILL	52.58	579.19	2.76	237.29
23	BARE	56.90	701.39	34.75	13010.40
24	TILL	55.63	668.38	0.59	133.59
25	CLIP	55.37	659.18	34.71	2028.29
26	NAT	57.66	718.75	14.42	589.83

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE WET RUN
FALL 1981

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	28.45	339.38	3.19	331.48
4	BARE	30.23	386.18	19.36	6826.86
5	CLIP	29.72	372.40	25.67	953.75
6	NAT	30.73	400.31	15.50	284.06
7	NAT	29.46	365.76	10.07	318.78
8	BARE	28.19	332.91	15.97	4858.39
9	CLIP	26.92	301.59	8.58	1428.76
10	TILL	28.70	345.85	17.66	2719.84
11	BARE	29.21	359.12	21.26	7024.70
12	NAT	30.48	393.33	14.98	708.28
13	TILL	27.94	326.44	16.11	4535.50
14	CLIP	30.99	407.29	21.97	1911.85
15	NAT	27.69	320.15	11.73	333.74
16	BARE	29.97	379.38	15.34	6332.58
17	CLIP	28.96	352.48	17.76	1589.29
18	TILL	29.97	379.38	19.89	1769.98
19	CLIP	28.45	339.38	19.44	1685.87
20	BARE	30.99	407.29	17.66	4682.64
21	NAT	27.18	307.72	16.34	542.63
22	TILL	30.23	386.18	7.34	596.36
23	BARE	28.19	332.91	18.73	6190.56
24	TILL	29.72	372.40	1.59	170.29
25	CLIP	27.18	307.72	17.61	754.86
26	NAT	29.97	379.38	10.00	382.45

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE VERY WET RUN FALL 1981

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	29.46	365.76	9.60	715.29
4	BARE	30.48	393.33	21.15	7237.26
5	CLIP	29.72	372.40	24.37	935.43
6	NAT	29.97	379.38	14.38	353.99
7	NAT	28.96	352.48	11.90	329.81
8	BARE	28.45	339.38	17.50	5419.12
9	CLIP	27.69	320.15	13.50	2372.36
10	TILL	28.45	339.38	17.30	2261.02
11	BARE	29.46	365.76	23.94	5806.63
12	NAT	30.48	393.33	16.72	657.55
13	TILL	28.96	352.48	17.63	5335.90
14	CLIP	31.50	421.76	22.17	1646.52
15	NAT	29.97	379.38	14.95	356.29
16	BARE	27.43	313.85	18.61	6873.42
17	CLIP	27.69	320.15	17.75	1747.18
18	TILL	28.70	345.85	18.74	1681.45
19	CLIP	28.70	345.85	19.28	1909.93
20	BARE	30.23	386.18	18.18	5618.55
21	NAT	27.43	313.85	17.21	500.97
22	TILL	29.46	365.76	11.59	782.90
23	BARE	28.19	332.91	20.55	6674.51
24	TILL	29.97	379.38	7.39	407.89
25	CLIP	25.65	271.98	15.24	670.24
26	NAT	28.45	339.38	11.32	383.74

APPENDIX—A (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FALL 1981

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
3	TILL	12.1	18.0	0.4	76.0	5.6	0.0	0.0	0.0	0.0
4	BARE	12.2	5.0	46.0	37.0	12.0	0.0	0.0	0.0	0.0
5	CLIP	10.8	27.0	39.0	21.0	13.0	0.0	0.0	0.0	0.0
6	NAT	11.1	18.0	55.0	23.0	3.0	52.0	13.0	2.0	67.0
7	NAT	11.5	25.0	52.0	17.0	5.0	40.0	24.0	4.0	68.0
8	BARE	11.7	3.0	47.0	47.0	3.0	0.0	0.0	0.0	0.0
9	CLIP	10.4	19.0	47.0	29.0	5.0	0.0	0.0	0.0	0.0
10	TILL	10.4	22.0	17.0	57.0	4.0	0.0	0.0	0.0	0.0
11	BARE	9.9	6.0	28.0	57.0	9.0	0.0	0.0	0.0	0.0
12	NAT	10.2	25.0	34.0	23.0	16.0	38.0	12.0	4.0	54.0
13	TILL	10.6	17.0	11.0	70.0	2.0	0.0	0.0	0.0	0.0
14	CLIP	12.1	30.0	29.0	36.0	5.0	0.0	0.0	0.0	0.0
15	NAT	10.4	23.0	32.0	26.0	16.0	36.0	8.0	8.0	52.0
16	BARE	9.7	7.0	22.0	58.0	13.0	0.0	0.0	0.0	0.0
17	CLIP	9.0	22.0	31.0	39.0	8.0	0.0	0.0	0.0	0.0
18	TILL	7.5	19.0	13.0	67.0	1.0	0.0	0.0	0.0	0.0
19	CLIP	10.4	15.0	43.0	30.0	12.0	0.0	0.0	0.0	0.0
20	BARE	10.8	5.0	33.0	55.0	7.0	0.0	0.0	0.0	0.0
21	NAT	9.9	16.0	43.0	26.0	15.0	11.0	17.0	2.0	30.0
22	TILL	10.5	46.0	16.0	32.0	6.0	0.0	0.0	0.0	0.0
23	BARE	9.1	6.0	26.0	63.0	5.0	0.0	0.0	0.0	0.0
24	TILL	8.8	55.0	9.0	31.0	5.0	0.0	0.0	0.0	0.0
25	CLIP	10.2	14.0	30.0	39.0	17.0	0.0	0.0	0.0	0.0
26	NAT	10.1	18.0	36.0	17.0	27.0	18.0	15.0	0.0	33.0

PLOTS	SOIL SERIES
3-10	BERNARDINO
11-18	HATHAWAY
19-26	CAVE

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE DRY RUN
SPRING 1982

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	68.58	1022.56	13.68	2429.00
4	BARE	67.31	982.56	46.50	66582.50
5	CLIP	61.72	885.72	8.80	1018.60
6	NAT	61.98	893.72	0.80	237.90
7	NAT	40.64	462.43	4.62	334.20
8	BARE	39.37	431.97	24.21	17669.00
9	CLIP	55.88	654.42	18.74	1630.10
10	TILL	55.63	648.12	0.00	99.08
11	BARE	63.75	879.59	29.92	27185.20
12	NAT	61.98	828.19	19.97	1523.90
13	TILL	64.77	905.63	34.08	15171.40
14	CLIP	60.96	795.68	28.03	3883.50
15	NAT	72.14	1069.37	21.10	1151.10
16	BARE	71.12	1035.67	40.03	32004.50
17	CLIP	55.88	804.88	19.40	2447.60
18	TILL	52.32	699.35	14.07	1814.20
19	CLIP	51.82	559.28	24.52	2839.70
20	BARE	56.13	663.78	30.60	22665.90
21	NAT	47.24	460.73	12.66	837.50
22	TILL	51.82	561.49	4.98	886.60
23	BARE	57.15	690.33	33.73	21876.30
24	TILL	51.82	559.79	4.96	523.80
25	CLIP	52.83	584.81	15.66	1204.10
26	NAT	54.36	621.40	4.25	450.80

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE WET RUN
SPRING 1982

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	27.94	326.44	11.89	1398.50
4	BARE	27.18	307.72	18.78	19551.80
5	CLIP	28.45	339.38	9.63	707.10
6	NAT	29.46	365.76	3.42	130.80
7	NAT	27.94	326.44	7.05	250.90
8	BARE	27.94	326.44	15.70	11225.40
9	CLIP	28.45	339.38	9.36	626.90
10	TILL	27.43	313.85	2.02	290.10
11	BARE	33.02	466.52	14.28	7690.10
12	NAT	31.75	429.07	5.46	345.80
13	TILL	30.48	393.33	20.03	7838.50
14	CLIP	32.51	451.37	15.86	1611.60
15	NAT	37.85	624.29	11.21	480.70
16	BARE	35.05	530.17	18.38	14605.50
17	CLIP	35.05	530.17	14.28	1656.30
18	TILL	34.54	513.83	18.84	2537.50
19	CLIP	28.19	332.91	15.05	1657.30
20	BARE	27.94	326.44	18.09	11704.70
21	NAT	27.94	326.44	12.74	462.00
22	TILL	27.94	326.44	11.72	1176.50
23	BARE	27.18	307.72	16.68	7909.50
24	TILL	28.45	339.38	7.84	448.60
25	CLIP	27.69	320.15	14.24	799.30
26	NAT	28.96	352.48	5.03	402.40

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE VERY WET RUN SPRING 1982

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	28.96	352.48	15.72	2072.80
4	BARE	25.65	271.98	16.03	13131.80
5	CLIP	29.72	368.99	12.61	946.10
6	NAT	29.97	383.12	8.41	239.70
7	NAT	28.19	332.91	9.49	399.50
8	BARE	27.94	326.44	20.12	10508.60
9	CLIP	27.94	326.44	11.55	1136.20
10	TILL	27.69	320.15	8.26	667.60
11	BARE	30.23	386.18	16.07	9757.60
12	NAT	28.70	345.85	7.28	456.50
13	TILL	32.26	443.88	17.48	6123.20
14	CLIP	32.00	436.39	18.11	1588.90
15	NAT	36.83	589.06	16.08	676.60
16	BARE	34.54	513.83	25.71	13670.80
17	CLIP	31.50	421.76	16.22	1431.90
18	TILL	34.29	505.66	19.25	2893.30
19	CLIP	27.18	307.72	15.48	1774.20
20	BARE	26.16	283.55	15.11	7799.20
21	NAT	28.19	332.91	13.43	526.70
22	TILL	28.70	345.85	15.40	1271.50
23	BARE	26.92	301.59	20.63	6938.60
24	TILL	27.69	320.15	17.53	782.40
25	CLIP	26.16	283.55	14.80	766.60
26	NAT	28.45	339.38	8.47	346.70

