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Symposium 1.—Land and Erosion and Control

INTRODUCTION

That many of the sedimentation problems encountered in water resource development programs are related to the rates and magnitude of erosion on watershed lands and in stream channel systems is the dominant theme of Symposium 1. Of the 26 papers included in Symposium 1, 14 deal with subjects of sediment sources and yield, 6 with erosion control, and 6 with miscellaneous topics somehow related to the origin of sediment, the measurement of sediment, and the factors affecting sediment genesis and movement.

The effects of land use and management practices upon runoff, erosion and sediment yield are discussed, including erosion control and conservation practices on agricultural lands, forest cover and logging practices, and the use and management of range lands. The significance of gullying and stream channel erosion as sources of sediment is indicated, and practices for controlling these sediment sources are mentioned.

Sediment problems associated with highway construction and urban housing and development projects are likewise pointed out. Factors affecting gullying, stream channel morphology, and the shear resistance of cohesive sediments are treated.

The papers in this Symposium point to the complexity of interrelations between erosion and related sediment problems. They do not contain all of the answers, but they are positive and optimistic by showing that much has been learned about these interrelations and that erosion control practices properly applied and maintained on watershed areas can be an effective means for dealing with many sediment problems.

EROSION AND ITS CONTROL ON AGRICULTURAL LANDS

[Paper No. 1]

By John W. Roehl, *geologist, Engineering and Watershed Planning Unit, Soil Conservation Service*

Erosion is the wearing away of the land surface by detachment and transport of soil and rock materials through the action of moving water, wind, or other geological agent. Normal, or geologic, erosion pertains to this wearing away of the land under natural environmental conditions. Accelerated erosion, brought about by man, is conceived to be the erosion occurring at a rate greater than normal for the site, usually through reduction of a vegetal cover. While both wind and water are the principal agents producing accelerated erosion, this discussion will be confined to the water-caused process.

The interest in erosion and its control on agricultural lands is twofold. First, unchecked accelerated erosion represents a loss of a natural resource upon which we depend for our food and fiber; and, second, its end product — sediment — can represent a damage to flood plain lands, to urban areas, to navigation facilities, to downstream reservoirs, and to other improvements.

As defined, the erosion induced by improper use of the land proceeds at a rate greater than that which should be expected under purely geological conditions. It is this accelerated rate of erosion in which our main interest lies, as it is the rate that can be altered. If the accelerated rate through the application of various measures on agricultural land is reduced, our basic soil

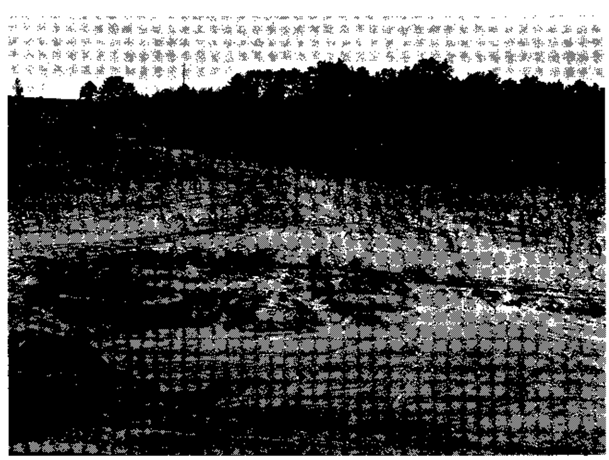

Figure 1. — An example of sheet erosion with accompanying rilling and deposition.

resource can be maintained and the production of sediment can be minimized.

Accelerated erosion can be classified into two main types: sheet and channel erosion. Sheet erosion is the more or less uniform removal of soil from an area without the development of conspicuous water channels. Included with sheet erosion, however, are the numerous small but conspicuous rivulets, or rills, that are caused by minor concentrations of runoff. The rills are easily obliterated by normal field cultivation. Figure 1 portrays an instance of sheet erosion. Channel-type erosion is that caused by the concentrated flow of water. Gullies, valley trenching, streambed, and streambank erosion are included in this latter type. A well-developed gully is shown in figure 2.

FIGURE 2. — An example of channel-type erosion.

The importance of the two types of erosion, both as to the loss of a resource and as a source of sediment, varies widely in different areas of the country. It can be stated fairly safely that in the humid part of the country sheet erosion is the prime offender, whereas in the more arid parts, where rainfall is experienced in short, high intensity storms, channel-type erosion is the source of greatest soil loss and ultimate sediment production. However, in small areas, as well, the relative importance of each type can be markedly different.

