NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **220**

EROSION CONTROL DURING HIGHWAY CONSTRUCTION

RESEARCH REPORT

TRANSPORTATION RESEARCH BOARD
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AREAS OF INTEREST:
- HYDROLOGY AND HYDRAULICS
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- CONSTRUCTION
- SOIL AND ROCK MECHANICS
- (HIGHWAY TRANSPORTATION)
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TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff
Transportation Research Board

This report, *NCHRP Report 220,* and a companion report, NCHRP Report 221, "Erosion Control During Highway Construction—Manual on Principles and Practices," will be of special interest and value to people responsible for the control of soil erosion during the construction of highway and other types of facilities. This report describes the adaptation of the universal soil loss equation, originally developed by the Agricultural Research Service of the U.S. Department of Agriculture, for estimating the water erosion potential and the effectiveness of erosion control measures on highway construction sites. An equation for estimating wind soil loss potentials is also included. The companion report describes many measures for control of both water and wind erosion and information that will aid in the selection of measures to meet specific site requirements. The procedures for estimating erosion potential and effectiveness of erosion control measures are suitable for immediate implementation. The manual contains appropriate tables, charts, and maps to facilitate use of the procedures.

Uncontrolled water and wind erosion resulting from construction activities causes significant damage to the environment. The sediment that is produced pollutes surface water, restricts drainage, fills reservoirs, damages adjacent land, and upsets the natural ecology of lakes and streams. Besides harming the environment, soil erosion during construction increases costs and causes extensive delays and repairs. *NCHRP Synthesis of Highway Practice 18,* "Erosion Control on Highway Construction," documented the need to develop more effective techniques, devices, and materials to control erosion during construction activities as well as the existence of much information on known erosion control measures likely to have application in highway construction. The objective of Project 16-3 was the preparation of a manual of recommended procedures for control of erosion during highway construction based on existing information.

To accomplish this objective the Utah State University researchers accumulated and evaluated a large volume of information on the subject by a literature review, circulation of a questionnaire, on-site visits to construction projects, and interviews. A modified version of the universal soil loss equation developed by the Agricultural Research Service was selected for use in estimating potential soil loss from a specific site by water erosion. An experimental program was conducted to verify the applicability of the equation to highway construction sites. An equation developed by Chepil and associates was selected for estimating wind erosion. The major product of the research is a manual that focuses on techniques for predicting erosion potential on highway construction sites and for estimating the effectiveness of various erosion control measures.

The research has resulted in the publication of two documents: *NCHRP Report 220,* "Erosion Control During Highway Construction—Research Report," and *NCHRP Report 221,* "Erosion Control During Highway Construction—Man-

ual on Principles and Practices." This document (*NCHRP Report 220*) describes the research that was conducted as background for preparation of the manual, including adaptation of the universal soil loss equation for highway construction sites, experimental verification of the equation, and the results of a limited erosion control product evaluation study. The companion document (*NCHRP Report 221*) contains detailed procedures for estimating water and wind soil loss from specific sites under various conditions. Maps, tables, and charts are included to provide generalized input data for the contiguous United States, Hawaii, and Puerto Rico.

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The research reported herein was performed under NCHRP Project 16-3 by the Utah Water Research Laboratory at Utah State University, and the Intermountain Forest and Range Experiment Station, Research Work Unit 1603, U.S. Forest Service. Utah State University was the contractor for the study. Work done by the Forest Service was performed under a cooperative agreement with the University which is part of a Master Memorandum of Understanding between the U.S. Forest Service and Utah State University.

The principal investigators and co-authors of this report were: Calvin G. Clyde, Professor of Civil and Environmental Engineering, Utah State University, and Acting Director, Utah Water Research Laboratory; C. Earl Israelsen, Associate Professor of Civil and Environmental Engineering, Utah State University, and Hydrologist, Utah Water Research Laboratory; and Paul E. Packer, Principal Forest Hydrologist, Intermountain Forest and Range Experiment Station, U.S. Forest Service. The other investigators and authors of this report are: Eugene E. Farmer, Associate Forest Hydrologist, Intermountain Forest and Range Experiment Station, U.S. Forest Service; Joel E. Fletcher, Professor of Civil and Environmental Engineering, Utah State University, and Hydrologist, Utah Water Research Laboratory; Eugene K. Israelsen, Research Engineer, Utah Water Research Laboratory; and Frank W. Haws, Research Engineer, Utah Water Research Laboratory. N. V. Rao, Post Doctoral Fellow, Utah Water Research Laboratory; Jay Hansen, Research Assistant, Utah Water Research Laboratory; and Jerald S. Fifield, Doctoral Candidate, Utah State University also contributed significantly to the project research.

The assistance and cooperation received from representatives of all federal, state, and local agencies are gratefully acknowledged.

EROSION CONTROL DURING HIGHWAY CONSTRUCTION

RESEARCH REPORT

SUMMARY

Highway construction as it is known today is a high-risk activity with respect to engendering soil erosion. In earlier days of road building, when rights-of-way were generally narrow and excavations mostly shallow, erosion was rarely a serious problem. Only occasionally was it considered necessary to design and apply specific measures for erosion control. With the advent of the toll roads and Interstate Highway System involving far greater widths of right-of-way, and much deeper disturbance of the natural ground to afford the horizontal and vertical highway geometry necessary for high-speed travel, came a several-fold increase in erosion potential and a direct need for specific action aimed at its control. Highway engineers have reacted by revising construction specifications to include many protective measures. Increasing public awareness of the desirability of protecting the environment has been a source of both support and pressure in the application of erosion control in highway construction.

Although improvement has been significant, unwanted soil erosion and accompanying sedimentation resulting from highway construction activity continue to be problems. A lack of knowledge within the highway industry of improved erosion control measures developed outside the industry, perhaps some resistance to change because of a lack of familiarity with erosion control measures, and, in some instances, a need for information not now available anywhere are probably the major contributors to continuation of the problem.

The present project was directed at improving erosion control practice in highway construction by providing assistance in all three of the foregoing areas contributory to the problem. The research is documented in two reports: *NCHRP Report 220,* "Erosion Control During Highway Construction—Research Report"; and *NCHRP Report 221,* "Erosion Control During Highway Construction—Manual on Principles and Practices."

The research team found, through questionnaire returns from 177 sources and visits to construction projects in 32 states, that:

1. Technology is available in the United States to control within reasonable limits the erosion and sedimentation that may originate on highway locations both during and following construction.

2. Erosion control specifications currently being prepared for specific highway construction projects are adequate in many instances to maintain erosion within reasonable limits if properly enforced and followed.

3. More effective means of ensuring compliance with erosion control specifications during construction are needed.

4. Over-all construction costs may be lower if erosion control measures are implemented on a project than if they are omitted.

5. Erosion amounts can be significant even in areas where the average annual rainfall is comparatively low.

6. Numerous small erosion control measures implemented at the proper times and locations may be more effective and less expensive than a few large or poorly timed ones.

7. Written erosion control specifications are effective only if they are enforced and followed by design, administrative, and construction personnel.

8. Training courses for administrative, design, and construction personnel are needed both to create an awareness of the importance of controlling erosion and of the advantages that accrue from doing so, as well as to provide information on control measures and techniques that are available.

9. The universal soil loss equation (*1, 52, 56, 57*) developed by the Agricultural Research Service is probably the best tool presently available for predicting soil loss caused by rill and sheet erosion during highway construction and for estimating the relative effectiveness of various erosion control measures.

10. A soil loss equation developed by Chepil and associates (*24, 39, 58*) appears to have application to highway construction sites for estimating potential soil losses due to wind.

The manual on erosion control principles and practices (*NCHRP Report 221*) focuses on techniques for predicting the erosion potential of highway construction sites, and for estimating the effectiveness of various erosion control measures. A wide variety of control measures are listed and described, and information that will aid in selecting measures to meet specific site requirements is presented. Design standards for control measures, and information on such matters as size selection for mechanical control measures, are not included in the manual because these are already widely available in highway engineering offices.

To develop the erosion control manual on which the project effort was centered, means had to be estabilshed for estimating the water and wind soil erosion potentials on highway construction sites and the effectiveness of various measures that might be considered for controlling the erosion. The universal soil loss equation (*1, 52, 56, 57*), developed by the Agricultural Research Service, was modified and extended to serve as a basis for estimating water soil loss potentials. An equation developed by Chepil and Woodruff (*24*), Skidmore et al. (*39*), and Woodruff and Siddoway (*58*) was adapted for estimating wind soil loss potentials. Appropriate maps, graphs, and tables providing information necessary for the solution of the equations for the United States and Puerto Rico were prepared and included in the manual. Nomographs and tables were constructed and included in the manual for solving the equations, and the process was illustrated by detailed examples.

CHAPTER ONE

INTRODUCTION

HISTORICAL BACKGROUND

Since ancient times, men have been aware that rain and wind move soil from bared land. Throughout the world, some people have always sought, by one means or another, to prevent this loss. The remains of erosion-control structures that antidate the Christian era can be found in the

hills above the ancient city of Antioch in Syria. Steeply sloping land in Ireland is protected by stone hedges, some of which were constructed on contours and which are believed to have been built with stone cleared from the land more than 5000 years ago. The vineyards in the valley of the Rhine and the rice paddies in the mountains of the Philippines have been terraced for centuries. In Peru 400 years ago, the Conquistadores found the Incas farming steep Andean slopes on terraces walled with stone. Computed on the basis of present labor cost in the United States, many of these terraces would be worth more than $40,000 per acre.

In this country, alert people have tried to protect their land from erosion since the earliest colonial period. By 1769, George Washington was experimenting with erosion control methods in connection with farming at Mt. Vernon. Following the Revolution, Patrick Henry declared that "since the achievement of independence, he is the greatest patriot who stops the most gullies." The concern about soil erosion and its control felt by colonial leaders failed generally to permeate the ranks of American people. There was a misleading abundance of good land, and communication facilities for diffusing information were grossly inadequate. Accordingly, for nearly two centuries the average American was either unaware of, or surprisingly apathetic toward, the progress of destructive erosion on the Nation's lands. Conservation practices now regarded as fundamentally good land management failed to find a place in the exploitive uses of the land that attended the development of this country. Not until the last three or four decades have Americans begun to regard soil conservation as being prerequisite to sound land management practices. Nevertheless, throughout the history of this country runs a thread of erosion-control effort.

Early attempts to control erosion tended to lean largely towards a single method of control. In a number of places, terracing was regarded as a complete defense against erosion and was employed rather extensively. It is now known, of course, that, although terracing is an important erosion control measure, it is only one of the many measures which, if used in combination, provide the most effective erosion control. Until rather recently, vegetative methods of erosion control were given scant attention and were only incidentally applied to the land. The use of mechanical and vegetative measures in mutual support of each other was infrequent and usually accidental. By comparison, present-day concepts of soil erosion control involve the integrated and systematic use of not one but many mechanical and vegetative measures, applied in accordance with the particular needs and adaptabilities of the various kinds of land requiring protection.

Serious interest in water and wind erosion control in relation to roads began in the United States with the advent of the automobile and hard surfaced highways. The federal government and some states have been concerned for several decades about soil erosion caused by highway construction and its deleterious effects on the stability of the highway as well as on off-site values. Most states, however, have been concerned about soil erosion from highways for a somewhat shorter period of time. Current interest and activity in erosion control during highway construction vary greatly from state to state and seemingly depend to a great extent on the customs and values with which people have grown up. If their streams have always run clear, they wish to keep them clear. If their streams have always carried a sediment load, they may be less concerned about a little more sediment as a result of highway erosion. These philosophies are reflected in present-day regulations and restrictions of the various states regarding requirements for controlling erosion from construction sites, including highways. A few states have passed restrictive legislation governing the control of soil erosion even to the extent of making it illegal to permit soil eroded as a result of construction to enter a stream. In most states legal requirements for erosion control are not very restrictive. In some, they are not even regulatory.

PROBLEM STATEMENT AND RESEARCH OBJECTIVES

Water that falls as rain and snow on the watersheds of America is one of her most important natural resources. As this water moves down the great river systems, considerable effort is directed toward regulating its flow to serve the numerous uses that depend on it. Increasingly, people become aware, often painfully so, that the amount and condition of water flowing in the river systems exert tremendous influences on individual, economic, social, and recreational affairs.

Most of the interest displayed over water flowing in river systems is related to development of facilities to control it and put it to use after it enters larger tributaries and main streams. Unfortunately, there has been much less concern about controlling water—and the soil erosion it can produce—where it is most susceptible to management control; namely, where it first falls on the land. Experience in many places has shown that a change in the disposition of only a small portion of the water received on the land may greatly affect the manner in which it is delivered as stream flow. The behavior of water and whether it is beneficial or harmful depends, in great measure, on the condition and the uses of the lands from which it drains.

The placement of a highway in land that is susceptible to erosion can be expected, without doubt, to cause erosion unless precautionary measures are taken. The general nature of the effects of highways on erosion and sedimentation are known, and include the following kinds of problems: (1) development of unsightly cuts and fills that have been riddled by uncontrolled erosion and gullying; (2) undermining and collapse of fills, structures, and hillsides; (3) unsightly deposition of sediment in streams, channels, structures, ponds, reservoirs, and along highway rights-of-way; (4) destruction of aquatic environments in nearby lakes, streams, and reservoirs caused by erosion and/or deposition of sediment; and (5) destruction of vegetation by burying or gullying.

Numerous practical measures including the use of berm ditches, mulching, vegetation, surface drainage, structures, sediment traps, debris basins, and others have been employed to reduce erosion during highway construction and to prevent sediment from reaching streams. Erosive forces that are prevalent during construction should be considered also following completion of construction activities.

Much is still to be learned, both within the transportation community and elsewhere, about the control of erosion. On the other hand, evidence exists to indicate that, either because of the difficulty of finding the knowledge that is already available on erosion control or because of understanding how to use it (and probably because of both), existing knowledge is not always being employed to the best advantage in controlling erosion during the construction and operation of highways.

Research is needed to study the effectiveness of existing techniques, devices, and materials to control erosion during construction activities, and to develop additional ones as new information and materials become available. This need was documented in a synthesis study, "Erosion Control on Highway Construction Projects," conducted under NCHRP Project 20-5 (*33*).