APPENDIX—A (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH SPRING 1982

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
3	TILL	12.1	10.0	48.0	33.0	4.0	0.0	0.0	0.0	0.0
4	BARE	12.2	7.0	19.0	70.0	4.0	0.0	0.0	0.0	0.0
5	CLIP	10.8	23.0	59.0	12.0	6.0	0.0	0.0	0.0	0.0
6	NAT	11.1	14.0	18.0	40.0	21.0	24.0	8.0	6.0	38.0
7	NAT	11.5	19.0	17.0	41.0	19.0	18.0	8.0	9.0	35.0
8	BARE	11.7	4.0	44.0	44.0	8.0	0.0	0.0	0.0	0.0
9	CLIP	10.4	26.0	41.0	30.0	3.0	0.0	0.0	0.0	0.0
10	TILL	10.4	24.0	5.0	70.0	1.0	0.0	0.0	0.0	0.0
11	BARE	9.9	8.0	25.0	58.0	9.0	0.0	0.0	0.0	0.0
12	NAT	10.2	14.0	41.0	20.0	24.0	18.0	12.0	7.0	37.0
13	TILL	10.6	24.0	28.0	44.0	4.0	0.0	0.0	0.0	0.0
14	CLIP	12.1	39.0	39.0	10.0	12.0	0.0	0.0	0.0	0.0
15	NAT	10.4	21.0	30.0	22.0	24.0	16.0	8.0	7.0	31.0
16	BARE	9.7	12.0	21.0	58.0	9.0	0.0	0.0	0.0	0.0
17	CLIP	9.0	28.0	42.0	12.0	18.0	0.0	0.0	0.0	0.0
18	TILL	7.5	29.0	0.0	67.0	4.0	0.0	0.0	0.0	0.0
19	CLIP	10.4	21.0	40.0	27.0	12.0	0.0	0.0	0.0	0.0
20	BARE	10.8	11.0	11.0	73.0	5.0	0.0	0.0	0.0	0.0
21	NAT	9.9	23.0	29.0	36.0	11.0	8.0	11.0	1.0	20.0
22	TILL	10.5	53.0	7.0	37.0	3.0	0.0	0.0	0.0	0.0
23	BARE	9.1	11.0	3.0	82.0	3.0	0.0	0.0	0.0	0.0
24	TILL	8.8	63.0	11.0	22.0	4.0	0.0	0.0	0.0	0.0
25	CLIP	10.2	18.0	35.0	23.0	24.0	0.0	0.0	0.0	0.0
26	NAT	10.1	20.0	29.0	30.0	21.0	16.0	22.0	0.4	38.4

PLOTS	SOIL SERIES
3-10	BERNARDINO
11-18	HATHAWAY
19-26	CAVE

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE DRY RUN
FALL 1982

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	51.05	546.00	24.75	862.39
4	BARE	51.82	563.53	39.50	21712.83
5	CLIP	55.63	656.29	28.80	991.43
6	NAT	56.90	688.80	13.66	179.44
7	NAT	56.13	672.12	5.76	127.96
8	BARE	51.82	566.09	45.16	17821.12
9	CLIP	52.32	568.64	22.35	1561.18
10	TILL	51.05	539.36	0.00	0.00
11	BARE	54.86	635.02	42.80	14519.32
12	NAT	49.53	510.26	33.15	1532.91
13	TILL	53.34	616.63	12.33	2089.80
14	CLIP	52.32	591.79	38.36	4022.58
15	NAT	46.99	470.09	30.33	801.27
16	BARE	53.34	616.80	41.71	25793.91
17	CLIP	23.88	237.94	18.60	1261.95
18	TILL	24.13	243.39	10.18	1578.49
19	CLIP	55.88	756.20	37.78	4716.83
20	BARE	55.63	748.88	40.32	30116.57
21	NAT	55.37	646.42	31.32	1980.97
22	TILL	52.83	584.64	0.00	37.50
23	BARE	55.88	656.12	45.55	24693.61
24	TILL	54.36	618.51	27.51	900.67
25	CLIP	53.59	624.29	40.51	3660.71
26	NAT	52.32	592.81	19.72	962.11

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE WET RUN
FALL 1982

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	28.19	332.91	20.92	773.59
4	BARE	27.18	307.72	22.80	14185.43
5	CLIP	25.91	224.83	11.88	384.13
6	NAT	24.38	194.54	3.68	53.30
7	NAT	27.18	307.72	7.42	92.64
8	BARE	27.69	320.15	21.18	10189.94
9	CLIP	26.92	301.59	17.09	1316.24
10	TILL	27.94	326.44	2.81	292.33
11	BARE	28.45	339.38	21.78	7448.53
12	NAT	27.94	326.44	15.65	754.05
13	TILL	26.16	283.55	19.24	4469.13
14	CLIP	26.92	301.59	18.54	2191.32
15	NAT	28.19	332.91	15.26	351.16
16	BARE	28.45	339.38	20.96	11207.95
17	CLIP	28.19	332.91	18.83	1707.71
18	TILL	28.45	339.38	25.72	5781.54
19	CLIP	28.96	352.48	19.66	2176.80
20	BARE	26.92	301.59	20.67	17298.35
21	NAT	29.46	365.76	19.31	819.38
22	TILL	28.70	345.85	3.31	199.48
23	BARE	28.70	345.85	25.55	9511.75
24	TILL	27.18	307.72	14.90	398.51
25	CLIP	27.94	326.44	23.62	2049.06
26	NAT	29.46	365.76	13.95	481.78

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE VERY WET RUN FALL 1982

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	28.45	339.38	22.97	864.93
4	BARE	27.94	326.44	25.46	13970.03
5	CLIP	24.64	249.34	14.21	347.41
6	NAT	24.38	243.90	3.99	50.59
7	NAT	28.45	339.38	10.49	161.54
8	BARE	27.69	320.15	24.54	10799.41
9	CLIP	26.67	295.47	17.68	967.52
10	TILL	26.67	295.47	10.65	764.18
11	BARE	29.97	379.38	25.81	10854.02
12	NAT	26.16	283.55	18.22	845.97
13	TILL	27.94	326.44	22.55	5520.81
14	CLIP	28.19	332.91	25.06	3072.85
15	NAT	27.94	326.44	18.52	587.67
16	BARE	27.94	326.44	22.88	12949.34
17	CLIP	26.67	295.47	23.43	1855.50
18	TILL	28.45	339.38	28.42	4683.25
19	CLIP	28.96	352.48	19.66	2320.26
20	BARE	26.92	301.59	24.59	16721.91
21	NAT	29.97	379.38	20.83	889.37
22	TILL	28.45	339.38	10.29	404.68
23	BARE	28.45	339.38	26.08	10698.57
24	TILL	29.21	359.12	19.73	494.93
25	CLIP	26.42	289.51	23.85	1908.00
26	NAT	28.45	339.38	13.63	405.28

APPENDIX—A (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FALL 1982

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
3	TILL	12.1	20.2	54.7	22.7	2.4	0.0	0.0	0.0	0.0
4	BARE	12.2	5.0	16.0	78.0	1.0	0.0	0.0	0.0	0.0
5	CLIP	10.8	29.0	44.0	27.0	0.0	0.0	0.0	0.0	0.0
6	NAT	11.1	32.0	37.0	27.0	4.0	60.0	15.0	2.0	77.0
7	NAT	11.5	28.0	45.0	26.0	1.0	48.0	26.0	4.0	78.0
8	BARE	11.7	3.0	21.0	73.0	3.0	0.0	0.0	0.0	0.0
9	CLIP	10.4	27.0	42.0	30.0	1.0	0.0	0.0	0.0	0.0
10	TILL	10.4	17.6	6.3	75.9	0.2	0.0	0.0	0.0	0.0
11	BARE	9.9	6.3	6.3	86.0	1.4	0.0	0.0	0.0	0.0
12	NAT	10.2	28.4	27.7	37.2	5.5	29.0	9.0	2.0	40.0
13	TILL	10.6	21.0	1.0	77.5	0.5	0.0	0.0	0.0	0.0
14	CLIP	12.1	35.3	32.7	31.0	1.0	0.0	0.0	0.0	0.0
15	NAT	10.4	26.7	24.9	36.8	9.8	26.0	11.0	3.0	40.0
16	BARE	9.7	7.8	1.2	89.8	1.2	0.0	0.0	0.0	0.0
17	CLIP	9.0	23.9	27.8	47.5	0.8	0.0	0.0	0.0	0.0
18	TILL	7.5	21.4	27.3	51.3	0.0	0.0	0.0	0.0	0.0
19	CLIP	10.4	20.0	32.7	44.9	2.4	0.0	0.0	0.0	0.0
20	BARE	10.8	4.9	1.2	93.1	0.8	0.0	0.0	0.0	0.0
21	NAT	9.9	20.8	28.2	47.1	3.9	5.0	22.0	1.4	28.4
22	TILL	10.5	54.7	0.0	44.9	0.4	0.0	0.0	0.0	0.0
23	BARE	9.1	5.1	0.6	94.1	0.2	0.0	0.0	0.0	0.0
24	TILL	8.8	10.2	11.2	75.9	2.7	0.0	0.0	0.0	0.0
25	CLIP	10.2	19.8	31.0	43.9	5.3	0.0	0.0	0.0	0.0
26	NAT	10.1	19.4	24.3	45.9	9.8	14.0	29.0	0.4	43.4

PLOTS	SOIL SERIES
3-10	BERNARDINO
11-18	HATHAWAY
19-26	CAVE

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE DRY RUN
SPRING 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	54.10	637.91	0.55	229.00
4	BARE	53.59	625.14	37.47	27266.00
5	CLIP	54.86	680.46	13.69	611.00
6	NAT	53.59	647.10	4.37	210.00
7	NAT	58.17	714.84	6.00	361.00
8	BARE	52.83	579.02	30.42	15620.00
9	CLIP	55.37	653.23	15.50	1022.00
10	TILL	53.85	615.44	0.91	159.00
11	BARE	53.34	592.81	35.17	28516.00
12	NAT	46.99	451.71	12.80	867.00
13	TILL	56.90	704.29	40.50	14941.00
14	CLIP	53.09	607.10	24.80	2149.00
15	NAT	51.56	560.13	14.51	508.00
16	BARE	53.34	602.34	30.62	19562.00
17	CLIP	57.15	695.27	23.21	1650.00
18	TILL	49.78	518.09	19.46	3025.00
19	CLIP	54.61	645.23	23.10	2831.00
20	BARE	52.58	595.19	40.32	32385.00
21	NAT	52.58	585.49	21.32	1467.00
22	TILL	55.12	647.61	0.00	0.00
23	BARE	54.61	624.80	41.96	32924.00
24	TILL	55.37	640.29	7.77	490.00
25	CLIP	49.28	519.45	24.93	3233.00
26	NAT	54.86	653.74	12.29	1066.00

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE WET RUN
SPRING 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	27.69	320.15	6.89	386.00
4	BARE	28.70	345.85	18.45	13396.00
5	CLIP	27.94	326.44	9.54	392.00
6	NAT	27.69	320.15	1.44	33.00
7	NAT	27.43	313.85	2.07	86.00
8	BARE	25.40	266.19	17.51	10140.00
9	CLIP	26.67	295.47	9.29	659.00
10	TILL	26.92	301.59	8.26	458.00
11	BARE	28.96	352.48	20.48	14001.00
12	NAT	26.92	301.59	9.46	412.00
13	TILL	29.21	359.12	20.13	7927.00
14	CLIP	23.62	227.90	11.22	611.00
15	NAT	26.92	301.59	8.41	218.00
16	BARE	25.65	271.98	14.21	7778.00
17	CLIP	30.23	386.18	14.38	762.00
18	TILL	29.97	379.38	22.45	3289.00
19	CLIP	29.21	359.12	16.28	2105.00
20	BARE	26.67	295.47	16.89	14181.00
21	NAT	27.18	307.89	15.12	761.00
22	TILL	29.46	365.76	1.82	165.00
23	BARE	27.18	307.72	22.29	13912.00
24	TILL	26.42	289.51	7.63	255.00
25	CLIP	25.65	271.98	20.69	2047.00
26	NAT	27.43	313.85	8.29	439.00

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE VERY WET RUN SPRING 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	26.92	301.59	11.63	640.00
4	BARE	27.94	326.44	19.97	13353.00
5	CLIP	27.43	313.85	12.58	511.00
6	NAT	27.69	320.15	6.77	88.00
7	NAT	30.23	386.18	9.12	256.00
8	BARE	26.67	295.47	17.76	13313.00
9	CLIP	25.91	277.77	16.11	1169.00
10	TILL	28.45	339.38	14.93	1108.00
11	BARE	28.70	345.85	24.88	14524.00
12	NAT	26.16	283.55	9.46	456.00
13	TILL	27.18	307.72	21.97	7055.00
14	CLIP	25.91	277.77	8.57	880.00
15	NAT	27.18	307.72	11.55	323.00
16	BARE	24.89	254.96	18.76	10406.00
17	CLIP	28.96	352.48	16.82	1358.00
18	TILL	27.18	307.72	23.70	4214.00
19	CLIP	28.96	352.48	17.90	2446.00
20	BARE	26.16	283.55	16.47	11408.00
21	NAT	27.69	316.91	16.99	924.00
22	TILL	29.21	362.70	9.53	618.00
23	BARE	26.67	295.47	24.59	12324.00
24	TILL	27.69	320.15	13.54	439.00
25	CLIP	25.15	260.58	23.37	3315.00
26	NAT	26.67	295.47	11.25	487.00

APPENDIX—A (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH SPRING 1983

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
3	TILL	12.1	15.9	48.2	34.7	1.2	0.0	0.0	0.0	0.0
4	BARE	12.2	4.3	2.9	92.0	0.0	0.0	0.0	0.0	0.0
5	CLIP	10.8	21.2	31.2	46.7	0.8	0.0	0.0	0.0	0.0
6	NAT	11.1	22.2	13.5	62.9	0.6	39.8	5.1	27.1	72.0
7	NAT	11.5	20.8	21.0	56.7	0.6	35.1	22.0	13.3	70.4
8	BARE	11.7	2.2	0.0	97.3	0.4	0.0	0.0	0.0	0.0
9	CLIP	10.4	20.8	25.3	53.7	0.2	0.0	0.0	0.0	0.0
10	TILL	10.4	18.6	23.9	57.6	0.0	0.0	0.0	0.0	0.0
11	BARE	9.9	4.9	2.9	90.8	1.4	0.0	0.0	0.0	0.0
12	NAT	10.2	21.2	28.4	46.3	2.7	31.2	6.5	0.0	37.7
13	TILL	10.6	22.2	20.0	57.1	0.8	0.0	0.0	0.0	0.0
14	CLIP	12.1	24.7	33.7	41.2	0.4	0.0	0.0	0.0	0.0
15	NAT	10.4	21.8	22.4	49.4	4.9	28.8	7.1	0.0	35.9
16	BARE	9.7	5.3	1.4	93.1	0.4	0.0	0.0	0.0	0.0
17	CLIP	9.0	19.8	28.8	51.0	0.4	0.0	0.0	0.0	0.0
18	TILL	7.5	19.2	29.4	51.0	0.4	0.0	0.0	0.0	0.0
19	CLIP	10.4	20.4	27.6	49.6	2.4	0.0	0.0	0.0	0.0
20	BARE	10.8	5.3	3.9	90.0	0.8	0.0	0.0	0.0	0.0
21	NAT	9.9	17.5	28.7	51.0	2.6	3.8	17.7	5.5	27.0
22	TILL	10.5	61.0	13.1	25.7	0.2	0.0	0.0	0.0	0.0
23	BARE	9.1	5.9	5.3	88.4	0.1	0.0	0.0	0.0	0.0
24	TILL	8.8	54.1	24.1	19.8	2.0	0.0	0.0	0.0	0.0
25	CLIP	10.2	17.6	30.8	47.6	4.1	0.0	0.0	0.0	0.0
26	NAT	10.1	19.0	22.2	53.5	4.7	10.8	32.7	1.0	44.5

PLOTS	SOIL SERIES
3-10	BERNARDINO
11-18	HATHAWAY
19-26	CAVE

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE DRY RUN FALL 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	52.32	575.45	23.47	440.19
4	BARE	54.36	627.02	47.61	20851.12
5	CLIP	54.36	615.44	15.97	349.79
6	NAT	57.40	691.69	2.71	11.36
7	NAT	49.02	495.96	3.43	64.60
8	BARE	52.58	576.30	29.11	21297.84
9	CLIP	52.83	602.00	19.93	651.57
10	TILL	52.58	592.47	30.23	508.90
11	BARE	53.85	605.91	47.67	33548.19
12	NAT	53.34	593.83	30.03	556.34
13	TILL	54.61	624.46	44.02	6568.98
14	CLIP	50.04	515.37	34.60	1993.52
15	NAT	55.88	652.89	25.01	353.77
16	BARE	52.32	567.28	37.79	23190.26
17	CLIP	53.59	608.47	35.58	1559.66
18	TILL	46.23	444.56	40.89	4358.93
19	CLIP	53.59	608.29	43.32	4578.54
20	BARE	52.83	590.25	42.66	31462.69
21	NAT	51.82	558.09	37.69	1374.59
22	TILL	54.36	618.34	32.94	258.80
23	BARE	49.78	512.47	47.04	14075.68
24	TILL	50.04	518.09	18.33	169.10
25	CLIP	51.82	563.70	43.12	3608.48
26	NAT	50.80	540.39	29.40	733.79