The synthesis study, although focusing attention on the need for a major research effort, also uncovered a large quantity of information, often fragmented or underevaluated, on known erosion control measures likely to have application in highway construction. In recognition of the existence of this information, the urgency of the problem, and research funding limitations, a first logical step in the eventual solution of the total problem was determined to be the development of recommendations for an interim set of specific guidelines for erosion control based on existing information. The development of technology for the control of erosion and sedimentation has been under way for many years, but it should now be put into its most usable form and disseminated for application in highway construction. This has been the thrust of the present studies.

The specific objectives of these studies were to: (1) assess the effectiveness of measures that have been or are presently being used within the United States to control erosion from highway construction; (2) develop a manual of recommended techniques and measures for the control of erosion; (3) conduct a workshop for selected highway personnel to train them in the use of the manual in highway construction and maintenance work; (4) conduct research in the laboratory using a rainfall simulator to determine the validity of the Wischmeier erosion equation on steep slopes; and (5) identify research needs in the subject area.

SCOPE OF STUDY

The intent of these studies was to assemble, evaluate, and place in usable form existing information from all possible sources that can be brought to bear in the control of erosion and sedimentation resulting from highway construction activities. Quantitative data on erosion from highway construction sites are practically nonexistent, because most erosion studies over the years have been associated with agricultural, range, and forest lands. Consequently, much of the information presented herein is interpreted from data derived from these sourecs. In addition, some new data were to be generated under controlled conditions in the laboratory using a rainfall simulator to determine the validity of the Wischmeier equation on steep slopes.

RESEARCH APPROACH

A comprehensive review of literature was made that included computer searches of several sources, library research, and correspondence with agencies, individuals, and companies where erosion control data and publications were thought to exist.

More than 300 questionnaires were sent to selected agencies and organizations in all of the states to request publications and information pertinent to the study. A sampling of the questions and the 177 responses are presented in Appendix B.

Some states have already developed their own erosion control manuals, which supplement those guidelines that had been provided to them by the Federal Highway Administration. Information and ideas from these have been incorporated in the present study. Additional helpful information was received from federal and state agricultural research and experiment stations where erosion control studies have been conducted.

On-site visits were made to construction projects in 32 states where first-hand impressions were gained of the effectiveness of various erosion control measures (see App. A). In addition, interviews were conducted at these same locations with highway officials, contractors and construction personnel, landscape architects, representatives of government agencies, and others to obtain their opinions and suggestions as to the strengths and weaknesses of erosion control measures with which they were familiar. At some of these sites, soil samples were collected for analyis, and measurements were made of actual erosion amounts occurring where climate, soil, slope, vegetative cover, and other pertinent factors were known. Each visit was documented with photographs.

The study considers water and wind erosion in the 48 contiguous states, and in Hawaii, Alaska, and Puerto Rico. All of the factors contributing to erosion are considered, including erodibility of the soil, slope length and steepness, rainfall and wind intensity, duration and recurrence interval, vegetative cover, and management practices.

A modified version of the universal soil loss equation developed by the Agricultural Research Service (*1, 52, 56, 57*) and a wind equation developed by Chepil and associates (*24, 39, 58*) were selected as the bases for estimating potential loss of soil on construction sites and for evaluating the effectiveness of control measures. Discussions of the equations, together with an explanation of limitations of the universal soil loss equation, appear in Chapter 3.

The equations were adapted and their applicabilities extended for use over the entire United States for determining erosion potentials and for comparing effectiveness of alternative erosion control systems. To enable the use of these equations as tools for evaluating the effectiveness of various vegetative and mechanical measures for controlling soil erosion and sedimentation, data pertaining to soil erodibility, rainfall kinetic energy, and wind magnitude and direction were collected and illustrated in map form. Data for the various terms of the equations appear in *NCHRP Report 221*. Physiographic data, including slope lengths and steepnesses and their effects on soil erosion, are illustrated as graphs and tables. Available information about the effectiveness of various vegetative covers and mechanical measures on soil erosion has been tabulated.

Detailed examples illustrating the use of these data in the soil loss equations to determine amounts of erosion that might be expected from alternative erosion control measures under given conditions of soil, climate, and physiography are presented in the manual.

The principal advantages of using the procedures illustrated are the ability they provide for assessing the consequences of scheduling and sequencing of erosion control measures, and the fact that the entire procedure can be computerized. Major disadvantages are the assumption of spatial and temporal homogeneity and the paucity of sound input data when the equations are used in connection with erosion control problems on nonagricultural lands. These examples assume that all vegetative measures and the engineering structures are adequately designed and installed and function properly. Also illustrated by examples is the use of the rainfall energy and soil erodibility maps, together with the slope length and steepness graphs and the vegetative and mechanical measures tables, to determine erosion amounts that might be expected from alternative erosion control practices. This latter procedure provides a means for quick estimation of the effects of alternative control practices without the necessity of mathematically computing all components of the soil loss equations.

CHAPTER TWO

FINDINGS

GENERAL

Throughout the United States there is a great variation in the interest in, and the need for, studies of erosion control on highway rights-of-way during the construction period. Some of the variations are due to differences that exist naturally in soils and climate, and others can be attributed directly to differences in attitudes and opinions of individuals who are responsible for the work. An important fact observed during the numerous visits made to construction sites throughout the country is the importance of the attitude of construction personnel toward controlling erosion. Written specifications, no matter how rigid or detailed they may be, are not effective unless enforced.

Technology is available in the United States to control, within reasonable limits, the erosion and sedimentation that may originate on highways both during and following construction. Most erosion control studies conducted throughout the country to date have been on surface soils for range, forest, and agricultural interests, and, thus, data pertaining to erosion from construction sites (primarily exposed subsurface soils) are very sparse. Because most of the available information on erosion control has been produced in fields alien to the highway community, state highway and transportation departments have found it difficult to locate, evaluate, and translate into highway use. This became obvious during the visits to construction sites where it was found that, with few exceptions, each state highway department had tackled the erosion and sediment control problems principally on its own without making full use of what is already known. This report is intended to fill the obvious need with the listing, descriptions, and pictures of erosion control measures that are included in the manual, and with explanations of how to apply existing erosion control technology to highway problems.

The semiempirical equation, known as the universal soil loss equation (USLE) (*1, 52, 56, 57*), was developed by the Agricultural Research Service for estimating gross erosion from rainfall on farmlands east of the Rocky Mountains. A modified equation, based on the USLE, was selected by the research team as the basis for estimating water erosion potential and for determining effectiveness of erosion control measures on highway construction sites. Other equations have been developed for estimating erosion, but probably none has as wide a range of application as does the USLE. More information concerning its development and limitations is given in Chapter 3. A wind soil loss equation developed by Chepil and associates (*24, 39, 58*) was found to have application in highway construction work and is the basis used in this study for estimating wind soil loss potentials.

Erosion control measures may be grouped generally into three broad categories: structural, vegetative, and chemical. One could list also a separate heading of management, which is important if one is to maintain a viable erosion control program. This would include the timing of implementation of the various measures, which is as important as the measures themselves. Also included would be the initial route selection of the highway because many serious erosion problems would never materialize if erosive soils were avoided to begin with. The severity of erosion problems varies greatly with climate and soils, and the designer needs to know as many of the facts as possible that may influence his decisions. For example, even in areas where the average annual rainfall is comparatively low, if much of this were to fall in one or even a few storms, significant erosion and sediment damage could occur unless adequate control measures were implemented. Sometimes, in low rainfall areas, wind erosion also may be significant unless measures to control it are used.

The structural controls include such items as sedimentation ponds, serrated cuts, drop structures, flumes, berms, dikes, check dams, gabions, down drains, and the like. Vegetative measures include such items as annual and pe-

rennial grasses and legumes, shrubs, vines, trees, mulches. The chemical controls are fairly recent and new ones are being added regularly. These may be used with or without vegetative measures and include such items as soil stabilizers, asphalt, chemical mulches, and soil sealants. Generally speaking, the chemicals have been less successful than other measures thus far in controlling erosion from construction sites.

It must be realized that soil and rainfall maps of the entire country, as presented in this report, cannot be site-specific, but are only generally indicative of conditions on a large scale. However, the methodologies presented can be applied to particular locations simply by substituting the data for those particular sites. Several of the states are preparing their own erosion control manuals that include information supplied by the Federal Highway Administration and workable measures they have developed from their own experience. Some of these also are acquiring rainfall and soil data on a county or subcounty basis. The more site specific are the data used in calculations, the more precise will be the estimates of erosion potentials, and their use is encouraged.

CONTROL MEASURES

Erosion control measures employed in the United States have been categorized according to their various uses and included in the manual. Photographs of most of the measures are presented there also. Some of the measures are used nearly universally throughout the country; others may be peculiar to a specific location or region. Some measures may be essentially the same in different states, but known by different names. The unique ones include such things as gobi blocks, which are perforated concrete blocks for stabilizing slopes against wave action; reinforced earth embankments, which are concrete blocks stacked vertically to form a retaining wall and to which are fastened long metal strips that are buried in an earth fill; floating plastic barriers for use in lakes and streams to contain sediment; rock-filled tubular fabric "sausages" used for stabilizing ditch bottoms; 1-ft diameter sand-filled tubular burlap containers for protecting embankments; and concrete blown onto wire-mesh-covered vertical rock embankments to stop sloughing. Some or perhaps all of these may serve equally well in other parts of the country where they are not now known. This project has made a serious attempt to bring together under one cover a listing of essentially all the erosion control measures used during highway construction in the United States.

There are relatively few control measures that actually prevent or reduce erosion directly by protecting the soil surface. These include vegetation, mulches, and chemical controls. Other measures serve as slope shorteners that act to slow the velocity of overland flow, thus reducing its kinetic energy and ability to start soil particles moving. Slope shorteners include such things as berms, ditches, slope intercept drains, and sod stripping. Another group of control measures serves to remove sediment from water after it has already started to move. This is accomplished by slowing the velocity of the sediment-laden water to such an extent that it can no longer keep the sediment particles in suspension or moving along the channel bottom. Examples of these measures are sediment traps, check dams, brush barriers, and silt fences.

Measures such as culverts, down drains, and lined ditches serve primarily to transport water along or across the right-of-way to where it can be safely disposed. Riprapping and energy dissipators slow the velocity of the water so that it will not erode and can be released safely off the right-of-way.

Various kinds of filters, coagulants, and settling ponds are used to remove suspended fine sediments from water. This fraction of the total sediment of a stream is proportionally small, but is by far the most difficult to remove. From the standpoint of economics, in many instances it may not be justifiable to remove it, but there are things other than economics that must be considered.

A program for controlling erosion and sedimentation during the construction of a highway project may require several of the different kinds of controls described previously. The proper sequencing of their use, their locations on the project, the timing of their installation, and their proper maintenance are all critical to the successful control of erosion and sedimentation.

Design drawings of all these measures are available to state highway departments, and it is not the purpose of the present study to provide additional ones. The manual, however, presents a listing of most of the control measures in use throughout the country, and strongly encourages their proper use.

DISCUSSION OF MEASURES

The effectiveness of a given control measure employed at different locations throughout the country may vary greatly because of differences in the erodibility of soils, climatic factors, and the time of its installation. The way in which it is maintained also influences its effectiveness. For example, if sediment is not removed from detention structures after every significant storm, these structures may very quickly become totally ineffective and serve only to "short circuit" eroded materials through the system. Undermining or piping must be promptly repaired or mass failure can occur, resulting in much greater damage than would have occurred with no controls at all.

In one observed instance a series of various kinds of detention structures and filters had been installed to prevent sediment from entering a lake. They were effective for awhile in doing this but were not maintained. At about the time they were all filled with sediment, a sizable storm occurred and washed all of the structures out together, depositing the accumulated sediment in the lake. Most of this could have been averted had the structures been cleaned regularly.

Many of the measures implemented for control during the construction period may be left in place as permanent controls to function throughout the life of the project. A continuing monitoring and/or maintenance schedule for these should be implemented if they are to remain effective.

Erosion control specifications in most states are adequate to maintain erosion within reasonable limits on highway construction jobs if they could be more effectively en-

forced. Better means of ensuring compliance with erosion control specifications during construction are needed. In many instances, the matter of whether or not to implement particular controls is left up to the contractor, and he may be reluctant to do them because they may be fairly expensive and may not have been budgeted. They may be handled on a force account, but this too is often a negotiable matter that can cause feelings and perhaps no action. Those states, generally, that are having the most success in getting control measures installed and maintained in a timely manner are those in which the desired measures are bid items in the contract, and in which monetary arrangements are made for maintaining them. *Erosion control measures are of no value if they are not installed properly in the right places at the appropriate times, and then adequately maintained.*

Proper education of personnel as to the need for controlling erosion and sedimentation is one of the best ways of improving the effectiveness of an erosion control program. If the managers and workers do not understand the purpose of a control measure or are not aware of the problems associated with it and how they can be solved, even the most carefully prepared erosion control specifications will fail to do the job. Many states have training programs in which reasons are discussed for controlling erosion, and instruction is presented on the use and maintenance of various measures. In some instances, the highway departments collaborate with the Soil Conservation Service, Agricultural Research Service, and other agencies in the presentation of training courses and seminars. Often during the off-season, construction personnel and contractors are invited to attend the sessions. People who are knowledgeable and enthusiastic about controlling erosion can do more toward solving the problem than even the best written and most detailed specifications.

There exist many varying opinions on the cost of controlling erosion. Estimates in the range of 0 to 33 percent of the total project cost were given on the questionnaire responses that were received from the states. However, some contractors who are doing particularly good jobs of controlling erosion believe that the over-all increase in cost is near zero when one takes into account the savings in not having to come back at the end of a job to refinish slopes. Other contractors who have had very little experience in erosion control work are sure that all of the added specifications, if they were to be enforced, would raise the costs so high that they would be prohibitive. Thus, it is seen that attitude plays an important role in the program.

On the basis of observations made during field visits, interviews, and sample calculations, it is concluded that numerous small erosion control measures implemented at the proper times are more effective and less expensive than a few large or poorly timed ones. This is because generally it costs less to retain sediment at or near its origin than to let it move and then have to collect and dispose of it or return it to the construction site. An example of this is the construction of large sediment basins, costing several thousands of dollars each, which are designed to catch and retain whatever sediment may leave the site. This sediment must then be disposed of or transported at intervals back to the site. An alternative would be to scoop out numerous small sediment traps costing a few dollars each on the site such that nowhere would sediment be allowed to move more than a few hundred feet from its origin. To remain effective, these would need to be cleaned regularly.