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE WET RUN FALL 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	26.67	295.47	18.89	387.20
4	BARE	27.94	326.44	22.15	11169.20
5	CLIP	27.43	313.85	11.50	273.14
6	NAT	27.69	320.15	2.14	15.71
7	NAT	28.45	339.38	5.40	108.87
8	BARE	28.70	345.85	20.20	13879.88
9	CLIP	26.16	283.55	22.92	560.52
10	TILL	28.45	339.38	22.24	328.79
11	BARE	27.94	326.44	20.46	10610.79
12	NAT	29.97	379.38	13.71	246.71
13	TILL	28.45	339.38	22.15	3269.62
14	CLIP	29.72	372.40	16.89	1203.88
15	NAT	27.94	326.44	11.09	118.12
16	BARE	28.45	339.38	17.08	11291.45
17	CLIP	26.92	301.59	19.74	978.10
18	TILL	26.16	283.55	20.32	2757.03
19	CLIP	28.19	332.91	19.88	2301.51
20	BARE	28.45	339.38	24.32	11669.79
21	NAT	26.92	301.59	21.78	789.76
22	TILL	28.70	345.85	20.26	215.02
23	BARE	29.21	359.12	22.34	5224.21
24	TILL	29.97	379.38	13.83	145.21
25	CLIP	27.69	320.15	20.77	1496.58
26	NAT	28.70	345.85	13.33	297.94

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE VERY WET RUN FALL 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	26.67	295.47	19.71	515.37
4	BARE	27.18	307.72	25.01	11614.46
5	CLIP	27.18	307.72	17.32	301.32
6	NAT	28.19	332.91	6.79	42.71
7	NAT	28.96	352.48	8.93	107.52
8	BARE	27.69	320.15	20.22	9553.04
9	CLIP	25.91	277.77	19.83	651.25
10	TILL	28.70	345.85	24.07	388.65
11	BARE	27.18	307.72	22.12	11735.43
12	NAT	28.45	339.38	14.35	213.20
13	TILL	27.94	326.44	22.35	2453.03
14	CLIP	29.21	359.12	18.14	952.23
15	NAT	29.21	359.12	13.82	223.67
16	BARE	27.94	326.44	19.38	11245.61
17	CLIP	27.18	307.72	22.74	1171.73
18	TILL	26.67	295.47	22.58	3213.42
19	CLIP	26.42	289.51	24.33	2418.14
20	BARE	27.43	313.85	23.95	8630.22
21	NAT	27.43	313.85	22.96	690.96
22	TILL	27.94	326.44	23.02	205.52
23	BARE	28.45	339.38	25.19	7157.46
24	TILL	28.45	339.38	16.78	172.42
25	CLIP	27.69	320.15	22.15	1529.73
26	NAT	29.46	365.76	14.92	321.18

APPENDIX—A (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FALL 1983

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
3	TILL	12.1	19.0	38.0	42.0	0.4	0.0	0.0	0.0	0.0
4	BARE	12.2	7.0	0.0	93.0	0.0	0.0	0.0	0.0	0.0
5	CLIP	10.8	20.0	27.0	53.0	0.0	0.0	0.0	0.0	0.0
6	NAT	11.1	20.0	12.0	66.0	2.0	67.0	15.0	5.0	87.0
7	NAT	11.5	20.0	21.0	58.0	0.6	37.0	47.0	3.0	87.0
8	BARE	11.7	4.3	0.0	95.7	0.2	0.0	0.0	0.0	0.0
9	CLIP	10.4	18.0	25.0	57.0	0.0	0.0	0.0	0.0	0.0
10	TILL	10.4	28.0	42.0	30.0	0.0	0.0	0.0	0.0	0.0
11	BARE	9.9	6.0	0.0	94.0	0.0	0.0	0.0	0.0	0.0
12	NAT	10.2	20.0	25.0	53.0	0.2	48.0	19.0	1.0	68.0
13	TILL	10.6	24.0	26.0	50.0	0.0	0.0	0.0	0.0	0.0
14	CLIP	12.1	31.0	30.0	39.0	0.0	0.0	0.0	0.0	0.0
15	NAT	10.4	24.0	30.0	41.0	3.0	44.0	14.0	3.0	61.0
16	BARE	9.7	13.0	6.0	78.0	3.0	0.0	0.0	0.0	0.0
17	CLIP	9.0	26.0	37.0	36.0	1.0	0.0	0.0	0.0	0.0
18	TILL	7.5	22.0	36.0	41.0	1.0	0.0	0.0	0.0	0.0
19	CLIP	10.4	19.0	32.0	47.0	2.0	0.0	0.0	0.0	0.0
20	BARE	10.8	7.0	5.0	87.0	1.0	0.0	0.0	0.0	0.0
21	NAT	9.9	21.0	18.0	58.0	2.0	7.0	18.0	3.0	38.0
22	TILL	10.5	70.0	14.0	16.0	0.2	0.0	0.0	0.0	0.0
23	BARE	9.1	7.0	5.0	87.0	0.6	0.0	0.0	0.0	0.0
24	TILL	8.8	53.0	18.0	28.0	0.6	0.0	0.0	0.0	0.0
25	CLIP	10.2	15.0	33.0	50.0	2.0	0.0	0.0	0.0	0.0
26	NAT	10.1	22.0	19.0	57.0	2.0	18.0	34.0	2.0	54.0

PLOTS	SOIL SERIES
3-10	BERNARDINO
11-18	HATHAWAY
19-26	CAVE

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE DRY RUN
SPRING 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	52.32	596.04	0.00	0.00
4	BARE	54.86	659.70	34.92	16524.29
5	CLIP	53.85	612.21	1.69	30.43
6	NAT	57.15	696.63	0.66	0.00
7	NAT	54.86	648.80	0.44	7.12
8	BARE	54.86	648.80	23.43	17877.34
9	CLIP	53.85	628.55	0.57	0.00
10	TILL	50.29	542.77	0.00	0.00
11	BARE	53.34	619.02	27.70	30251.71
12	NAT	58.42	751.94	0.51	0.00
13	TILL	47.50	544.47	6.95	722.96
14	CLIP	40.13	532.05	11.72	1053.47
15	NAT	53.85	613.91	3.53	208.34
16	BARE	52.83	589.40	17.74	27790.88
17	CLIP	55.63	657.31	7.24	422.72
18	TILL	51.82	564.89	14.54	911.14
19	CLIP	54.10	752.28	13.26	2197.36
20	BARE	58.17	725.22	40.32	25034.24
21	NAT	55.88	669.74	8.40	662.99
22	TILL	56.39	682.84	0.00	0.00
23	BARE	54.36	618.51	38.63	20609.15
24	TILL	56.39	670.25	1.21	144.61
25	CLIP	55.37	656.12	12.08	1341.68
26	NAT	55.12	649.48	4.28	399.11

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE WET RUN
SPRING 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	27.18	307.72	0.63	0.00
4	BARE	25.40	265.00	19.46	11217.07
5	CLIP	28.45	339.21	2.96	39.06
6	NAT	28.70	345.68	0.36	11.22
7	NAT	27.94	326.61	0.39	6.86
8	BARE	28.45	339.21	16.89	13423.28
9	CLIP	26.42	286.96	4.53	205.73
10	TILL	27.18	305.17	1.47	28.62
11	BARE	27.94	332.91	16.43	16496.24
12	NAT	29.72	372.40	1.17	102.42
13	TILL	28.96	352.31	10.95	1212.46
14	CLIP	28.70	345.68	9.84	815.27
15	NAT	28.45	339.21	2.23	107.04
16	BARE	28.45	339.21	10.12	13845.21
17	CLIP	28.96	352.31	9.60	571.67
18	TILL	28.45	339.21	13.35	1032.08
19	CLIP	27.43	352.31	13.96	1975.70
20	BARE	28.96	314.02	21.99	12218.54
21	NAT	29.46	365.59	12.61	692.53
22	TILL	30.23	386.35	0.00	0.00
23	BARE	28.45	339.21	21.08	6856.58
24	TILL	28.45	339.21	2.12	233.26
25	CLIP	28.96	352.31	14.51	1266.67
26	NAT	28.96	352.31	4.59	303.66

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE VERY WET RUN SPRING 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	28.70	345.68	1.87	43.63
4	BARE	26.16	283.55	24.91	10019.72
5	CLIP	28.96	352.31	6.52	81.66
6	NAT	28.19	332.91	0.67	9.14
7	NAT	27.94	326.61	1.07	11.14
8	BARE	29.21	359.12	18.38	13918.52
9	CLIP	25.65	272.15	8.09	191.88
10	TILL	27.18	307.72	4.68	70.17
11	BARE	27.94	326.61	18.34	17037.35
12	NAT	28.70	345.68	2.20	109.15
13	TILL	27.69	319.98	13.06	1454.71
14	CLIP	27.94	326.61	13.34	1087.72
15	NAT	28.70	345.68	3.38	93.80
16	BARE	28.96	352.31	23.12	16425.96
17	CLIP	29.72	363.55	13.68	799.72
18	TILL	32.00	425.84	18.90	2610.45
19	CLIP	27.69	319.98	16.72	2242.76
20	BARE	29.21	359.12	18.34	8234.09
21	NAT	27.43	314.02	14.31	551.42
22	TILL	29.97	379.21	4.87	266.99
23	BARE	28.70	345.68	23.80	6835.51
24	TILL	27.69	319.98	4.00	281.21
25	CLIP	28.45	339.21	15.19	1424.30
26	NAT	29.97	379.21	7.91	344.66

APPENDIX—A (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH SPRING 1984

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
3	TILL	12.1	14.0	28.0	58.0	0.0	0.0	0.0	0.0	0.0
4	BARE	12.2	4.0	0.0	94.0	0.0	0.0	0.0	0.0	0.0
5	CLIP	10.8	19.0	28.0	53.0	0.0	0.0	0.0	0.0	0.0
6	NAT	11.1	21.0	18.0	59.0	1.0	57.0	17.0	3.0	77.0
7	NAT	11.5	18.0	19.0	63.0	0.0	29.0	41.0	1.0	71.0
8	BARE	11.7	3.0	0.0	97.0	0.0	0.0	0.0	0.0	0.0
9	CLIP	10.4	21.0	24.0	55.0	0.0	0.0	0.0	0.0	0.0
10	TILL	10.4	26.0	36.0	38.0	0.0	0.0	0.0	0.0	0.0
11	BARE	9.9	4.0	0.0	96.0	0.0	0.0	0.0	0.0	0.0
12	NAT	10.2	22.0	30.0	46.0	1.0	46.0	21.0	3.0	70.0
13	TILL	10.6	23.0	15.0	60.0	2.0	0.0	0.0	0.0	0.0
14	CLIP	12.1	25.0	24.0	51.0	0.0	0.0	0.0	0.0	0.0
15	NAT	10.4	22.0	23.0	52.0	2.0	51.0	15.0	3.0	69.0
16	BARE	9.7	4.0	0.0	96.0	0.0	0.0	0.0	0.0	0.0
17	CLIP	9.0	22.0	28.0	49.0	2.0	0.0	0.0	0.0	0.0
18	TILL	7.5	21.0	25.0	53.0	1.0	0.0	0.0	0.0	0.0
19	CLIP	10.4	18.0	27.0	53.0	1.0	0.0	0.0	0.0	0.0
20	BARE	10.8	6.0	0.0	94.0	0.0	0.0	0.0	0.0	0.0
21	NAT	9.9	18.0	20.0	58.0	4.0	6.0	18.0	6.0	30.0
22	TILL	10.5	63.0	16.0	21.0	0.0	0.0	0.0	0.0	0.0
23	BARE	91	9.0	0.0	91.0	0.0	0.0	0.0	0.0	0.0
24	TILL	8.8	49.0	19.0	30.0	2.0	0.0	0.0	0.0	0.0
25	CLIP	10.2	15.0	22.0	60.0	3.0	0.0	0.0	0.0	0.0
26	NAT	10.1	18.0	19.0	59.0	3.0	12.0	37.0	0.0	49.0

PLOTS	SOIL SERIES
3-10	BERNARDINO
11-18	HATHAWAY
19-26	CAVE

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE DRY RUN FALL 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	54.86	629.23	11.87	154.60
4	BARE	52.83	580.38	43.76	13769.45
5	CLIP	54.10	614.93	16.05	578.28
6	NAT	56.13	665.31	0.70	7.57
7	NAT	54.10	616.29	3.91	48.16
8	BARE	54.10	616.29	45.05	19682.87
9	CLIP	51.82	567.45	23.48	507.46
10	TILL	55.88	667.01	18.83	319.28
11	BARE	56.39	668.89	32.67	22432.48
12	NAT	55.88	656.12	17.32	316.33
13	TILL	53.34	654.59	38.62	3201.33
14	CLIP	53.85	604.72	36.89	3003.77
15	NAT	52.83	596.21	17.04	139.94
16	BARE	50.80	548.21	41.02	26768.64
17	CLIP	56.39	675.01	36.16	1232.47
18	TILL	51.05	545.66	41.39	2336.48
19	CLIP	51.56	582.08	36.17	3090.47
20	BARE	47.75	496.47	42.91	30535.94
21	NAT	56.90	727.78	24.16	601.61
22	TILL	53.85	646.93	6.93	74.42
23	BARE	49.78	548.90	37.53	12403.55
24	TILL	58.17	765.73	6.83	328.51
25	CLIP	53.34	592.47	33.63	1930.57
26	NAT	54.10	610.68	23.05	413.30

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE WET RUN FALL 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	26.67	295.47	9.14	135.53
4	BARE	28.45	339.38	17.02	8419.82
5	CLIP	28.45	337.68	13.98	549.91
6	NAT	33.78	489.84	1.99	25.19
7	NAT	26.92	301.59	2.64	23.39
8	BARE	27.43	313.85	20.95	7687.15
9	CLIP	26.92	301.59	15.35	430.98
10	TILL	28.96	352.48	15.24	123.50
11	BARE	28.19	332.91	21.26	15051.60
12	NAT	27.43	313.85	5.84	127.35
13	TILL	28.19	332.91	21.65	1453.76
14	CLIP	28.45	339.38	21.03	915.08
15	NAT	26.42	289.51	5.65	41.94
16	BARE	28.96	352.48	24.59	12626.84
17	CLIP	29.97	379.38	19.18	767.55
18	TILL	30.23	386.18	24.28	1739.80
19	CLIP	28.45	339.38	19.13	1800.66
20	BARE	27.18	307.72	23.64	14375.44
21	NAT	28.45	339.38	14.70	358.91
22	TILL	27.43	313.85	8.07	78.98
23	BARE	26.67	295.47	22.13	8026.99
24	TILL	28.45	339.38	4.77	295.33
25	CLIP	23.37	222.62	17.03	754.31
26	NAT	29.46	365.76	9.31	171.08

APPENDIX — A (Continued)

DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FOR THE VERY WET RUN FALL 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
3	TILL	27.43	313.85	12.02	113.92
4	BARE	28.96	352.48	23.76	7458.08
5	CLIP	27.94	326.44	15.53	651.64
6	NAT	28.45	339.38	6.73	27.07
7	NAT	27.43	313.85	6.63	56.03
8	BARE	27.43	313.85	21.76	7683.63
9	CLIP	26.67	295.47	16.22	497.47
10	TILL	28.70	345.85	17.97	151.29
11	BARE	28.45	339.38	22.78	12546.10
12	NAT	27.69	320.15	8.97	141.00
13	TILL	27.43	313.85	23.07	2054.69
14	CLIP	28.19	332.91	25.09	1369.53
15	NAT	25.91	277.77	5.76	66.82
16	BARE	25.65	271.98	24.04	12930.66
17	CLIP	27.43	313.85	20.95	831.49
18	TILL	31.75	429.07	25.32	1538.91
19	CLIP	26.67	295.47	19.94	1438.25
20	BARE	28.45	339.38	26.10	9759.21
21	NAT	27.43	313.85	16.33	360.79
22	TILL	27.43	313.85	12.62	437.53
23	BARE	24.38	243.90	24.02	6969.75
24	TILL	29.21	359.12	8.92	559.39
25	CLIP	23.37	222.62	19.36	1041.48
26	NAT	27.94	326.44	13.64	288.65

APPENDIX—A (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT WALNUT GULCH FALL 1984

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
3	TILL	12.1	19.8	43.5	34.9	1.8	66.7	3.3	1.8	71.8
4	BARE	12.2	10.6	4.5	84.9	0.0	0.0	0.0	0.0	0.0
5	CLIP	10.8	26.3	43.5	26.9	3.3	0.0	0.0	0.0	0.0
6	NAT	11.1	21.4	24.3	50.6	3.7	65.5	20.6	1.4	87.6
7	NAT	11.5	25.1	29.2	36.5	9.2	30.6	53.9	2.9	87.3
8	BARE	11.7	6.3	2.2	91.4	0.0	0.0	0.0	0.0	0.0
9	CLIP	10.4	26.1	31.6	41.6	0.6	0.0	0.0	0.0	0.0
10	TILL	10.4	28.4	43.9	26.1	1.6	39.2	1.8	0.0	41.0
11	BARE	9.9	4.5	3.1	92.4	0.0	0.0	0.0	0.0	0.0
12	NAT	10.2	22.9	31.6	40.0	5.5	52.0	19.0	2.0	73.1
13	TILL	10.6	23.5	23.9	51.4	1.2	3.1	0.6	0.6	4.3
14	CLIP	12.1	29.2	28.4	39.2	3.3	0.0	0.0	0.0	0.0
15	NAT	10.4	25.5	22.2	45.5	6.7	50.0	16.1	2.9	69.0
16	BARE	9.7	8.4	0.8	90.8	0.0	0.0	0.0	0.0	0.0
17	CLIP	9.0	19.6	33.1	43.7	3.7	0.0	0.0	0.0	0.0
18	TILL	7.5	23.5	33.1	40.2	3.3	0.8	0.2	0.0	1.0
19	CLIP	10.4	17.1	41.4	40.0	1.4	0.0	0.0	0.0	0.0
20	BARE	10.8	7.1	0.0	92.9	0.0	0.0	0.0	0.0	0.0
21	NAT	9.9	18.4	31.4	42.2	8.0	4.7	22.4	1.0	28.2
22	TILL	10.5	65.1	19.0	12.0	3.9	1.6	4.5	0.2	6.3
23	BARE	9.1	7.8	0.0	92.2	0.0	0.0	0.0	0.0	0.0
24	TILL	8.8	52.0	26.3	17.1	4.5	0.6	2.0	13.7	16.3
25	CLIP	10.2	19.4	40.8	35.7	4.1	0.0	0.0	0.0	0.0
26	NAT	10.1	16.7	34.3	29.6	19.4	9.2	44.3	0.2	53.7