Included in the manual is a summary of all available effectiveness data, together with a reliable method for evaluating the effectiveness of erosion control measures at any location in the country. With the aid of the method and data presented, the user can readily determine the potential erosion of any particular site and the effectiveness of most erosion control measures.

LEGISLATIVE CONTROLS

It became apparent as a result of visits to the various states that there exists very little uniformity as to the amount of interest and effort that is devoted to solving erosion and sedimentation problems related to highway construction. Federal regulations and guidelines are interpreted in different ways, and even state highway specifications for erosion control are adhered to in varying degrees of completeness.

Some states have enacted laws to deal with the erosion problem more specifically and to provide additional incentives to those in the construction industry to protect the environment. Some of these laws are very strict and specify a degree of control that may not be completely attainable in practice, but they produce better results than have ever been achieved before. As information about the success of these programs becomes known, the trend will no doubt continue toward increasingly more states enacting legislation to protect their streams and lakes from pollution by sediment.

Practically all of the states are updating their specification handbooks as they relate to erosion control to comply with new federal laws and regulations that have been enacted.

OUTLOOK FOR THE FUTURE

The increasing pressures of public opinion, the upsurge of environmental activists, and increased enforcement of clean water and clean air standards by such enforcement authorities as the Environmental Protection Agency will, no doubt, foster a general movement toward stronger regulations governing the control of soil erosion from all sources including highways. Needed to intelligently regulate activities capable of controlling soil erosion are better criteria to predict the degree of control needed and to assess the degree of control obtained. Providing these criteria is the principal objective of these studies.

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATION

INTRODUCTION

This chapter summarizes information that is presented in detail in the manual on erosion control principles and practices. The manual (*NCHRP Report 221*) contains in one form or another a synthesis of all information that has been assembled during the course of the projects, together with its interpretation and evaluation. Also included are step-by-step examples of how to use the information for the solution of practical problems that relate to sediment production and control, and how to determine the effectiveness of various erosion control measures.

WATER EROSION

Processes of Water Erosion

The processes of soil erosion by water involve detachment of soil particles, their transport primarily by flowing water, and their eventual deposition. At least the coarse particles will be deposited; colloidal particles may remain in suspension almost indefinitely.

The chief mechanisms for soil detachment are raindrop impact and shear forces imposed by flowing water. Although the detachment of soil particles by flowing water cannot be ignored, soil detachment by raindrop impact is by far the most effective of the two mechanisms.

The transportation of detached soil particles occurs primarily through channelized runoff of surface water. Raindrop impact is a less important transporting agent and usually becomes a significant factor only on slopes whose steepness is 2:1 or greater. Channelized surface water runoff will not occur unless the rainfall intensity exceeds the soil infiltration rate. However, once runoff begins, the amount of soil carried is a function of runoff velocity and turbulence which are strongly affected by slope steepness. Overland flow will move down a 2½:1 slope at twice the velocity of that down a 10:1 slope. However, by doubling the velocity, the energy of the flow will increase four times; the size of particle that can be transported will be increased 64 times; and the mass of soil that can be carried is increased 32 times.

The deposition of eroded soils will occur whenever the runoff velocity or turbulence significantly decreases. Deposition of sediments is usually an ordered process with the largest and densest particles settling first and finer ones last. Therefore, the original soil materials being eroded strongly affect the properties and amount of sediment being deposited.

Soil particles eroded from upland areas come from rill and interrill areas. Rills form as the result of small volumes of channelized flow. Interrill areas are those surfaces between rills that are eroded from raindrop splash and from nonchannelized flow (sheet flow). The universal soil loss equation provides a method for estimating rill and interrill erosion. If the average annual computed soil loss is greater than the tolerable soil loss, the highway designer will want to consider some alternatives for reducing it. Possibly one or more factors in the soil loss equation can be altered such as the slope length or slope steepness to achieve a reduction in the topographic (LS) factor.

Perhaps the entire construction job can be scheduled so that a minimum of bare soil will be exposed during the period of maximum rainfall erosion potential. Mulching and seeding requirements may need to be updated or rescheduled to an earlier time. Any one of these actions or all of them together will reduce the computed soil loss. Because the factors in the soil loss equation are multiplicative, even small changes in several factors can affect the computed soil loss to a considerable degree.

Another way of reducing off-site soil loss is by the use of sediment traps and debris basins. The amount of sediment caught in a trap depends on the total volume of the trap, the amount of sediment and water entering the trap from upland areas, and the locations of the trap inlet and outlet in relation to each other. Trap efficiency has been discussed at length in the engineering literature and is beyond the scope of this discussion. However, even sediment basins with high trap efficiencies may discharge very turbid water. If the volume of off-site sediment is the major consideration, turbid outflow water may be acceptable. On the other hand, the discharge of turbid water into clear lakes or streams is usually unacceptable. In that case the use of chemical flocculants or water filtration should be considered.

Estimating Water Soil Loss

Development of equations for calculating field soil loss began in about 1940. Improvements were made from time to time to include additional factors that might affect erosion, and in 1958 a semiempirical equation was developed that became known as the universal soil loss equation (USLE) which overcame many of the limitations of the earlier equations. The improved equation was developed at the Runoff and Soil-Loss Data Center of the Agricultural Research Service, established at Purdue University in 1954. Improvements incorporated into the new equation included: (1) an improved rainfall-erosion index; (2) a method of evaluating cropping-management effects on the basis of local climatic conditions; (3) a quantitative soil-erodibility factor; and (4) a method of accounting for effects of interrelationships of such variables as productivity level, crop sequence, and residue management.

The soil loss equation is

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad (1)$$

in which:

A = the computed soil loss per unit area, generally expressed as tons/acre/yr;
R = the rainfall factors, which is the number of erosion-index units in a normal year's rain (the erosion index is a measure of the erosive force of specific rainfall);
K = the soil erodibility factor, which is the erosion rate per unit of erosion index for a specific soil in cultivated continuous fallow, on a 9 percent slope 72.6 ft long;
L = the slope-length factor, which is the ratio of soil loss from the field slope length to that from a 72.6-ft length on the same soil type and gradient;
S = the slope-gradient factor, which is the ratio of soil loss from the field gradient to that from a 9 percent slope;
C = the cropping management factor, which is the ratio of soil loss from a field with specified cropping and management to that from the fallow condition on which the factor K is evaluated; and
P = the erosion control practice factor, which is the ratio of soil loss with contouring, strip cropping, or terracing to that with straight-row farming, up and down slope.

In adapting this equation for use in the highway industry the present study eliminated the C and P factors which relate specifically to agricultural lands, and substituted in their place an erosion control factor VM to be used on construction sites. The VM factor is applied in the water soil loss equation as a single unit. It accounts for the effects of all erosion control measures that may be applied on any given site including vegetation, mechanical means, and chemicals. The L and S factors are combined to form LS, the topographic factor, which depends on the length and steepness of the slope.

The procedures for determining the erosion of the land surface do not constitute an exact science. The physical and biological processes governing soil erosion are complicated and interact together in changing and undefined ways. These complications have necessitated many simplifying assumptions in order to reduce the problem to manageable proportions. The statistical interpretation of observed data obtained under rigorous conditions is one of the approaches that has produced a wealth of information on soil erosion processes. It was precisely this procedure that produced the universal soil loss equation. However, it is probably impossible for any equation, statistical or otherwise, to correctly express the response of the soil to all of the natural or man-imposed forces acting on it. One of the basic assumptions of the universal soil loss equation is that both the forces acting to cause erosion and the response of the soil to those forces are homogeneous in time and space. While it is known that this assumption is frequently violated, it is also true that the universal soil loss equation has proven its utility through many years.

The control of soil erosion and the disposition of sediments is a distinct problem area of its own. But, it is not an exact science. Often the desired level of erosion control can be achieved in many ways. Practical field people (e.g., farmers) have often been successful in controlling erosion with only a rudimentary knowledge of the technical aspects of soil erosion. Erosion control seems to have an "intuitive" aspect to it, and some people are very good at inferring the correct procedures. However, "intuitive" erosion control is difficult to assess, and the degree of control cannot be evaluated. The procedures in this report are an attempt to put the requirements of erosion control and an evaluation of their performance on a semiquantitative basis. The procedures have been designed specifically for highway construction sites.

The calculations involved in evaluating the performance of any erosion control system may give the impression of a precision that can not be attained on actual construction sites. In all soil erosion estimates there is an element of art—i.e., an element of skill acquired by experience, study, and observation. These skills involve both engineering and agronomic estimates. The procedures involved in evaluating erosion control systems can best be used in the design and planning stages, months or even years before actual construction. However, it is believed that these procedures, whether used in the office or in the field, represent the current state of the art in erosion control technology. They permit the semiquantitative evaluation of erosion control systems that heretofore could be evaluated only qualitatively.

Use of the Universal Soil Loss Equation on Steep Slopes

The USLE was developed on relatively flat slopes and few reliable data for evaluating its accuracy existed for slopes greater than about 20 percent. One of the primary objectives of the present research was to test the equation for steeper slopes, up to the maximum 93 percent (43°) that can be provided by the UWRL erosion control testing facility. At about the same time that this research was being conducted Wischmeier and Smith (*56*) were collecting additional data as well of erosion on slopes steeper than those on which the equation had been developed, and their results appear also in the manual.

Data were gathered at the UWRL using the erosion control testing facility and rainfall simulator described in Appendix C. Soils used in the test were a washed sand, a silty clay loam, and Cecil gravelly clay loam. Test plot dimensions were 19.5 ft long by 4 ft wide, and the plots were evaluated at slopes of 9 percent, 25 percent, 50 percent, and 84 percent under rainfall intensities of 2.51, 3.95, and 7.65 in. per hr.

Results of this testing are presented in Appendix C of this report and in the manual and indicate that the universal soil loss equation is valid for use on steep slopes.

"VM" Values

The erosion control factor, VM, is applied in the water soil loss equation as a single unit, and accounts for all ero-

sion control measures that may be applied, whether they are vegetative, mechanical, or chemical. It became apparent from the literature review, field visits, correspondence, and personal interviews that very few data exist for determining the effectiveness of control measures. Scattered determinations have been made of *VM* values for use in the water soil loss equation and these are tabulated in the manual. Graphs are presented for particular measures of the number of tons per acre required plotted against values of $(R \cdot K \cdot LS)$. Explanations are given for their use.

Limitations

The universal soil loss equation includes all major factors influencing soil erosion. It is universally applicable wherever locational values of the equation's individual factors are known or can be determined. About 10,000 plot-years of runoff and soil-loss data assembled from 47 research stations in 24 states were analyzed during the equation's initial development. In spite of these impressive facts, the equation does have limitations that should be taken into account when it is used:

1. The equation is semiempirical and does not necessarily express its several factors in their correct mathematical relationships. This limitation is overcome by the use of empirical coefficients. The physical data upon which the present coefficients are based were limited to maximum uniform slopes of 20 percent and lengths of 300 ft.
2. The rainfall-erosion index measures only the erosivity of rainfall and associated runoff. Therefore, the equation does not predict soil loss that is due solely to thaw, snowmelt, or wind. In areas where such losses are significant, they must be estimated separately and combined with those predicted by the equation.
3. Gully erosion such as is caused by large concentrated flows of water cannot be accounted for by the equation which applies only to sheet and rill erosion. This means that the conveyance of concentrated flows must be adequate or the computed soil loss will be underestimated.
4. The equation was developed to predict soil loss on an average annual basis. Soil-loss predictions on a storm-by-storm basis often result in error because of complicated interactions between forces governing soil-loss rates. Even the computed average annual soil loss may be greatly different from the observed soil loss. This is due to fluctuations of rainfall characteristics from year to year.

Erosion Control Product Testing

Throughout the United States many different kinds of products are being used for controlling erosion that can be classified generally as either mulches or chemicals. Additionally, many kinds of vegetation are used as well. Various claims as to the effectiveness of each product are made but very little comparative testing of products has been done. The present study provided for the preliminary testing of some of these products under the rainfall simulator described in Appendix C. A single test of each was made on a 2:1 (50 percent) slope, on a silty loam soil, under a rainfall intensity of 8 in. per hr. Particular products included in the testing were asphalt emulsion, tackifiers, wood fibers, straw, wood chips, and gravel.

Details of testing procedures and their results are given in Appendix D.

WIND EROSION

In most areas of the United States the amount of erosion attributable to wind as opposed to that from water may be equal to or near zero. However, in some places it is significant, and ways and means are needed for its control. The reader will get a better understanding of wind erosion problems by studying the examples presented in the manual.

Wind erosion potential may be estimated in a manner similar to that for water by the use of a soil-loss equation. The wind-erosion equation, selected by the present study for estimating soil loss due to wind on highway construction sites, resulted from years of work by Chepil, his associates, and others (*5-7, 12-26, 38, 39, 53*). The equation as developed by these researchers is as follows:

$$E' = I' \cdot C' \cdot K' \cdot V' \cdot L' \qquad (2)$$

in which:

E' = soil loss by wind, in tons/acre/yr;
I' = soil wind erodibility factor;
C' = local wind erosion climatic factor;
K' = soil surface roughness factor;
V' = vegetative factor; and
L' = length of the unshielded distance parallel to wind in the direction of the wind fetch.

The I value is determined in the field by dry-sieving a soil sample through a 20-mesh (0.84-mm) screen. Knowing the percentage of particles larger than 20 mesh and if there is no crusting, the tons per acre can be read from a table. If the soil has a well-developed crust, a different table is used. The tons/acre value read from a table becomes I' in the wind soil loss equation whenever there is no correction required for the windward knoll effect.

The soil wind erodibility index, I, is the potential soil loss in tons/acre/yr from a wide unsheltered, isolated, bare, and smooth noncrusted soil expanse. Whenever the slope is facing the dominant wind direction so that the wind impinges against the slope, erosion is accelerated. This acceleration is known as the windward knoll effect, and the knoll erodibility factor, I_8, is used to correct the soil wind erodibility index, I, for this exposure. Erosion is increased also by slope steepness. The relation between the slope steepness and I_8 is used to obtain the multiplier to correct I for the knoll effect for slopes shorter than 500 ft. When these same slopes are to the lee of the wind, the slope is completely shielded down to a 10 to 1 grade (10 percent slope gradient).