PLOTS	SOIL SERIES
3-10	BERNARDINO
11-18	HATHAWAY
19-26	CAVE

APPENDIX—B

DATA FOR RAINFALL SIMULATOR AT REYNOLDS CREEK AND SAVAL RANCH FOR THE DRY RUN
1982

Plot	Treatment	Precipitation (mm)	Erosion index (MJ•mm/ha•h)	Runoff (mm)	Sediment (gm)
FTR3	TILLED	54.61	624.40	45.03	17244.81
L3	TILLED	55.88	659.01	43.24	18367.61
FKR3	TILLED	59.44	745.48	45.63	20568.72
L3	TILLED	56.13	664.97	41.42	18080.16
FTR9	TILLED	57.15	689.31	45.96	35515.39
L9	TILLED	56.90	683.18	50.07	53680.91
NTR6	TILLED	57.15	689.31	34.36	18037.85
L6	TILLED	56.90	683.18	29.18	23581.84
LTR9	TILLED	60.45	771.35	32.35	24017.39
L9	TILLED	57.15	689.31	32.27	23649.69
CTR3	TILLED	59.18	738.67	26.67	8233.79
L3	TILLED	56.13	659.18	24.00	5715.65
FBR3	CLIPPED	59.44	745.48	8.81	408.56
L3	CLIPPED	57.15	689.31	6.36	284.53
FBR9	CLIPPED	58.17	713.99	4.60	158.32
L9	CLIPPED	58.67	726.58	14.37	1508.75
NBR6	CLIPPED	57.40	695.44	23.48	3895.17
L6	CLIPPED	57.15	689.31	22.84	4098.72
LBR9	CLIPPED	57.91	707.86	0.17	25.53
L9	CLIPPED	58.17	713.99	0.58	91.93
MCR3	PART. CLIPPED	59.18	738.33	2.48	107.22
L3	PART. CLIPPED	56.13	659.18	8.36	881.94
FGR3	GRAZED	55.88	659.01	7.34	339.25
L3	GRAZED	56.64	677.06	8.69	545.72
NGR6	GRAZED	59.69	751.94	14.12	981.27
L6	GRAZED	58.17	713.99	5.60	341.44
LGR9	GRAZED	57.40	695.44	0	53.99
L9	GRAZED	57.15	689.31	0.43	148.83
CVR3	GRAZED	54.36	625.14	5.83	1578.25
L3	GRAZED	58.42	728.97	4.10	850.95
MVR3	GRAZED	52.83	614.25	4.70	645.68
L3	GRAZED	55.63	687.27	10.02	1324.93
FUR3	UNGRAZED	48.51	496.64	0	29.18
L3	UNGRAZED	51.82	566.60	0	25.53
NUR6	UNGRAZED	57.15	689.31	0.57	92.66
L6	UNGRAZED	58.42	720.29	1.15	74.42
LUR9	UNGRAZED	52.32	577.83	0	35.02
L9	UNGRAZED	58.17	713.99	0	11.67

APPENDIX—B (Continued)

DATA FOR RAINFALL SIMULATOR AT REYNOLDS CREEK AND SAVAL RANCH FOR THE WET RUN 1982

Plot	Treatment	Precipitation (mm)	Erosion index (MJ•mm/ha•h)	Runoff (mm)	Sediment (gm)
FTR3	TILLED	30.73	398.78	26.95	14789.08
L3	TILLED	29.21	360.14	25.08	10632.73
FKR3	TILLED	30.73	398.78	25.65	14236.07
L3	TILLED	30.23	385.67	27.02	15625.90
FTR9	TILLED	28.96	353.85	25.87	19401.41
L9	TILLED	29.21	360.14	26.68	25051.92
NTR6	TILLED	29.97	379.21	24.75	19791.00
L6	TILLED	30.99	405.25	22.94	19823.83
LTR9	TILLED	30.23	385.67	19.89	15063.40
L9	TILLED	28.70	347.72	20.34	14189.38
CTR3	TILLED	30.73	400.31	23.09	10491.18
L3	TILLED	29.46	365.76	21.21	7869.07
FBR3	CLIPPED	32.77	453.24	11.99	604.81
L3	CLIPPED	31.24	412.05	11.17	396.89
FBR9	CLIPPED	29.97	379.21	6.75	362.60
L9	CLIPPED	29.72	372.74	12.40	1386.18
NBR6	CLIPPED	30.48	392.14	15.99	2616.23
L6	CLIPPED	29.97	379.21	15.47	3530.38
LBR9	CLIPPED	30.48	392.14	0.52	67.12
L9	CLIPPED	31.24	412.05	0.85	99.95
MCR3	PART. CLIPPED	30.23	386.18	5.99	234.81
L3	PART. CLIPPED	29.97	379.55	8.87	742.10
FGR3	GRAZED	28.45	341.59	6.87	238.57
L3	GRAZED	27.94	329.51	8.73	389.59
NGR6	GRAZED	31.50	418.69	9.55	582.20
L6	GRAZED	32.00	432.31	6.38	321.74
LGR9	GRAZED	29.97	379.21	0.12	29.18
L9	GRAZED	29.97	379.21	0.69	138.62
CVR3	GRAZED	29.72	374.44	7.36	1114.44
L3	GRAZED	30.73	402.18	5.68	712.58
MVR3	GRAZED	30.48	395.03	7.13	476.91
L3	GRAZED	30.48	395.03	12.21	914.69
FUR3	UNGRAZED	25.65	277.77	0.24	28.45
L3	UNGRAZED	26.67	300.23	0.17	40.86
NUR6	UNGRAZED	30.23	385.67	0.58	51.80
L6	UNGRAZED	27.94	329.51	2.45	106.52
LUR9	UNGRAZED	31.24	412.05	0	10.94
L9	UNGRAZED	31.24	412.05	0	5.11

APPENDIX—B (Continued)

DATA FOR RAINFALL SIMULATOR AT REYNOLDS CREEK AND SAVAL RANCH FOR THE VERY WET RUN 1982

Plot	Treatment	Precipitation (mm)	Erosion index (MJ•mm/ha•h)	Runoff (mm)	Sediment (gm)
FTR3	TILLED	28.45	341.59	13.88	6864.51
L3	TILLED	27.69	323.55	12.85	4853.09
FKR3	TILLED	28.45	341.59	27.37	15150.22
L3	TILLED	26.92	306.02	28.01	17220.73
FTR9	TILLED	27.18	311.81	25.69	17282.75
L9	TILLED	28.70	347.72	25.98	20066.78
NTR6	TILLED	29.21	360.14	26.93	21396.78
L6	TILLED	27.69	323.55	25.23	18441.30
LTR9	TILLED	27.69	323.55	23.60	16842.09
L9	TILLED	27.94	329.51	23.39	15705.42
CTR3	TILLED	28.45	339.38	25.23	15459.55
L3	TILLED	27.43	313.85	23.72	10421.88
FBR3	CLIPPED	29.21	360.14	17.31	753.64
L3	CLIPPED	28.45	341.59	17.16	910.50
FBR9	CLIPPED	29.72	372.74	14.40	796.50
L9	CLIPPED	29.46	366.44	17.93	2670.95
NBR6	CLIPPED	28.96	353.85	18.29	2272.61
L6	CLIPPED	27.94	329.51	19.11	3670.46
LBR9	CLIPPED	29.46	366.44	.77	71.50
L9	CLIPPED	29.46	366.44	1.15	102.14
MCR3	PART. CLIPPED	28.45	339.38	10.07	426.80
L3	PART. CLIPPED	25.65	271.81	12.41	944.06
FGR3	GRAZED	24.38	251.05	12.25	368.43
L3	GRAZED	28.70	347.72	14.74	547.18
NGR6	GRAZED	28.96	353.85	12.13	652.96
L6	GRAZED	28.70	347.72	13.01	464.74
LGR9	GRAZED	26.16	288.83	.69	94.84
L9	GRAZED	28.19	335.46	1.39	236.38
CVR3	GRAZED	25.65	285.60	9.88	1231.51
L3	GRAZED	26.67	311.47	8.06	708.41
MVR3	GRAZED	28.70	346.02	11.22	750.00
L3	GRAZED	26.92	301.42	14.19	1072.47
FUR3	UNGRAZED	27.18	311.81	4.15	37.94
L3	UNGRAZED	27.94	329.51	3.06	61.28
NUR6	UNGRAZED	28.96	353.85	2.77	113.81
L6	UNGRAZED	29.97	379.21	6.74	223.25
LUR9	UNGRAZED	26.92	306.02	0	11.67
L9	UNGRAZED	24.89	261.60	0	3.65

APPENDIX—B (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR REYNOLDS CREEK AND SAVAL RANCH SIMULATOR PLOTS 1982

Plot	Treatment	Slope %	Ground cover, %					Canopy cover, %				
			Live	Litter	Rock	Total	Bare	Grass	Forb	Shrub	Litter	Total
FTR3	TILL	3.3	0	3.1	1.9	5.0	95.0	0	0	0	0	0
FTL3	TILL	3.9	0	5.0	2.5	7.5	92.5	0	0	0	0	0
FKR3	TILL	3.3	0	3.1	1.9	5.0	95.0	0	0	0	0	0
FKL3	TILL	3.9	0	5.0	2.5	7.5	92.5	0	0	0	0	0
FTR9	TILL	8.6	0	3.1	5.1	8.2	91.8	0	0	0	1.3	1.3
FTL9	TILL	9.3	0	1.2	4.4	5.6	94.4	0	0	0	0	0
NTR6	TILL	5.6	1.3	31.8	6.9	40.0	60.0	0	0	0	0	0
NTL6	TILL	6.5	0.6	28.8	12.6	42.0	58.0	0	0	0	0	0
LTR9	TILL	9.6	0	6.9	15.0	21.9	78.1	0	0	0	0	0
LTL9	TILL	9.0	0	9.3	13.2	22.5	77.5	0	0	0	0	0
CTR3	TILL	3.9	0	5.0	11.7	16.7	83.3	0	0	0	0	0
CTL3	TILL	3.9	0	7.3	10.0	17.3	82.7	0	0	0	0	0
FBR3	CLIP	4.1	12.3	55.0	7.7	75.0	25.0	0.8	0	0	0	0.8
FBL3	CLIP	4.3	14.1	54.4	7.1	75.6	24.4	0.2	0	0	0.4	0.6
FBR9	CLIP	8.6	31.0	61.3	2.3	94.6	5.4	0	0	0	0	0
FBL9	CLIP	8.9	25.6	52.5	2.9	81.0	19.0	0	0	0	0	0
NBR6	CLIP	5.8	33.3	42.6	7.2	83.1	16.9	0	0.2	0	0	0.2
NBL6	CLIP	6.7	36.9	41.1	5.8	83.8	16.2	0.2	0	0	0	0.2
LBR9	CLIP	8.1	29.6	49.6	16.0	95.2	4.8	1.7	0.2	0	0.2	2.1
LBL9	CLIP	9.5	39.3	45.5	11.9	97.7	3.3	2.5	0.8	0	1.0	4.3
MCR3	P. CLIP	3.5	4.0	47.0	22.7	73.7	26.3	0	0	17.3	0	17.3
MCL3	P. CLIP	3.6	2.3	56.7	14.0	73.0	27.0	0	0	18.0	0	18.0
FGR3	GRAZED	3.0	22.0	57.4	3.1	82.5	17.5	20.4	3.9	2.1	14.8	41.2
FGL3	GRAZED	3.3	24.8	51.3	3.7	79.8	20.2	21.7	2.1	3.4	18.4	45.6
NGR6	GRAZED	7.1	45.0	36.7	8.1	89.8	10.2	7.9	1.2	13.1	22.3	44.5
NGL6	GRAZED	6.5	43.1	37.9	9.2	90.2	9.8	7.6	1.4	12.7	28.1	49.8
LGR9	GRAZED	9.7	27.1	43.2	17.4	87.7	12.3	6.3	5.5	19.2	23.3	54.3
LGL9	GRAZED	9.4	31.4	42.1	15.2	88.7	11.3	5.6	5.1	16.6	23.9	51.2
CVR3	GRAZED	3.7	3.0	51.0	11.3	65.3	34.7	11.3	8.3	15.7	0	35.3
CVL3	GRAZED	3.7	2.7	47.3	13.7	63.7	36.3	10.7	3.3	9.3	0	23.3
MVR3	GRAZED	3.5	3.7	57.0	14.7	75.4	24.6	8.0	7.0	21.3	0	36.3
MVL3	GRAZED	3.0	6.3	60.7	15.0	82.0	18.0	5.7	2.3	29.7	0	37.7
FUR3	UNGRAZ	3.0	20.2	67.1	1.5	88.8	11.2	24.9	4.2	5.0	20.2	54.3
FUL3	UNGRAZ	3.3	24.6	57.9	3.9	86.4	13.6	23.4	1.9	5.6	21.3	52.2
NUR6	UNGRAZ	5.0	44.7	37.3	6.8	88.8	11.2	9.4	2.2	11.5	25.0	48.1
NUL6	UNGRAZ	5.4	44.0	30.6	11.2	85.8	14.2	10.2	3.0	12.5	19.8	45.5
LUR9	UNGRAZ	9.3	54.7	29.1	8.3	92.1	7.9	6.5	5.8	18.3	33.0	63.6
LUL9	UNGRAZ	9.7	50.4	37.9	6.3	94.6	5.4	8.0	4.4	23.1	31.3	66.8

*Plot Designation-FIRST DIGIT: F is Flats, N is Nancy, L is Lower Sheep, C is Saval Ranch control and M is Saval Ranch Managed Plots; SECOND DIGIT: T is tilled, K is tilled second time, B is clipped bare, G is grazed, U is ungrazed, C is clipped forage, and V is natural vegetation; THIRD DIGIT: R is right plot and L is left plot of pair; FOURTH DIGIT: Number is approximate slope in percent.

APPENDIX—C

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE DRY RUN SPRING 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	54.10	635.87	0.76	83.47
2	BARE	50.55	549.75	8.64	2519.47
3	CLIP	54.10	629.40	TRACE	74.86
4	NAT	48.51	498.35	0.00	0.00
5	BARE	55.37	656.80	11.94	2851.93
6	CLIP	47.24	467.54	0.00	0.00
7	NAT	56.39	672.80	23.37	2120.13
8	CLIP	48.01	471.45	28.96	1685.61
9	BARE	54.86	639.44	44.70	18807.46
10	CLIP	47.75	480.47	26.16	2339.14
11	NAT	54.86	636.72	15.24	1101.84
12	BARE	50.04	528.47	34.54	17300.76

APPENDIX—C (Continued)

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE WET RUN SPRING 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	27.43	313.85	6.60	391.67
2	BARE	26.92	301.59	14.22	4435.22
3	CLIP	26.67	295.47	1.52	163.64
4	NAT	27.43	313.85	0.00	0.00
5	BARE	25.15	266.19	8.38	2337.48
6	CLIP	27.94	326.44	2.54	369.66
7	NAT	30.48	381.76	14.73	925.82
8	CLIP	30.23	355.04	17.27	1078.38
9	BARE	28.96	352.48	25.15	16047.16
10	CLIP	26.16	283.55	22.86	1926.34
11	NAT	29.21	359.12	14.48	758.32
12	BARE	25.91	277.77	21.08	10187.68

APPENDIX—C (Continued)

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE VERY WET RUN SPRING 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	27.94	326.44	12.95	663.93
2	BARE	26.92	295.47	16.00	7217.97
3	CLIP	26.67	295.47	6.35	337.40
4	NAT	25.65	271.98	0.25	137.76
5	BARE	25.65	271.98	13.72	4421.58
6	CLIP	27.94	326.44	7.87	714.97
7	NAT	27.94	326.44	16.76	940.58
8	CLIP	30.48	386.18	20.32	1429.98
9	BARE	30.99	407.29	29.97	13842.54
10	CLIP	26.42	289.51	24.89	1993.44
11	NAT	27.69	320.15	16.76	947.86
12	BARE	23.37	222.62	20.83	5816.44

APPENDIX—C (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE
SPRING 1983

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
1	NAT	7.7	15.1	48.2	20.0	15.9	2.7	14.7	2.2	19.6
2	BARE	8.5	4.7	4.3	86.5	4.5	0.0	0.0	0.0	0.0
3	CLIP	5.9	14.9	46.3	24.5	13.9	0.0	0.0	0.0	0.0
4	NAT	6.7	13.9	44.0	22.7	19.2	10.6	6.3	1.6	18.5
5	BARE	7.1	2.5	14.9	80.4	2.2	0.0	0.0	0.0	0.0
6	CLIP	7.0	16.5	37.8	29.4	15.3	0.0	0.0	0.0	0.0
7	NAT	8.4	12.7	51.4	23.1	12.0	0.2	17.1	1.0	18.3
8	CLIP	9.0	24.7	49.2	16.7	9.2	0.0	0.0	0.0	0.0
9	BARE	8.6	4.9	8.8	85.1	1.2	0.0	0.0	0.0	0.0
10	CLIP	8.2	21.4	51.3	20.8	6.5	0.0	0.0	0.0	0.0
11	NAT	9.3	12.0	49.6	20.4	18.0	0.6	16.3	0.4	17.3
12	BARE	8.8	6.3	4.7	87.2	1.8	0.0	0.0	0.0	0.0

APPENDIX—C (Continued)

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE DRY RUN
FALL 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	54.61	633.65	14.48	258.32
2	BARE	50.04	520.30	32.77	11356.81
3	CLIP	49.28	498.86	9.40	558.26
4	NAT	49.78	509.92	0.51	30.50
5	BARE	50.04	523.88	25.91	8461.86
6	CLIP	51.05	546.68	9.14	3027.68
7	NAT	55.37	655.61	36.58	1434.55
8	CLIP	49.28	516.39	34.54	1385.62
9	BARE	51.05	541.24	45.72	12772.41
10	CLIP	52.07	555.53	41.66	1785.62
11	NAT	49.53	505.66	26.92	585.69
12	BARE	51.56	550.94	39.88	15022.28

APPENDIX—C (Continued)

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE WET RUN
FALL 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	26.16	289.51	5.08	87.08
2	BARE	28.19	339.38	16.26	5939.31
3	CLIP	25.65	271.98	8.64	257.80
4	NAT	27.69	320.15	1.52	28.34
5	BARE	28.19	332.91	16.76	5404.52
6	CLIP	27.43	313.85	7.37	470.06
7	NAT	28.19	332.91	17.53	769.28
8	CLIP	27.69	320.15	21.59	927.73
9	BARE	28.45	339.38	26.16	7870.14
10	CLIP	24.13	233.17	23.11	940.40
11	NAT	26.42	289.51	16.76	391.56
12	BARE	26.92	301.59	23.62	9479.35

APPENDIX—C (Continued)