In order to determine I' for the wind erosion formula, the I value is multiplied by I_8

$$I' = I \times I_8 = \text{tons/acre/yr} \qquad (3)$$

The monthly isovalues of the local wind erosion climatic factor, C', are given on appropriate maps. C' is the cube of the mean wind velocity for each month divided by the square of the annual precipitation effectiveness index, *PE*, developed by Thornthwaite (*46*). It is computed from the equation:

$$C' = 34.483 \frac{V^3}{(PE)^2} \qquad (4)$$

in which:

$V =$ mean monthly wind velocity at a height of 30 ft for all winds in excess of 12 mph; and

$PE =$ Thornthwaite's precipitation effectiveness index $=$ PE index $= 115(P/T - 10)^{1.111}$ in which P is the mean annual precipitation and T is the mean annual temperature.

The C' factor maps on a monthly basis are composed of the monthly $V^3/(\text{annual } (PE)^2) \times 34.483$.

The prevailing wind direction and preponderance (prevalence) are obtained from the wind erosion force vector. (See App. D of the manual.)

If the value of preponderance is 1.0, there is no preponderant direction so a barrier could be placed in any direction with equal results. A value of 2.0 indicates that the preponderance is twice as great in total wind force as for 1.0.

In using wind preponderance and direction maps, the dominant wind direction is determined for the period of time required by assuming that an east dominant wind is the zero direction. From this point measurements are made in a counterclockwise direction through the 16 principal points of the compass, or 360 deg. The direction number is multiplied by the magnitude of the preponderance, and finally the sum of the products is divided by the sum of the preponderance values to arrive at a weighted average resultant wind direction. This direction is the effective prevailing wind direction.

The surface roughness factor K' is a measure of the natural or artificial roughness of the soil surface in the form of ridges or small undulations. It can be determined by knowing the height of the individual roughness elements and then using an appropriate graph.

The V' factor represents equivalent pounds of vegetative matter as a roughness element. The V' value is obtained by wet sieving the air-dried soil to separate the organic material from the mineral portion. The organic matter is then dried and weighed. The weight in thousands of pounds per acre is entered on an appropriate graph to determine the V' factor.

The unshielded wind fetch distance, L', is defined as the distance parallel to the preponderant wind direction in excess of the shielded distance. In the field, the preponderant direction is layed out with a compass or transit, then the distance across the exposed area in excess of 10 times the height of any barriers is recorded in feet as the value of L'.

MAPS

Numerous maps have been produced to aid in the determination of erosion from wind and water.

Soil Maps

Soil erodibility maps were created for the 48 contiguous states. These are based on the most recent information available as received from individual states and the Soil Conservation Service. The maps are color coded with each color representing a narrow-range erodibility, or K value, as indicated in the water soil loss equation. The soil erodibility factor K is a numeric indicator of the ability of a soil to resist the erosive energy of rain. The researchers are aware that the values shown on the maps are very nonspecific and that, within each area of color shown, there are in reality many different types of soil. Some states are completing more detailed soil surveys, such as on a county basis or smaller; where these data are available they should be used in preference to those shown on the colored maps.

Wind Maps

Wind erosion climatic factor, C', maps have been prepared also for the 50 U.S. states and Puerto Rico. The wind climatic factor is related to wind velocity, mean annual precipitation, and temperature. These are on a mean monthly basis, and values taken from them are used in the determination of erosion caused by wind. The manual also contains maps of monthly wind direction and preponderance that are necessary for meaningful calculations.

Isoerodent Maps

At the time of the development of the universal soil loss equation by the Agricultural Research Service, an isoerodent map was constructed for the area of the United States east of the Rocky Mountains. This map has been extended by Project 16-3 to include also that area west of the Rocky Mountains. In addition, isoerodent maps have been prepared of Alaska, Hawaii, and Puerto Rico. The isoerodent maps are used in combination with the regional maps, next described, to estimate the rainfall factor, R, in the water soil loss equation. The rainfall factor is computed from rainfall records, considering the kinetic energy of storms and rainfall intensities. The isoerodent maps provide R factors on a mean annual basis.

Regional Maps

A regional map was constructed by the Agricultural Research Service in which the 37 eastern states were divided into 33 geographic areas in each of which the monthly distribution of the erosion index, EI, could be considered uniform. The erosion index of any particular location can be determined by summing EI values of individual storms. Project 16-3 has extended this procedure to also include the western states, producing an additional 18 geographic areas. A map showing these areas, as well as those defined previously, has been constructed, and the areas are numbered in an orderly manner from west to east from 1 to 51. Similarly, regional maps have been constructed for Alaska, Hawaii, and Puerto Rico.

Values from these maps are applied to values from the isoerodent maps to find R factors for the time period of interest for use in the water soil loss equation.

NOMOGRAPHS

Maximum use will be made of the manual only if it is easy to use. Individuals working in a design office with ready access to calculators may take the time to solve

complicated equations for determining potential erosion amounts, but this is generally not true of field crews. They usually prefer short-cut methods and rule-of-thumb procedures. For this purpose, the authors have attempted to present necessary data and information in tabular and map or graph form, and to provide for the solution of equations by means of nomographs or tables. A brief discussion of nomographic procedures is presented in the manual. Each nomograph is presented separately with a graphic explanation of its use. A step-by-step example is given to lead the reader through each nomograph to particular solutions. Nomographs are presented in the manual for the determination of the soil erodibility factor *K*, the solution of the wind erosion equation, and the solution of the water soil loss equation. The only tool needed to use the nomographs is a straightedge. Tables give the solution of the equation for the *LS* factor for single and multiple slopes.

PHOTOGRAPHS

Photographs have been made of most of the different kinds of erosion control measures that are being used in the United States and are presented in an appendix to the manual. Explanations of each measure are given, including special characteristics of each and where it might be used in a construction program.

PROCEDURE FOR DEVELOPING EROSION CONTROL PLAN

The manual provides the appropriate maps, tables, graphs, etc., and explains the use of the water and wind soil loss equations both for calculating erosion potentials for construction sites and for evaluating the effectiveness of various erosion control measures. The outlined procedures also permit one to determine the amount of control needed to decrease anticipated soil loss from an area to any predetermined level.

1. During the planning stage within the proposed corridor of the highway, gather information about erosion-sensitive zones and adjacent areas wherein sediment, even in small amounts, might become a problem. These would include such places as streams, ponds, lakes, inhabited areas, and other high-value concerns.
2. Identify the locations that may produce acute erosion problems, such as steep and deep cuts and fills, sandy zones, windy areas, springs, high water tables, erodible soils, and natural drainages.
3. Consider 1 and 2 in selecting the optimum location for the highway within the corridor.
4. When the route within the corridor is fixed, determine the parameters in the water soil loss equation, $A = R \cdot K \cdot LS \cdot VM$, for estimating the erosion potential for each section of the highway. These data may be obtained from appropriate maps, charts, tables, soil samples, and job specifications for every section along the right-of-way. Each section would normally extend from one drain to the next.
5. Repeat 4, where appropriate, using the wind soil loss equation, $E' = I' \cdot C' \cdot K' \cdot V' \cdot L'$.
6. For every section having erosion potentials in excess of those deemed appropriate for its location, designate erosion control measures for reducing the anticipated soil loss to acceptable levels. Step-by-step procedures for accomplishing this are presented in the manual.
7. Include sufficient information regarding the erosion control plan in the design drawings so that there will be no misunderstanding by construction personnel as to what is required. Supplemental instructions and explanations may be required.
8. Provide adequate means of enforcing the frequent review and implementation of the erosion control specifications. An effective means of encouraging compliance is to foster proper attitudes among contractors by including erosion control measures as bid items in the contract and by providing appropriate training sessions for selected construction personnel.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

The principal product of this research is the manual on erosion control principles and practices that is published as a separate document, *NCHRP Report 221*. The manual is concerned primarily with techniques for predicting the erosion potential of highway construction sites and for estimating the effectiveness of various erosion control measures. Many control measures are listed and described, and information that will aid in selecting measures to meet specific site requirements is presented. Modification and extension of the universal soil loss equation for application to sites other than gently sloping farmland (e.g., construction sites) has greatly expanded its use.

The following research and training are suggested to alleviate the paucity of erosion control research data applicable to construction sites. Priority is suggested by the numbers 1 to 4; however, for work suggested under any given number, no priority is intended:

1. Statistically controlled experiments are needed in the following areas:

a. The verification of the relationship between annual *EI* and the 2-yr 6-hr rainfall.
b. The development of a snowmelt equivalent *R* factor.
c. The development of suitable *LS* values for long, steep slopes (i.e., lengths greater than 300 ft, and steepnesses greater than 5:1 (20 perecnt)).
d. The development of reliable soil erodibility values for highway fill slopes and compacted cut slopes, especially on heavy textured soils.
e. The testing of the effect of vegetative and mulching erosion control measures commonly used on highway construction sites on a variety of soil types. This research should test the effect of straw mulch anchoring tools on different soils; also, the effect of spacing between the anchoring blades should be determined. Straw mulch tacking also should be evaluated. Other mulch materials should be tested as well.
   Agronomic research to match plant species with newly constructed environments is badly needed in some states. All vegetative controls need to be rigorously tested on long, steep slopes to determine what changes occur in *VM* factor values with increasing length or steepness. These suggestions are not exhaustive.
f. The development of techniques for predicting gully erosion.
g. The determination of the efficiencies of small- and medium-sized sediment traps.
h. The development of technical guides for determining allowable off-site soil losses and allowable increases in turbidity of nearby water courses.

2. A computer program for use in highway design offices should be developed. The program suggested would be based on the soil erosion equations and not on the meager data presently available. It would be used to optimize slope angle and length combinations, types of vegetative and mechanical measures and their extents and timing, distances between erosion control structures, and all else necessary to enable the design of any given project for minimum erosion. It would be used also for defining future data collection requirements for efficient erosion control. Such a research study would be a natural successor of the current projects and would use information and techniques developed thereon.

3. Additional testing of erosion control products should be undertaken to provide the user with reliable information on their effectiveness under various conditions. At present, performance claims are made by individual companies or salesmen, often without substantiation. The researchers are aware of limited tests that have been made at various locations of erosion control products, including those undertaken by state highway and transportation departments and included in the AASHTO-FHWA document, "Special Products Evaluation List," dated August 1974. All of these are incomplete and make it difficult to compare the effectiveness of one product against another for a particular use.

To accelerate the testing of erosion control products and to assure uniformity throughout, many of the measurements should be made indoors using a rainfall simulator, an adjustable test bed, and controlled laboratory conditions. Each product could be tested all the way to failure under the same conditions of soil, slope, rainfall, etc.; and everything could be completed in the laboratory in a much shorter time span than in the open, waiting for natural rainfall to occur. The most effective products could then undergo final testing in the field under natural conditions. Testing of products in the laboratory by the UWRL is a beginning, but sufficient replications should be made of each product test so that some statistical significance in the results is obtained.

4. Additional research is needed to determine the accelerating effect of wind on erosion on steep slopes that face the dominant wind direction. This acceleration is known as the windward knoll effect, and the knoll erodibility factor, I_s, is used to correct the soil wind erodibility index, *I*, for this exposure.

Published information includes values only up to 10 percent slopes, and these should be extended to include steeper slopes.

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APPENDIX A

SUMMARY OF FIELD SITE VISITS

Members of the project staff made on-site visits to highway construction projects in 32 states to view temporary erosion control measures and to interview experienced individuals at each location as to the effectiveness of various measures used. Repeat visits were made to particular projects in 5 states. The selection of states to visit was made on the basis of their being representative of the different climates and soil areas of the 48 contiguous states. The ad hoc committee appointed to Project 16-3 determined that site visits would not be made to Alaska, Puerto Rico, or the Hawaiian Islands. In some instances the decision to visit a specific site was made because it was known that a particularly good job was being done there in the use of temporary erosion control measures; or that special erosion and/or sedimentation problems existed there; or that an individual specializing in temporary erosion control measures was working there. Because the project did not provide for the generation of any new research data, it was important to include visits to as many on-going construction projects as possible as well as interviews with recognized erosion control experts from throughout the country.

Visits were made to highway construction projects in each of the states listed in Table A-1, and second visits were made to those indicated. In every instance, the initial contact was the state Transportation Research Board representative. He, in turn, recommended the individuals to be contacted for arranging the visit. These individuals selected the specific construction sites, arranged for knowledgeable people to accompany Project 16-3 personnel, and provided necessary transportation. In every case complete cooperation and assistance were provided by the state highway department, and their help and suggestions were sincerely appreciated.

TABLE A-1
STATES VISITED FOR INTERVIEWS

Alabama	Missouri
Arizona	Montana
California[1]	New Hampshire
Colorado	New Mexico
Connecticut	New York
Florida	North Carolina
Georgia[1]	North Dakota
Illinois	Oklahoma
Indiana	Pennsylvania[1]
Iowa[1]	Tennessee
Louisiana	Texas
Maryland[1]	Utah
Massachusetts	Vermont
Michigan	Washington
Minnesota	West Virginia
Mississippi	Wyoming

[1]Visited twice.

One of the original intents of site visits was to measure actual erosion occurring on particular slopes, for which precipitation data were available, and then to compare these amounts with those calculated for the same slopes, using the water soil loss equation. This part of the study could not be pursued extensively because of the nonavailability of on-site precipitation data in most of the areas visited. On those sites where data were available a fair correlation existed between the calculated and measured values.

On some construction projects, measurements were made of actual erosion amounts, specific soil samples were analyzed to determine their erodibilities, and calculations were made of predicted erosion using rainfall data from nearby weather stations. These tests were not satisfactory because of the temporal and spatial variability existing in natural rainfall. Erosion and precipitation measurements must be made at the same site to be of value.

Another difficulty encountered in making erosion measurements was in finding where the material was deposited so that the measurements taken on slopes could be verified. At only two locations was it possible to measure the erosion that had occurred on a slope and then go downslope and measure the deposited material that had originated on that particular slope.

The primary values of the field trips are the following:

1. They provided first-hand information to project personnel of the kinds of erosion control measures that are being used throughout the United States.
2. They enabled interviews to be conducted with erosion control experts throughout the country and with others who are working in the field to solve erosion control problems. Ideas and suggestions put forth by those individuals have been incorporated into the manual and will upgrade erosion control efforts everywhere.
3. During the course of the field visits and interviews, many papers, reports, and publications have been discovered and included in the list of references and bibliography of the final report and manual, which probably could not have been included otherwise.
4. The visits and interviews verified the fact that there is a great sparcity of quantitative data relating to erosion on construction sites and particularly on highways where steep slopes are encountered. Much could and should be done to provide these kinds of data.
5. Many of the available data pertaining to the effectiveness of various erosion control measures were found to be very site-specific and are often not valid at other locations, even under similar conditions. For this reason Project 16-3 has devised and presented in detail in the manual a different method of expressing effectiveness that is more universally applicable.

APPENDIX B

SAMPLING OF QUESTIONS AND ANSWERS TO QUESTIONNAIRES

QUESTIONNAIRES

Soon after the initiation of the project a questionnaire was prepared and mailed to agencies and individuals in the 50 states and Puerto Rico, requesting information from them concerning erosion control activities in their particular areas. Table B-1 indicates where the questionnaires were sent and the number of responses received. At least one completed questionnaire was received from every state and Puerto Rico, and only one of the 52 highway departments contacted failed to respond at all.

The following are representative of answers received to

TABLE B-1
QUESTIONNAIRES AND RESPONSES

Recipient of Questionnaires	Questionnaires Sent	Replies Received	Percentage Response
State Highway Departments	110	95	86
Special Interest Groups	10	3	30
Regional Forestry Offices	10	6	60
Bureau of Land Management	12	5	42
Corps of Engineers	37	13	35
Soil Conservation Service	52	41	79
U.S. Bureau of Reclamation	7	5	71
Associated General Contractors	68	9	13
TOTAL	306	177	58

some of the general interest type questions that were included in the questionnaire:

Question: Do you feel that additional legislation is necessary in your state for controlling erosion? If so, what kind?

Answers:

1. There is a need to require that erosion potential hazards be made an integral part of the Land Use Plan for planning purposes. Some areas should not be considered for transportation routes.
2. There is a need for more uniform specifications.
3. Structures and other improvements including vegetation need to be cost-shared or made reimbursable to the lessee of state-owned lands, also erosion control or disturbed areas of surface-mined land.
4. Supplemental legislation is needed to make enforcement of existing legislation more timely and responsible to needs.
5. Sediment and erosion control is needed for commercial, industrial, residential, recreational, and governmental construction sites.
6. We need regulations to control sediments in subdivisions, shopping centers, etc., and in all road construction, not just that which is federally financed.
7. We need to establish regulatory functions over individuals and agencies.
8. We need statewide erosion control standards in dealing with land. Also needed are means of enforcing legislation.
9. The Sedimentation Pollution Control Act should include also agriculture, forestry, and impoundments.
10. Need to increase the quality of control and need also to control the quantity of sediment that is produced at a particular site.
11. Need more controls for strip mining.
12. Need to minimize the time that soil can be exposed and that sediment can be entrapped.

Question: Do you use the Universal Soil Loss Equation to estimate potential erosion from highway construction sites? If not, what do you use?

Answer:

1. Twenty-one of the states indicated they are using the Universal Soil Loss Equation in whole or in part. The remainder either do not try to estimate erosion or they base their estimates on things such as Musgrave's equation or their own professional experiences.

Question: In your state, is any training related to erosion control being provided for state employees and/or construction personnel? Who is invited to attend and who conducts the training?

Answers:

1. Training sessions are given for design and material engineers. Engineers, landscape architects, and maintenance specialists attend lectures and seminars from time to time that are sponsored by the University, the Soil Conservation Service, and the Agricultural Extension Service.
2. All Forest Service inspectors certified for earthwork inspection receive some training in erosion control. Courses are conducted (1) in-service by Forest Service materials and construction engineers and (2) out-of-service by technical institutes or universities under contract with the Forest Service.

3. Yes, formal training programs are under contract to inform and involve various levels of construction personnel in environmental awareness, i.e., erosion control.
4. Yes, technical training pertaining to erosion control and turf establishment makes up one of our training modules at our Highway Construction Workshop.
5. Training sessions are provided by FHWA and the state for design and construction personnel.
6. Two sessions are conducted annually by the construction division and another is conducted by instructors selected by the Construction Division, Material Section, and training supervisor for grading inspectors, design engineers, project engineers, and resident engineers.
7. Training sessions are conducted by the State Highway Department for construction personnel.
8. Sessions are provided on an irregular basis for designers. In-house training is provided during the winter for field personnel.
9. Training is available for all Soil Conservation Service employees, and for others who may be interested, beginning 1974.
10. Members of the Erosion and Sedimentation Task Force conduct training for designers and construction inspection personnel.
11. We regularly show erosion control films to our personnel.
12. Construction Standards Engineers provide training for Assistant District Engineers, Construction District State Aid Engineers. Training is sponsored by ASCE and conducted by the university.
13. Training meetings are held during the winter months to instruct inspectors on up-to-date methods of controlling erosion. This meeting is usually conducted by the Area Landscape Engineer with assistance from the State Office.
14. Short training courses are provided by the state, university, and all federal agencies; local governments and private companies are invited to attend and participate.
15. Monthly meetings and a yearly seminar are conducted for our district construction engineers where erosion and pollution control are usually discussed. Each district is required to include this subject in its winter training seminar for project engineers/supervisors and other key construction personnel.

Question: Do you feel that overall construction costs have been or will be increased by employing erosion control measures during construction? If so, approximately how much?

Answers:

1. We believe the overall cost will increase since the contractor must maintain almost continuous dressing and grassing crews because we require this work to be done now in stages.
2. No overall increase anticipated.
3. We anticipate an overall increase of 10 percent.
4. Seven to ten percent increase.
5. Three to five percent increase.
6. Yes, the overall construction costs will increase by employing any erosion control measures during construction.
7. If there is an increase, it will be less than 5 percent.
8. Good planning will prevent increased cost.
9. Construction costs will increase from 5 to 10 percent, but overall project costs will decrease in view of possible damage suits.
10. It is our estimate that the full requirements of OSHA and EPA will increase normal construction costs by 20 to 25 percent.
11. On the first few projects the contractor reacts to "something new" by bidding very high. Later as experience is gained in applying erosion control measures during construction, he bids at a normal or no increase cost. However, the most unique situation occurs when experience shows the contractor that the environmental protection provisions actually reduce overall costs, i.e., early stabilization of slopes through temporary grassing reduces shoulder reworking, and he saves.
12. Approximately 1 percent.
13. The cost of erosion control and turf establishment has gone from a range of $243-$411-$800 per acre in 1968 to an average of $594 per acre in 1973. We figure that our concept of "grade-a-mile/grass-a-mile" has added approximately $130 per acre to our turf establishment prices.
14. Very minimal increase. Contractors are aware that erosion control measures reduce finishing costs.
15. Two to five percent on grade and drain projects.
16. Depends on contractor.
17. Yes, definitely, by approximately 2 percent of overall project construction costs.
18. Not increased unless temporary measures are used unnecessarily.
19. The addition of temporary erosion control items in the proposals has increased the total awarded contract prices about one-tenth of one percent.
20. Yes, greatly!
21. It is estimated that we can expect construction costs to increase by one-fourth to one-third when a full program is initiated. This

increase in cost would include additional personnel, training, and more stringent demands taken in the location, survey, and design phases.

22. Yes, from one-fourth to one-half of one percent.
23. From 0 to 10 percent.
24. Minimal.
25. On bids, an increase of from 10 to 15 percent, but to the contractor only 2 to 3 percent.
26. From 10 to 13 percent.
27. From 10 to 25 percent.

Most of the remaining answers stated there would be a slight increase, but no indication as to how much.

APPENDIX C

RAINFALL SIMULATOR AND TEST OF USLE

RAINFALL SIMULATOR

The rainfall simulator is a drip-type device in which individual raindrops are formed by water emitting from the ends of small-diameter brass tubes. The rate of flow is controlled by admitting water into a manifold chamber through fixed orifice plates under constant hydraulic pressure. Five separate inlet orifices are used in each chamber or module. The ratios of the areas of orifices are 1:2:4:8:16. By controlling the flow to the orifice with an electrically operated solenoid valve it is possible to vary flow in on-off increments with 31 equal steps. Outlet from the chambers or modules is through uniform equally spaced brass tubes. Each module is a 24 in. square box about 1 in. deep and oriented so that the tubes or needles form a horizontal level plane from which the water drips. Each module contains 672 needles spaced on a 1-in. triangular grid pattern. The simulator is shown in Figures C-1, C-2, and C-3 and has been fully described by Chen (PRWG106-2, Utah Water Research Laboratory, Utah State University, Logan, Utah (1975) 56 pp.—an urban storm runoff inlet hydrograph study; also laboratory studies of the resistance coefficient for sheet flow over natural turf surfaces).

The rainfall simulator consists of 100 modules spaced and supported to form a square horizontal surface containing 400 ft^2. Each module has separate controls so that a spatially moving storm with time-changing intensities can be simulated. Its 500 control switches are operated manually or by a programmed computer, as desired.

Raindrop sizes and velocities of impact represent the energy of typical high intensity storms. The spatial distribution of rainfall is essentially uniform and the control of application rates is within the accuracy requirement of most experiments.

Tilting Flume

The tilting flume or test bed is positioned directly beneath the rainfall simulator, and both units are located inside the laboratory. The flume is square, measuring 20 ft on a side, and contains a 1-ft thick layer of soil. Hydraulic hoists beneath the flume enable it to be tilted to any angle up to about 43° from horizontal. The flume is designed with a vacuum chamber beneath the soil to aid infiltration, and flowing water can be maintained over the top of the soil in addition to the rainfall from the simulator.

Calibration of Rainfall Simulator

The calibration of the rainfall simulator was done in an indirect manner for convenience and control. This was carried out by first calibrating two tipping bucket raingages against weighing raingages which had been calibrated with weights. The tipping bucket gages recorded remotely on an event recorder located beside the rainfall simulator control panel, so any change in intensity during a run could be immediately recognized by the operator. The following equation represents the actual rainfall in inches per hour for each apparent intensity on the tipping bucket gage:

$$Y = 0.73497\, X^{1.19832} \qquad \text{(C-1)}$$

in which Y = true rainfall intensity; and X = intensity indicated on tipping bucket gage. The confidence band is ±0.59.

The intensity read from Eq. C-1 in conjunction with drop size and fall distance is used to determine $EI/100$ or the value called R in the universal soil loss equation (USLE).

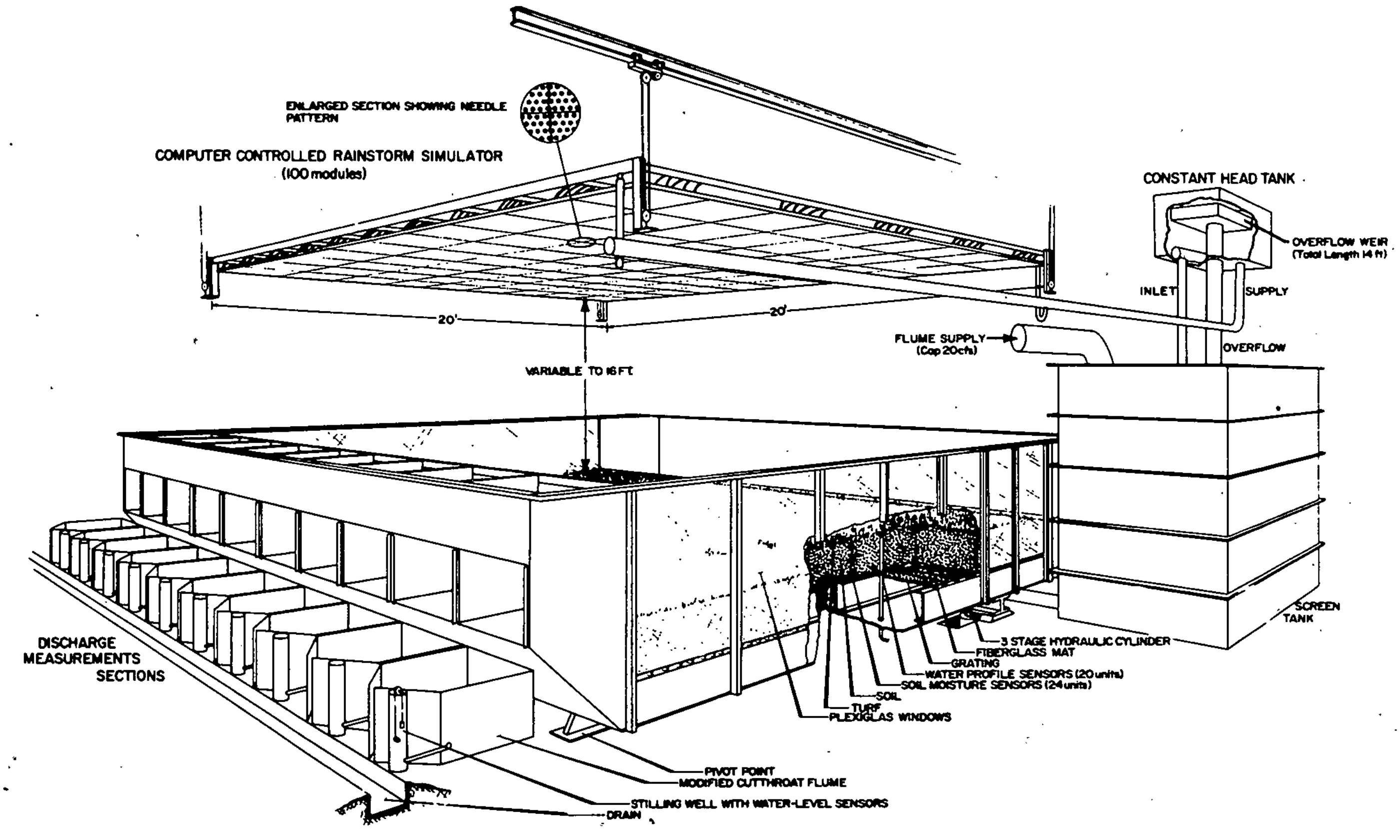

Figure C-1. Computer-controlled rainstorm simulator with tilting flume.