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE VERY WET RUN
FALL 1983

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	26.16	283.55	12.45	215.88
2	BARE	29.21	352.48	18.29	7223.04
3	CLIP	28.19	332.91	11.68	361.43
4	NAT	28.19	332.91	4.57	82.14
5	BARE	27.69	320.15	19.05	7037.30
6	CLIP	27.94	326.44	8.89	453.14
7	NAT	27.94	332.91	22.10	833.25
8	CLIP	26.92	301.59	22.35	959.65
9	BARE	27.94	332.91	23.88	6607.67
10	CLIP	24.89	254.96	23.98	979.36
11	NAT	28.70	345.85	20.83	585.24
12	BARE	24.13	233.17	23.37	7573.86

APPENDIX—C (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE
FALL 1983

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
1	NAT	7.7	6.7	70.6	18.9	3.9	3.0	19.0	1.0	23.0
2	BARE	8.5	3.3	25.1	70.4	1.2	0.0	0.0	0.0	0.0
3	CLIP	5.9	2.9	61.0	35.9	0.2	0.0	0.0	0.0	0.0
4	NAT	6.7	4.1	60.3	27.8	7.8	5.0	22.0	2.0	29.0
5	BARE	7.1	1.6	13.7	83.9	0.8	0.0	0.0	0.0	0.0
6	CLIP	7.0	5.1	45.1	49.0	0.8	0.0	0.0	0.0	0.0
7	NAT	8.4	4.5	82.1	12.1	1.3	0.0	23.0	0.0	23.0
8	CLIP	9.0	3.1	68.6	27.3	1.0	0.0	0.0	0.0	0.0
9	BARE	8.6	1.6	21.8	76.2	0.4	0.0	0.0	0.0	0.0
10	CLIP	8.2	3.0	73.3	23.5	0.2	0.0	0.0	0.0	0.0
11	NAT	9.3	1.6	66.7	21.6	10.1	1.0	24.0	0.2	25.2
12	BARE	8.8	3.9	10.8	85.3	0.0	0.0	0.0	0.0	0.0

APPENDIX—C (Continued)

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE DRY RUN
SPRING 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	52.83	580.55	5.08	269.28
2	BARE	54.86	629.40	18.29	12705.07
3	CLIP	52.32	570.17	1.78	132.69
4	NAT	54.61	624.80	0.25	41.27
5	BARE	53.34	623.10	13.46	10651.43
6	CLIP	53.85	635.87	0.51	89.27
7	NAT	53.59	614.93	18.80	615.69
8	CLIP	51.56	566.09	18.29	1128.42
9	BARE	51.82	566.60	32.00	15852.62
10	CLIP	50.29	531.53	24.13	1428.05
11	NAT	34.29	398.10	7.87	336.97
12	BARE	34.04	391.80	22.10	25915.33

APPENDIX—C (Continued)

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE WET RUN
SPRING 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	27.69	319.98	6.86	379.88
2	BARE	28.19	332.91	17.02	16446.91
3	CLIP	27.18	307.72	6.86	323.65
4	NAT	29.21	359.12	0.51	13.25
5	BARE	27.43	314.02	13.21	10231.63
6	CLIP	30.48	393.16	3.81	201.76
7	NAT	28.96	352.31	12.19	304.72
8	CLIP	26.92	301.76	14.48	508.14
9	BARE	27.43	316.91	18.54	11876.08
10	CLIP	25.40	268.92	15.75	665.46
11	NAT	30.99	407.29	13.46	307.71
12	BARE	28.19	332.91	21.84	21687.03

APPENDIX—C (Continued)

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE VERY WET RUN
SPRING 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	26.67	295.47	12.95	661.67
2	BARE	28.19	327.81	18.29	19527.35
3	CLIP	28.70	345.68	11.18	457.61
4	NAT	27.69	319.98	1.78	143.47
5	BARE	26.92	301.76	16.76	11924.95
6	CLIP	28.70	345.68	8.64	581.43
7	NAT	30.48	410.18	14.99	388.78
8	CLIP	27.43	314.02	20.07	900.90
9	BARE	29.97	379.21	22.61	11846.00
10	CLIP	27.18	307.72	19.56	763.19
11	NAT	30.23	386.35	15.49	314.03
12	BARE	27.18	307.72	25.40	21003.17

APPENDIX—C (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE
SPRING 1984

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
1	NAT	7.7	34.0	31.0	25.0	9.0	3.0	17.0	0.0	20.0
2	BARE	8.5	4.0	4.0	91.0	1.0	0.0	0.0	0.0	0.0
3	CLIP	5.9	28.0	42.0	28.0	3.0	0.0	0.0	0.0	0.0
4	NAT	6.7	21.0	33.0	30.0	13.0	6.0	16.0	0.0	22.0
5	BARE	7.1	2.0	8.0	88.0	2.0	0.0	0.0	0.0	0.0
6	CLIP	7.0	24.0	31.0	36.0	8.0	0.0	0.0	0.0	0.0
7	NAT	8.4	21.0	38.0	32.0	9.0	1.0	20.0	0.0	21.0
8	CLIP	9.0	27.0	48.0	23.0	2.0	0.0	0.0	0.0	0.0
9	BARE	8.6	6.0	6.0	88.0	0.0	0.0	0.0	0.0	0.0
10	CLIP	8.2	30.0	49.0	21.0	0.0	0.0	0.0	0.0	0.0
11	NAT	9.3	21.0	39.0	30.0	9.0	1.0	21.0	1.0	23.0
12	BARE	8.8	4.0	6.0	90.0	0.0	0.0	0.0	0.0	0.0

APPENDIX—C (Continued)

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE DRY RUN FALL 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	51.56	605.91	21.59	727.70
2	BARE	43.43	419.88	23.11	23551.64
3	CLIP	51.56	574.25	22.35	711.79
4	NAT	42.67	384.99	5.08	198.59
5	BARE	51.31	603.36	36.32	22435.27
6	CLIP	46.48	488.30	14.99	474.30
7	NAT	54.10	610.68	29.46	705.66
8	CLIP	54.61	623.10	41.40	2053.22
9	BARE	50.80	536.47	45.47	15675.73
10	CLIP	54.86	632.80	33.78	1391.87
11	NAT	41.15	443.71	15.75	1010.49
12	BARE	43.69	504.30	35.81	23241.82

APPENDIX—C (Continued)

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE WET RUN FALL 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	27.43	314.02	9.91	329.41
2	BARE	28.19	332.91	19.81	21894.91
3	CLIP	26.92	301.76	9.40	292.16
4	NAT	29.72	372.40	4.06	74.35
5	BARE	26.16	283.55	15.49	8951.38
6	CLIP	28.70	345.68	6.60	187.28
7	NAT	29.97	379.21	19.30	529.30
8	CLIP	27.94	326.61	20.07	1056.37
9	BARE	32.51	451.37	27.18	12525.46
10	CLIP	25.91	277.77	19.56	751.82
11	NAT	29.72	372.40	13.46	286.46
12	BARE	24.38	244.07	21.08	10901.66

APPENDIX—C (Continued)

DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE FOR THE VERY WET RUN FALL 1984

PLOT	TREATMENT	PRECIP (mm)	EROSION INDEX (MJ*mm/ha*h)	RUNOFF (mm)	SEDIMENT (gm)
1	NAT	22.86	218.03	11.43	297.28
2	BARE	23.37	228.58	17.27	15184.31
3	CLIP	22.61	212.75	11.18	367.53
4	NAT	23.62	233.85	4.83	92.44
5	BARE	23.88	239.30	14.22	9436.87
6	CLIP	23.62	233.85	8.89	302.58
7	NAT	24.38	250.36	16.00	475.57
8	CLIP	22.10	202.54	20.07	1137.55
9	BARE	26.16	290.87	24.38	9265.69
10	CLIP	21.59	192.84	16.00	535.13
11	NAT	25.15	267.38	12.95	381.06
12	BARE	20.57	174.11	20.06	10362.37

APPENDIX—C (Continued)

PLOT CHARACTERISTIC DATA FOR RAINFALL SIMULATOR AT NEVADA TEST SITE
FALL 1984

			GROUND COVER (%)				CANOPY COVER (%)			
PLT	TRT	SLOPE	ROCK	GRAVEL	SOIL	LITTER	GRASS	FORB	SHRUB	TOT
1	NAT	7.7	13.0	47.0	19.0	21.0	0.6	15.0	3.0	18.6
2	BARE	8.5	4.0	18.0	78.0	0.4	0.0	0.0	0.0	0.0
3	CLIP	5.9	11.0	79.0	10.0	0.0	0.0	0.0	0.0	0.0
4	NAT	6.7	4.0	56.0	9.0	31.0	0.6	5.0	13.0	18.6
5	BARE	7.1	2.0	11.0	87.0	0.2	0.0	0.0	0.0	0.0
6	CLIP	7.0	11.0	68.0	21.0	0.2	0.0	0.0	0.0	0.0
7	NAT	8.4	28.0	29.0	28.0	14.0	0.4	20.0	2.0	22.4
8	CLIP	9.0	24.0	52.0	24.0	0.2	0.0	0.0	0.0	0.0
9	BARE	8.6	10.0	12.0	77.0	0.4	0.0	0.0	0.0	0.0
10	CLIP	8.2	7.0	74.0	19.0	0.0	0.0	0.0	0.0	0.0
11	NAT	9.3	4.0	57.0	21.0	18.0	0.4	7.0	18.0	25.4
12	BARE	8.8	5.0	17.0	78.0	0.2	0.0	0.0	0.0	0.0