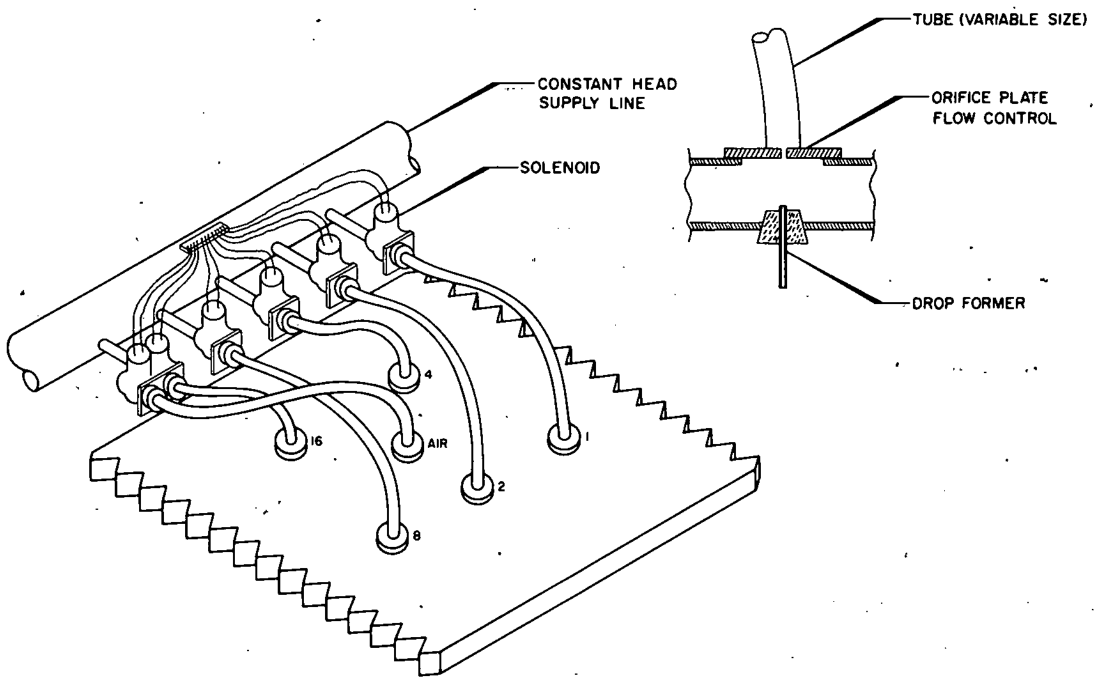

Figure C-2. Typical rainstorm simulator module.

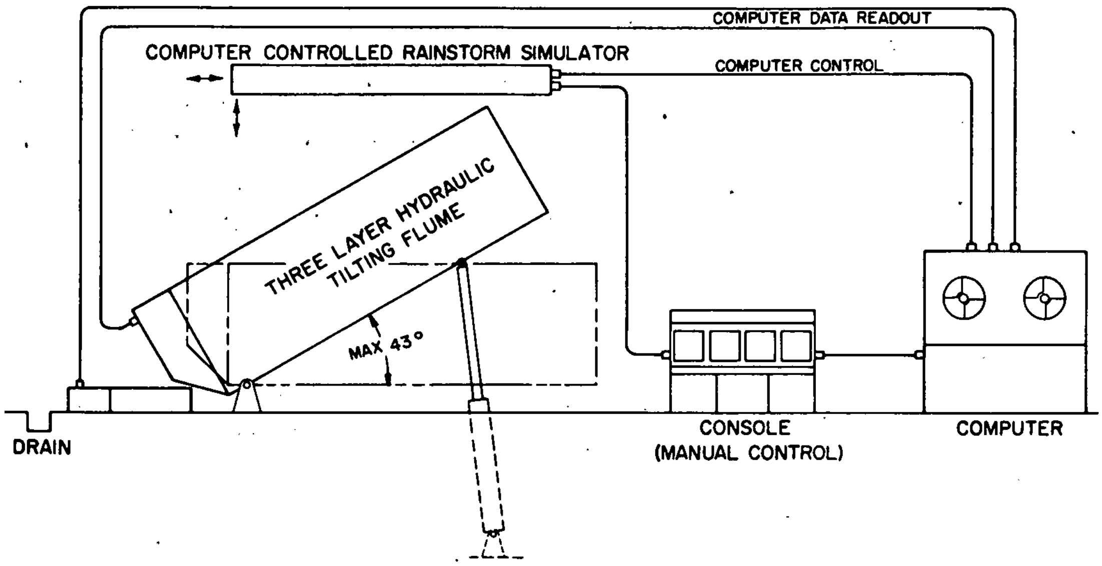

Figure C-3. Block diagram of stormflow experimentation system.

Energy of Drops

Drop sizes delivered by the rainfall simulator were determined by measuring the volumes of replicates of 10 drops each. The drop diameter as determined in this manner was 4.0 mm, which is slightly larger than the mean drop diameter of natural rainfall.

The heights of fall from the simulator were all somewhat less than required for the drops to reach terminal velocity. Also, the fall heights were variable according to the slope steepness. When the test bed is tilted to the desired slope, its upper edge is closer to the horizontal rainfall simulator than is the lower edge, so that raindrop fall distance increases with distance down the slope, and is different for each slope. It was necessary to carefully measure the fall distance for the drops at each slope setting of the test plots, and from this distance to calculate the velocity of the drops on their impact with the soil. The experimental values published by Laws (*C-1*) for 4-mm drops at different fall distances were used to determine this velocity for each bed slope used. This relationship is:

$$V = 16.00204 \log H + 5.49695 \qquad \text{(C-2)}$$

in which:

V = velocity, ft per sec; and
H = fall height, ft.

Individual values are converted to energy by the relationship

$$E = 1.76082\, V^2 \qquad \text{(C-3)}$$

in which:

E = rainfall impact energy, ft tons/acre in.; and
V = velocity, ft per sec.

E values at the top and bottom of each test plot were averaged to obtain the mean E for the plot.

Values of $EI/100$ were calculated for each slope, rainfall intensity, and duration. These R values are somewhat lower than those for the same mean drop size in natural rain because of the lesser fall height under the simulator. On the other hand, the simulated rain consists of drops that are slightly larger than the average for natural rain, and thus the impact energies are slightly greater as well, making the over-all simulated effect very nearly the same as natural rain. Table C-1 shows a comparison on a 9 percent slope of energy values obtained with the UWRL rainfall simulator with those obtained by other methods.

TEST OF UNIVERSAL SOIL LOSS EQUATION

The USLE was developed on relatively flat slopes, and few reliable data for evaluating its accuracy exist for slopes greater than about 20 percent. One of the objectives of the present research was to test the equation for steeper slopes using the UWRL erosion control testing facility.

The universal soil loss equation as proposed by Wischmeier and Smith (*C-2, C-3*) and modified for this study can be expressed by the relationship

$$A = R \cdot K \cdot LS \cdot VM \qquad \text{(C-4)}$$

in which:

A = soil loss, tons/acre;
R = a rainfall factor ($R = (EI/100)$ mean annual value);
K = soil erodibility factor (ratio);
LS = slope length steepness factor or topographic factor; and
VM = erosion control factor (ratio).

In the field, the only parts of Eq. C-4 which are manageable are *LS* and *VM*. Wischmeier and Smith (*C-3*) developed and tested Eq. C-4 and found that the topographic factor could be expressed by

$$LS = \left(\frac{l}{72.6}\right)^m \left(\frac{65.41\, s^2}{s + 10{,}000} + \frac{4.56\, s}{\sqrt{s^2 + 10{,}000}} + 0.065\right) \qquad \text{(C-5)}$$

in which:

LS = topographic factor;
s = slope gradient, percent;
l = slope length, ft; and
m = exponent depending on slope steepness (0.2 for slopes <1%, 0.3 for slopes 1-3 percent, 0.4 for slopes 3.5-4.5 percent, and 0.5 for slopes >5 percent).

The erosion control factor *VM* accounts for the effects of all erosion control measures that may be implemented on any particular site, including vegetation, mechanical manipulation of the soil surface, and chemical treatments. A partial listing of *VM* values is given in Table 2-2 (Chap. 2 of the manual).

Testing Procedures

Assuming that the universal soil loss equation is valid as used by Wischmeier and Smith (*C-2, C-3*), then $A = R \cdot K \cdot LS \cdot VM$ and $K \cdot VM = A/R \cdot LS$ should be independent of slope. In order to test this hypothesis $K \cdot VM$ values were measured for four soil conditions, four slopes, and three rainfall intensities.

The tilting flume was divided into test plots each one 19.5 ft long and approximately 4 ft wide, separated from the others and from the flume sidewalls by 2-ft-wide buffer strips. The plots were filled with three different soils as follows: (1) a washed sand commercially available in Logan, Utah; (2) Nibley silty clay loam from North Logan, Utah; (3) Cecil gravelly clay loam from Watkinsville, Georgia Experiment Station of U.S. Department of Agriculture and University of Georgia; and (4) the same Nibley soil as (2) except it was compacted and not tilled. The first three soils

TABLE C-1

VALUES OF KINETIC ENERGY, *E*, OBTAINED BY THREE DIFFERENT METHODS

Rainfall Duration (minutes)	Rainfall Intensity (in/hr)	E (ft tons/acre inch)						
		Wischmeier	McGregor-Mutchler	UWRL				
				0% slope	9% slope	25% slope	50% slope	84% slope
30	2.51	1310	1322	1294	1248	1160	819	651
15	3.95	1102	1083	1018	982	913	809	643
8	7.65	1233	1056	1051	1014	943	835	664

were tilled up and down the slopes to simulate the treatment defined by Wischmeier and Smith (*C-2*) as having a C value of 1.0. Number 4 was not tilled except when soil was replaced and then it was recompacted as originally.

After the soil had been prepared, the plots were tilted to the desired slope and rain was applied. Runoff from each plot was split, and 1/12 was caught in a polypropylene bottle. The sediment in each was separated from the water, dried and weighed. The aliquot weight was multiplied back to the original erosion rate and divided by the plot area to obtain the A value for the universal soil loss equation in tons per acre. (All areas considered were measured on the slope, and are not the slope areas projected to a horizontal plane.)

Results and Discussion

Table C-2 gives the rainfall and test plot characteristics, the soil lost in tons per acre, and the computed $K \cdot VM$ values for each plot and run. The $K \cdot VM$ values for the 9 percent slope are not significantly different from those for the steeper slopes, indicating that the universal soil loss equation is equally valid for all slopes.

Figure C-4 shows curves of topographic factor LS plotted against slope gradients in percent. LS values shown as crosses are those measured for the various slopes in the UWRL test plots. LS values shown as circles are those computed for various slopes using the USLE Eq. C-5 (Wischmeier and Smith, *C-3*). Figure C-4 provides further indication that the universal soil loss equation is valid also for steep slopes.

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C-3 WISCHMEIER, W. H., and SMITH, D. D., "Predicting Rainfall Erosion Losses—a Guide to Conservation Planning." *USDA Agric. Handbook 537* (1978).

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TABLE C-2

PLOT AND RAINFALL CHARACTERISTICS, SOIL LOSS, AND $K \cdot VM$ FOR RUNS TESTING USLE

Percent Slope	Rain Intensity in/hr	Rain Duration minutes	R·LS on Plot	Tilled for Each Rain A = R·K·LS·VM (Tons/Acre)				$K \cdot VM = \frac{A}{R \cdot LS}$			
				Sand	Nibley	Cecil	Nibley (Not Tilled)	Sand	Nibley	Cecil	Nibley (Not Tilled)
9	2.51	30	16.29	0.00163	0.02169	0.07502	0.06838	0.00010	0.00133	0.00461	0.00420
9	3.95	15	10.08	0.00163	0.40635	0.15614	0.19172	0.00016	0.04031	0.02902	0.01902
9	7.65	8	10.75	0.00163	0.90696	0.17565	0.11001	0.00015	0.08437	0.03055	0.01023
25	2.51	30	75.71	0.00081	0.04926	0.14024	0.04163	0.00001	0.00065	0.00185	0.00054
25	3.95	15	46.88	0.00081	0.41383	0.44436	0.49214	0.00002	0.00882	0.00949	0.01050
25	7.65	10	50.02	0.00081	1.06294	0.78068	4.51493[a]	0.00002	0.02125	0.01567	0.09026
50	2.51	30	203.04	0.00163	0.32292	0.95062	5.78311	0.000001	0.00159	0.00468	0.02848
50	3.95	15	125.76	0.00489	0.12094	2.04497	2.80682	0.00004	0.00096	0.01626	0.02232
50	7.65	10	134.03	0.08146	0.15605	0.38546	5.66263	0.00061	0.00116	0.00288	0.04225
84	2.51	30	319.55	0.00081	4.30263	2.14862	6.87730	0.000002	0.01346	0.00672	0.02152
84	3.95	15	197.87	0.00163	5.18789	1.89246	3.49365	0.000008	0.02622	0.00956	0.01766
84	7.65	10	211.11	0.00899	4.76652	2.44047	8.37585	0.000042	0.02258	0.01156	0.03968

[a]This value not included in the analyses.

Note: Differences in K·VM values at 9% slope and steeper slopes are not significant as tested by "Students" t test and Brandts unique sample test.

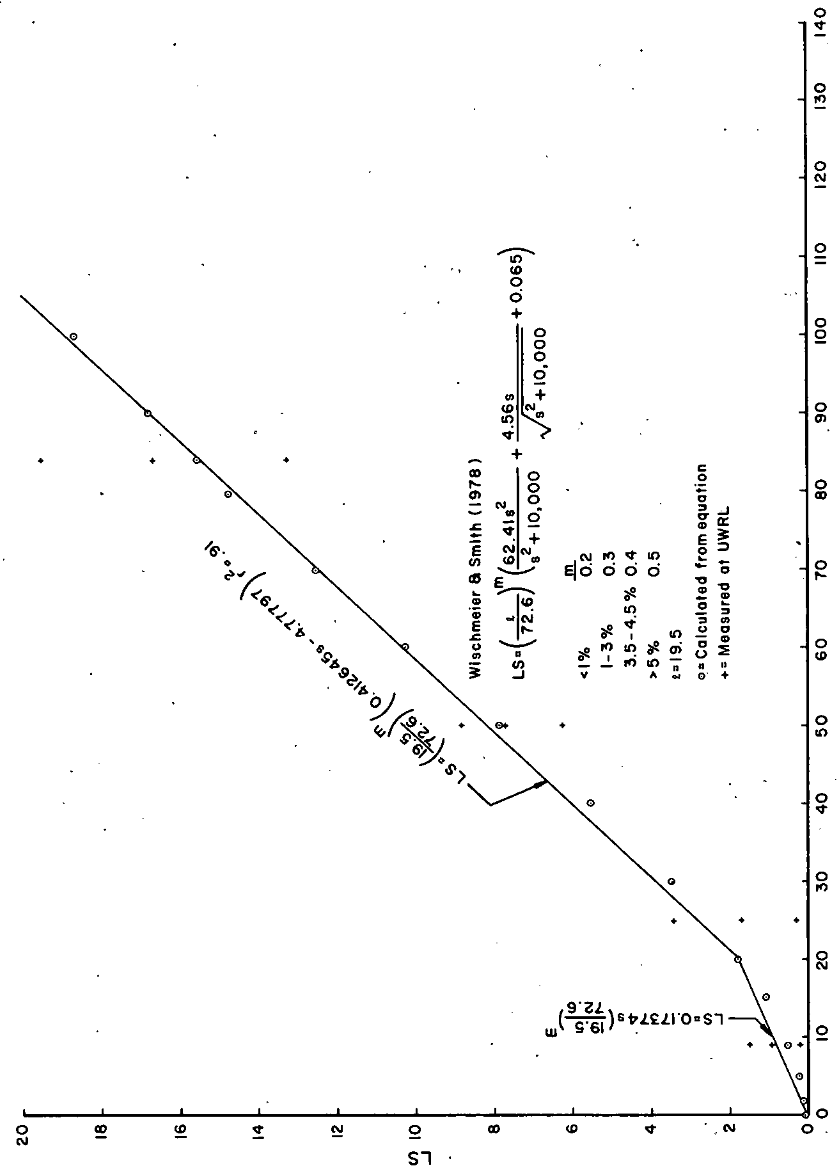

Figure C-4. Topographic factor LS vs. slope gradient in percent.

APPENDIX D

EROSION CONTROL PRODUCT TESTING

INTRODUCTION

In preparation for the testing of erosion control products the 20-ft by 20-ft test bed described in Appendix C was partitioned into three separate plots with walkways between them and filled with a Nibley silt loam soil. Each plot was 4 ft wide and 19.5 ft long, and the walkways were 2 ft wide. Each product was applied according to the manufacturer's recommendation while the test bed was in a horizontal position. Then it was tilted to a 2:1 slope before rainfall was applied. Each test was run and timed until a visible incipient failure of the plot surface occurred and/or significant amounts of sediment began running from the plot, and it was allowed to continue until rills formed. After each test, soil loss was made up with fresh soil and the plot was smoothed ready for the next application. Recording raingages were used beneath the simulator to verify rainfall rates.

TABLE D-1
PRODUCT TEST RESULTS

Run #	Control Product	Product Cost[a]	Application Rate	Finished Condition	Cost Per Acre[b]	Rainfall Rate	Time Until Incipient Failure	Time Until Formation of Rills
1.	Straw	$25/ton	2 tons/acre	Punched in	$ 50	8 in/hr	10 min 5 sec	10 min 5 sec
2.	Straw	$25/ton	2 tons/acre	Punched in	$ 50	16 in/hr	10 min 12 sec	10 min 12 sec
3.	Straw	$25/ton	2 tons/acre	Punched in	$ 50	24 in/hr	7 min 30 sec	7 min 30 sec
4.	Straw	$25/ton	2 tons/acre	Disked with slope	$ 50	24 in/hr	1 min 10 sec	7 min 0 sec
5.	Straw	$25/ton	2 tons/acre	Disked across slope	$ 50	24 in/hr	3 min 38 sec	5 min 30 sec
6.	Straw Tackifier 1	$25/ton **$2.50/gal	2 tons/acre 40 gals/acre	Tacked & punched	$150	24 in/hr	No failure within 3 hrs	No failure within 3 hrs
7.	Straw Asphalt	$25/ton $0.10/gal	2 tons/acre 300 gals/acre	Tacked	$ 80	24 in/hr	No failure within 3 hrs	No failure within 3 hrs
8.	Straw Wood Fiber 1 Tackifier 2	$25/ton 185/ton *1.25/lb	2 tons/acre 400 lbs/acre 150 lbs/acre	Tacked	$275	24 in/hr	No failure within 3 hrs	No failure within 3 hrs
9.	Wood Fiber 1 Tackifier 2	$185/ton *1.25/lb	1500 lbs/acre 120 lbs/acre	Tacked	$289	8 in/hr	4 min 0 sec	8 min 15 sec
10.	Wood Fiber 2 Tackifier 3	$200/ton *3.75/lb	1500 lbs/acre 40 lbs/acre	Tacked	$300	8 in/hr	2 min 25 sec	2 min 25 sec
11.	Wood Fiber 2 Tackifier 4	$200/ton *3.79/gal	1200 lbs/acre 100 gals/acre	Tacked	$499	8 in/hr	2 min 8 sec	8 min 15 sec
12.	Tackifier 5 Wood Fiber 2	**$0.80/gal 200/ton	80 gals/acre 2000 lbs/acre	Tacked	$264	8 in/hr	4 min 0 sec	4 min 0 sec
13.	Tackifier 6 Wood Fiber 2	**$1.20/gal 200/ton	80 gals/acre 2000 lbs/acre	Tacked	$296	8 in/hr	2 min 30 sec	3 min 0 sec
14.	Tackifier 1 Wood Fiber 2	**$2.50/gal 200/ton	80 gals/acre 2000 lbs/acre	Tacked	$400	8 in/hr	4 min 40 sec	6 min 0 sec
15.	Tackifier 1 Wood Fiber 2	**$2.50/gal 200/ton	40 gals/acre 2000 lbs/acre	Tacked	$300	8 in/hr	5 min 40 sec	9 min 0 sec
16.[c]	Wood Fiber 2 Tackifier 5	$200/ton **0.80/gal	2000 lbs/acre 726 gals/acre	Tacked	$781	8 in/hr 24 in/hr	No failure within 32 min	33 min 30 sec
17.	Wood Fiber 2	$200/ton	2000 lbs/acre	Loose	$200	8 in/hr	3 min 45 sec	3 min 45 sec
18.	Wood Fiber 1 Tackifier 7	$185/ton *3.58/gal	400 lbs/acre 150 gals/acre	Tacked	$574	8 in/hr	2 min 38 sec	3 min 10 sec
19.	Wood Chips	$10/ton	9 tons/acre	Loose	$ 90	8 in/hr	48 sec	9 min 44 sec
20.	Wood Chips Tackifier 1	$10/ton **$2.50/gal	9 tons/acre 80 gals/acre	Tacked	$290	24 in/hr	31 min 0 sec	40 min 0 sec
21.	Wood Chips Tackifier 1	$10/ton **$2.50/gal	9 tons/acre 120 gals/acre	Tacked	$390	24 in/hr	1 hr. 37 min	1 hr. 37 min
22.	Shredded Paper Tackifier 1	$9.00/cwt **$2.50/gal	2200 lbs/acre 40 gal/acre	Tacked	$298	24 in/hr	1 min 3 sec	1 min 3 sec
23.	Crushed Stone	$2/ton	238 tons/acre	Loose	$476	24 in/hr	No failure within 3 hrs	No failure within 3 hrs
24.	Asphalt	$0.10/gal	600 gals/acre	Bare soil	$ 60	8 in/hr	3 min 58 sec	4 min 0 sec
25.	Portland Cement Tackifier 8	$60/ton 8/gal	545 lbs/acre 14 gals/acre	Bare soil	$128	8 in/hr	2 min 20 sec	3 min 20 sec
26.	Portland Cement Tackifier 8	$60/ton 8/gal	1090 lbs/acre 28 gals/acre	Bare soil	$257	8 in/hr	7 min 30 sec	8 min 30 sec
27.	Portland Cement Tackifier 8	$60/ton 8/gal	1635 lbs/acre 42 gals/acre	Bare soil	$385	8 in/hr	11 min 0 sec	16 min 20 sec
28.	Tackifier 1	**$2.50/gal	40 gals/acre	Bare soil	$100	8 in/hr	1 min 30 sec	1 min 30 sec
29.	Tackifier 5	**$0.80/gal	726 gals/acre	Bare soil	$581	8 in/hr	5 min 45 sec	5 min 45 sec
30.	Tackifier 6	**$1.20/gal	726 gals/acre	Bare soil	$871	8 in/hr	2 min 30 sec	2 min 30 sec
31.	Asphalt	$0.10/gal	1200 gal/acre	Bare soil	$120	8 in/hr	4 min 0 sec	4 min 30 sec

[a] These are costs of products delivered to Logan, Utah, unless identified with asterisks. Single asterisk indicates cost at site of manufacturer. Double asterisk indicates product is experimental and cost figure is only approximate.

[b] These figures do not include application costs.

[c] After 32 min at 8"/hr. the rate was increased to 24"/hr.

TEST RESULTS

A summary of the tests performed and their results is given in Table D-1. The order of appearance of a product in the table does not indicate its effectiveness in controlling erosion in relation to other products in the table, but it is simply the order in which the testing was done. Because no replications were made of any of the tests, it is not possible to rank the products in order of their effectiveness in controlling erosion. A brief description of the preparation of each test, its performance, and the end result are as follows.

Run 1

Slope: 50 percent
Plot area: 0.00158 acre
Product tested: straw-punched
Application rate of product: 2 tons/acre
Pretest soil conditions: packed
Precipitation intensity: 8 in./hr
Time to incipient failure: 10 min 5 sec
Time to formation of rills: 10 min 5 sec

Punching of the straw was accomplished by use of a three-pronged cultivator. With the straw covering the plot,

it was impossible to determine when rills were formed. Consequently, failure was assumed when a "significant" amount of sediment began leaving the bottom of the plot. At the end of the test, the straw was carefully removed, thus exposing some rills and pockets of erosion.

Run 2

Slope: 50 percent
Plot area: 0.00158 acre
Product tested: straw—punched
Application rate of product: 2 tons/acre
Pretest soil conditions: packed
Precipitation intensity: 16 in./hr
Time to incipient failure: 10 min 12 sec
Time to formation of rills: 10 min 12 sec

Comments are the same as for Run 1.

Run 3

Slope: 50 percent
Plot area: 0.00158 acre
Product tested: straw—punched
Application rate of product: 2 tons/acre
Pretest soil conditions: packed
Precipitation intensity: 24 in./hr
Time to incipient failure: 7 min 30 sec
Time to formation of rills: 7 min 30 sec

Comments are the same as for Run 1.

Run 4

Slope: 50 percent
Plot area: 0.00165 acre
Product tested: straw—disked down slope
Application rate of product: 2 tons/acre
Pretest soil conditions: packed
Precipitation intensity: 24 in./hr
Time to incipient failure: 1 min 10 sec
Time to formation of rills: 7 min 0 sec

The straw was "disked" into the soil in the direction of the slope. Disked rows were approximately 1-ft apart. Water quickly ran down the slight furrows made by the disk and carried sediment from the plot. Failure was assumed when a significant amount of soil had left.

Run 5

Slope: 50 percent
Plot area: 0.00165 acre
Product tested: straw—disked across slope
Application rate of product: 2 tons/acre
Pretest soil conditions: packed
Precipitation intensity: 24 in./hr
Time to incipient failure: 3 min 38 sec
Time to formation of rills: 5 min 30 sec

The straw was "disked" into the soil across the plot, normal to the slope. Rows were approximately 6 in. apart. Water gathered in the furrows until they overflowed, then ran in streamlets downslope. Failure came more slowly than in Run 4, but quicker than in Runs 1, 2, and 3.

Run 6

Slope: 50 percent
Plot area: 0.00158 acre
Product tested: straw—punched and tacked with tackifier 1
Application rate of product: straw = 2 tons/acre, tackifier 1 = 40 gal/acre
Pretest soil conditions: packed
Precipitation intensity: 24 in./hr
Time to incipient failure: None within 3 hr
Time to formation of rills: None within 3 hr

Straw was applied at the rate of 2 tons/acre and punched into the soil with a 3-pronged cultivator. The tackifier was mixed at the rate of 40 gal with 360 gal of water per acre, and a proportionate amount of this mix was applied to the straw on the test plot with a hand-operated sprayer. The prepared plot was allowed to dry for 24 hr before rain was applied.

After 3 hr of running time the rain was turned off and the straw carefully removed. No rills had formed except along the borders of the plot, and very small "pockets" of erosion were noted elsewhere.

Run 7

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: straw tacked with asphalt
Application rate of product: straw = 2 tons/acre, asphalt = 300 gal/acre
Pretest soil conditions: tilled
Precipitation intensity: 24 in./hr
Time to incipient failure: None within 3 hr
Time to formation of rills: None within 3 hr

Straw was applied at the rate of 2 tons/acre, then covered by an asphalt emulsion mixed at the rate of 300 gal/acre mixed with an equal amount of water. After the matt dried it appeared to be well bonded, and was still intact after 3 hr of 24-in./hr rainfall. When the straw was removed, there were a few pockets of erosion where the straw cover had been thin, but a negligible amount of sediment left the plot.

Run 8

Slope: 50 percent
Plot area: 0.00158 acre
Product tested: straw tacked with wood fiber 1 and tackifier 2
Application rate of product: straw = 2 tons/acre, wood fiber 1 = 400 lb/acre, tackifier 2 = 150 lb/acre
Pretest soil conditions: tilled
Precipitation intensity: 24 in./hr
Time to incipient failure: None within 3 hr
Time to formation of rills: None within 3 hr

Straw was applied at 2 tons/acre followed by a hydromulch application of 400 lb/acre of fiber, 150 lb/acre of tackifier, and 800 gal of water/acre. After drying for 48 hr, it was noted that the straw was dry and bonded strongly together. Precipitation was applied for 3 hr with

no failure of material observed. However, a small amount of sediment transport was detected during the initial period of the test and decreased with time. Posttest observations indicated that a small amount of erosion had taken place, resulting in pockets of soil being removed and formation of rills along the borders of the plots only. It was noted that the pockets of erosion were greater where the straw was less dense.

Run 9

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: wood fiber 1 tacked with tackifier 2
Application rate of product: wood fiber 1 = 1,500 lb/acre, tackifier 2 = 120 lb/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 4 min 0 sec
Time to formation of rills: 8 min 15 sec

The fiber was applied with a hydromulcher at a rate of 1,500 lb/acre. Next, a solution of 120 lb/acre of tackifier and 800 gal/acre of water was sprayed on the fiber. After 48 hr the fiber and soil were still damp. When precipitation had been applied for 5 min heavy sediment transport was observed, but definite rills did not form until 8 min 15 sec. Posttest observations indicated numerous pockets of erosion.

Run 10

Slope: 50 percent
Plot area: 0.00165 acre
Product tested: wood fiber 2 tacked with tackifier 3
Application rate of product: wood fiber 2 = 1,500 lb/acre, tackifier 3 = 40 lb/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 2 min 25 sec
Time to formation of rills: 2 min 25 sec

The tackifier, at a rate of 40 lb/acre, was mixed with 1,500 lb/acre of the fiber and 10 gal of water, and a proportionate amount of the mix was applied to the plot with a hydromulcher. After 48 hr the fiber and soil were still damp. When precipitation had been applied for 2 min and 25 sec massive failure occurred as evidenced by severe slumping of soil and material.

Run 11

Slope: 50 percent
Plot area: 0.00158 acre
Product tested: wood fiber 2 tacked with tackifier 4
Application rate of product: wood fiber 2 = 1,200 lb/acre, tackifier 4 = 100 gal/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 2 min 8 sec
Time to formation of rills: 8 min 15 sec

The fiber was applied with a hydromulcher at a rate of 1,200 lb/acre on bare soil. Next, one part of the tackifier (at a rate of 100 gal/acre) mixed with 6 parts of water was sprayed on the fiber using a hand-operated sprayer. After 48 hr the fiber and soil were still damp. When precipitation had been applied for 5 min, heavy sediment transport was observed, but definite rills did not form until 8 min 15 sec.

Run 12

Slope: 50 percent
Plot area: 0.00165 acre
Product tested: wood fiber 2 tacked with tackifier 5
Application rate of product: wood fiber 2 = 2,000 lb/acre, tackifier 5 = 80 gal/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 4 min 0 sec
Time to formation of rills: 4 min 0 sec

The fiber was applied at a rate of 2,000 lb/acre. The tackifier was mixed at a rate of 80 gal/acre with 720 gal of water/acre, and a proportionate amount was applied to the fiber on the plot. After 48 hr it was noted that the surface was damp but not sticky, with the fiber appearing to be bonded together. Noticeable amounts of sediment began leaving the plot after 4 min. Precipitation was allowed to run for 15 min; at this time substantial erosion had taken place creating numerous shallow rills.

Run 13

Slope: 50 percent
Plot area: 0.00158 acre
Product tested: wood fiber 2 tacked with tackifier 6
Application rate of product: wood fiber 2 = 2,000 lb/acre, tackifier 6 = 80 gal/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 2 min 30 sec
Time to formation of rills: 3 min 0 sec

The fiber was applied at a rate of 2,000 lb/acre. The tackifier was mixed at a rate of 80 gal/acre with 720 gal of water/acre, and a proportionate amount was applied to the fiber on the plot. After 48 hr the surface was still damp and somewhat sticky, with the fiber appearing to be bonded together. When precipitation had occurred for 3 min movement of fiber was detected and rills began to form. After 15 min substantial erosion had taken place creating numerous rills.

Run 14

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: wood fiber 2 tacked with tackifier 1
Application rate of product: wood fiber 2 = 2,000 lb/acre, tackifier 1 = 80 gal/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 4 min 40 sec
Time to formation of rills: 6 min 0 sec

The fiber was applied at a rate of 2,000 lb/acre. The tackifier was mixed at a rate of 80 gal/acre with 720 gal/acre of water. A proportionate amount of the mix was applied to the fiber on the plot. After 48 hr it was noted that the surface was damp and the fiber was strongly bonded together. When precipitation had fallen on the plot for 5 min and 5 sec, material was observed to begin slumping off the bottom allowing for substantial erosion by 6 min. Throughout the test, it was observed that the material failed in spots only, then these chunks of mulch flowed downslope, lodging against other chunks and creating small dams, thus impeding erosion. After 15 min substantial erosion had occurred and deep rills existed.

Run 15

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: wood fiber 2 tacked with tackifier 1
Application rate of product: wood fiber 2 = 2,000 lb/acre, tackifier 1 = 40 gal/acre
Pretest soil conditions: packed
Precipitation intensity: 8 in./hr
Time to incipient failure: 5 min 40 sec
Time to formation of rills: 9 min 0 sec

The fiber was applied at a rate of 2,000 lb/acre. The tackifier was mixed at a rate of 40 gal/acre with 320 gal of water/acre and applied to the fiber. Forty-eight hours of drying time were allowed before precipitation was applied. After 5 min and 40 sec the mulch began to slip off the plot. After 9 min small rills were evident at the bottom of the plot, which became larger with time. Substantial erosion developed by 10 min and 10 sec. At the end of the test it was noted that the mulch had been removed from the lower 20 percent of the slope.

Run 16

Slope: 50 percent
Plot area: 0.00165 acre
Product tested: wood fiber 2 tacked with tackifier 5
Application rate of product: wood fiber 2 = 2,000 lb/acre, tackifier 5 = 726 gal/acre
Pretest soil conditions: packed
Precipitation intensity: 8 in./hr and 24 in./hr
Time to incipient failure: None within 32 min
Time to formation of rills: 33 min 30 sec

The fiber was applied at the rate of 2,000 lb/acre. The tackifier was mixed at the rate of 1 part to 4 parts water and applied at ¾ gal/yd². After applying precipitation at 8 in./hr for 32 min, no noticeable sediment was detected in the runoff waters. At this time, the intensity was increased to 24 in./hr and after 1 min and 30 sec massive failure occurred with soil and mulch slumping off the lower portion of the plot.

Run 17

Slope: 50 percent
Plot area: 0.00158 acre
Product tested: wood fiber 2
Application rate of product: 2,000 lb/acre
Pretest soil conditions: packed
Precipitation intensity: 8 in./hr
Time to incipient failure: 3 min 45 sec
Time to formation of rills: 3 min 45 sec

Precipitation was applied to the plot after it had dried for a 48-hr period. A uniform density of cover on the plot is difficult to achieve, and it was in the lighter covered areas that failure began, and then progressed rapidly.

Run 18

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: wood fiber 1 tacked with tackifier 7
Application rate of product: wood fiber 1 = 400 lb/acre, tackifier 7 = 150 gal/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 2 min 38 sec
Time to formation of rills: 3 min 10 sec

A hydromulch solution mixed at the rate of 400 lb/acre of fiber, 150 gal/acre of tackifier, and 800 gal of water/acre was applied to bare soil. After 48 hr the fiber and soil still appeared damp. When precipitation had been applied for 3 min and 10 seconds rills began to form.

Run 19

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: wood chips—loose
Application rate of product: 9 tons/acre
Pretest soil conditions: packed
Precipitation intensity: 8 in./hr
Time to incipient failure: 48 sec
Time to formation of rills: 9 min 44 sec

The wood chips were formed by running spruce trees, which included large amounts of needles, through a chipper. During the test, distinct movement of the chips was evident prior to formation of rills.

Run 20

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: wood chips tacked with tackifier 1
Application rate of product: wood chips = 9 tons/acre, tackifier 1 = 80 gal/acre
Pretest soil conditions: packed
Precipitation intensity: 24 in./hr
Time to incipient failure: 31 min 0 sec
Time to formation of rills: 40 min 0 sec

The chips were applied at the rate of 9 tons/acre. The tackifier was mixed at the rate of 80 gal/acre with 720 gal of water/acre, and applied to the chips with a hand sprayer. The material was allowed to dry for 24 hr before rain was applied. There was not enough tack material to bind all the needles in the chips together, and they soon began to float away. After 31 min a significant amount of material began moving, and after 40 min rills began to form.

Run 21

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: wood chips tacked with tackifier 1
Application rate of product: wood chips = 9 tons/acre, tackifier 1 = 120 gal/acre
Pretest soil conditions: packed
Precipitation intensity: 24 in./hr
Time to incipient failure: 1 hr 37 min
Time to formation of rills: 1 hr 37 min

The chips were applied at the rate of 9 tons/acre. The tackifier was mixed at the rate of 120 gal/acre with 1080 gal of water/acre, and applied to the wood chips with a hand sprayer. The material was allowed to dry for 24 hr before rain was applied. It was noted that the chips tended to float downslope, then lodge against other chips forming small dams which slowed erosion. Eventually the soil and chips became saturated, and rills began to form after about 1 hr and 37 min of time had elapsed.

Run 22

Slope: 50 percent
Plot area: 0.00165 acre
Product tested: shredded paper tacked with tackifier 1
Application rate of product: shredded paper = 2200 lb/acre, tackifier 1 = 40 gal/acre
Pretest soil conditions: packed
Precipitation intensity: 24 in./hr
Time to incipient failure: 1 min 3 sec
Time to formation of rills: 1 min 3 sec

Paper mulch was applied at 2200 lb/acre. The tackifier was mixed at a rate of 40 gal/acre with 360 gal of water/acre, and applied to the shredded paper with a hand sprayer. The plot was subjected to a 24-hr drying period before application of precipitation. Failure occurred by a sudden movement of the paper and almost instantaneous formation of rills, which, in turn, led to substantial erosion.

Run 23

Slope: 50 percent
Plot area: 0.00158 acre
Product tested: crushed stone—loose
Application rate of product: 238 tons/acre
Pretest soil conditions: lightly tilled
Precipitation intensity: 24 in./hr
Time to incipient failure: None within 3 hr
Time to formation of rills: None within 3 hr

Crushed stone, which had been screened and consisted of a mixture of stone particles varying in size from 3/8 in. to 1½ in. diameter, was applied on bare soil at a rate of 238 tons/acre. After applying precipitation at 24 in./hr for 3 hr, no movement of the crushed stones occurred during this period.

Run 24

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: asphalt—bare soil
Application rate of product: 600 gal/acre
Pretest soil conditions: lightly tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 3 min. 58 sec.
Time to formation of rills: 4 min 0 sec

Asphalt was mixed at a rate of 600 gal/acre with an equal amount of water and applied to the soil with a sprayer. After 48 hr the soil and asphalt were still damp. Rills began to form almost immediately after the asphalt film failed.

Run 25

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: portland cement and tackifier 8
Application rate of product: portland cement = 545 lb/acre, tackifier 8 = 14 gal/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 2 min 20 sec
Time to formation of rills: 3 min 20 sec

Portland cement was mixed at the rate of 545 lb/acre with water and 14 gal/acre of tackifier 8, and then the mixture was applied to the freshly tilled soil and allowed to dry for 6 days. At that time the soil surface appeared damp and there was little evidence of the cement. Rain was applied at a rate of 8 in./hr, and after 2 min and 20 sec sediment began to move. A minute later rills had begun to form.

Run 26

Slope: 50 percent
Plot area: 0.00158 acre
Product tested: portland cement and tackifier 8
Application rate of product: portland cement = 1090 lb/acre, tackifier 8 = 28 gal/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 7 min 30 sec
Time to formation of rills: 8 min 30 sec

Portland cement and tackifier were mixed the same as for Run 25, but applied to the test plot at twice the rate. Warm air was blown across the test plot and it was allowed to dry for 6 days. At that time it had a white tint to it where the cement had dried. This covering was less than 1/16 in. thick and was brittle to the touch. After an application of 8 in./hr rainfall for 7 min and 30 sec, sediment began to move down the slope, and about a minute later sheet erosion was noticeable near the bottom of the slope.

Run 27

Slope: 50 percent
Plot area: 0.00165 acre
Product tested: portland cement and tackifier 8
Application rate of product: portland cement = 1635 lb/acre, tackifier 8 = 42 gal/acre

Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 11 min 0 sec
Time to formation of rills: 16 min 20 sec

Portland cement and tackifier were mixed the same as for Run 25, but applied to the plot at 3 times the rate. Warm air was blown across the test plot and it was allowed to dry for 6 days. At that time the entire surface appeared dry and white, and had a brittle layer of cement approximately 1/16 in. thick. After 11 min of rain at the rate of 8 in./hr, some sediment began moving down the slope. After 16 min and 20 sec distinct rills had formed on the soil surface.

Run 28

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: tackifier 1
Application rate of product: 40 gal/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 1 min 30 sec
Time to formation of rills: 1 min 30 sec

The tackifier was mixed at the rate of 40 gal/acre with 360 gal of water/acre, and applied to bare soil in the test plot. After 2½ days the plot was not yet dry. Rain was applied at the rate of 8 in./hr, and after 1 min and 30 sec noticeable sediment began to move and rills formed. After the test, very little product could be found on the soil surface anywhere on the plot.

Run 29

Slope: 50 percent
Plot area: 0.00158/acre
Product tested: tackifier 5
Application rate of product: 726 gal/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 5 min 45 sec
Time to formation of rills: 5 min 45 sec

The tackifier was mixed at the rate of 1 part tackifier to 4 parts water, and the mixture was applied to the soil at the rate of ¾ gal/yd². After 7 days of drying the surface was like "sticky" matting. After 5 min and 45 sec of 8-in./hr rainfall noticeable amounts of sediment began to move, but it was sheet erosion and no rills formed. After the test there was no observable tackifier on the soil surface but the soil was very compact.

Run 30

Slope: 50 percent
Plot area: 0.00165 acre
Product tested: tackifier 6
Application rate of product: 726 gal/acre
Pretest soil conditions: tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 2 min 30 sec
Time to formation of rills: 2 min 30 sec

Application was made at the same rate as described for Run 29. After drying for 6 days the material appeared as "sticky" matting on the soil surface. After 2 min and 30 sec of 8-in./hr rainfall sediment began to move and rills formed at the lower end of the test plot. After the test, a sticky layer still was noticeable on the soil and penetrated the surface about ¼ in. Scraping the surface resulted in many "threads" of the tackifier attached to soil particles.

Run 31

Slope: 50 percent
Plot area: 0.00169 acre
Product tested: asphalt—bare soil
Application rate of product: 1200 gal/acre
Pretest soil conditions: lightly tilled
Precipitation intensity: 8 in./hr
Time to incipient failure: 4 min 0 sec
Time to formation of rills: 4 min 30 sec

Asphalt was mixed at a rate of 1200 gal/acre with an equal amount of water and applied to the soil with a hand sprayer. Rills began to form very soon after incipient failure was noted.

APPENDIX E

BIBLIOGRAPHY

The bibliography contained in Volume III of the agency report is not published herein, but is available on a loan basis upon request to the NCHRP Program Director.

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