To pinpoint these generalities, erosion estimates obtained in the course of watershed planning in the Southeastern United States were analyzed as to the importance of the two types.[1] This analysis, involving some 1,720 square miles well scattered throughout the Southeast, indicated that sheet erosion accounted for the greater part of the computed erosion; ranging from 66 to 100 percent of the total. In four major land resource areas, sheet erosion accounted for essentially all of the computed erosion. This is in terms of rather broad areas.

To show that there is a wide disparity in importance between the two types within small adjacent areas, data obtained by the Agricultural Research Service[2] in the Pigeon Roost Watershed of northern Mississippi was analyzed. This analysis indicated that, in contributing watersheds of 0.2 to 23 square miles in size within a total watershed area of some 65 square miles, sheet erosion comprised 47 percent to over 90 percent of the total or gross computed erosion.

In terms of sediment yield, it is probable that, in the humid areas, sheet erosion accounts for the greater part of the total sediment load. Due to the processes of erosion, materials derived from sheet erosion sources are the fine-grained materials swept from fields and carried in suspension to and through the conveyance system. Owing to the small particle sizes there is little opportunity for deposition until an area of slack water (i.e., a downstream reservoir) is encountered. Channel-type erosion generally is the source of larger grained materials, and this material is obtained from areas already a part of the transportation system. Thus, from the viewpoint of damaging sediment (infertile overwash, stream channel fill, etc.), channel-type erosion may be of more importance than the sheet type.

If the sediment delivery ratio is assumed in terms of the total erosion, the measure of importance of each type of erosion as a source of sediment will be the same as its distribution within the several types. It is probable, however, that the delivery of erosional debris from each type is different, but to what degree is a matter of continuing and needed study.

Many means are employed on agricultural lands to control accelerated erosion. Basic to almost all efforts for the reduction of erosion is land treatment. This is accomplished mainly through the improvement of protective cover on the soil surface exposed to the eroding forces. This improvement in cover conditions is achieved by the establishment of various agronomic and forestry practices. The capability of the land to support a desired agricultural use with a minimum amount of erosion must be considered in the application of land treatment measures. In its most simple sense, one might express this philosophy as the growing of clean-tilled crops on the level, least erodible land and

[1] ROEHL, J. W. SEDIMENT SOURCE AREAS, DELIVERY RATIOS, AND INFLUENCING MORPHOLOGICAL FACTORS. Internatl. Assoc. Sci. Hydraulics Commission of Land Erosion Pub. 59, pp. 202-213. 1962.

[2] SPRABERRY, J. A., WOODBURN, RUSSELL, and MCHENRY, J. R. SEDIMENT DELIVERY RATIO STUDIES IN MISSISSIPPI, A PRELIMINARY REPORT. Agron. Jour. 52: 434-436, 1960.

of hay, pasture, and forest crops on the steep erodible slopes. Inherent properties of soils, however, as well as the landscape, do not permit such a simple solution.

Land treatment measures in conjunction with supporting mechanical field practices are effective in controlling accelerated erosion. First, consider the measures that improve the protective cover, such as:

(1) Conservation cropping systems that encompass the growing of crops in combination with needed cultural and management systems. The cropping systems involve the use of rotations that may include grasses and legumes grown in desirable sequence. Such systems do much to maintain fertility and good structure in the soil, assisting the soil to resist erosion.

FIGURE 3. — Severely eroded area, formerly cultivated, that would be classified as a critical area.

FIGURE 4.— Stabilization of critical area, shown in figure 3, accomplished by the establishment of trees (in background), lovegrass (in center), and kudzu (in foreground).

(2) Cover and green manure crops are crops of close-growing grasses, legumes, or small grain used primarily for summer or winter protection. The crop usually occupies the land for a period of 1 year or less and provides resistance to erosion during periods when the soil surface would otherwise be bare.

(3) Critical area planting that is done to establish vegetative cover on severely eroding and silt-producing areas. Stabilization of such areas can be accomplished by the planting of woody vegetation or the seeding or sodding of adapted grasses or legumes to provide long-term ground cover. (Figs. 3 and 4.)

(4) Hay land planting that provides protective cover through the establishment of long-term hay stands of grasses or legumes.

(5) Crop-residue use that utilizes plant residues left in cultivated fields by incorporating them into the soil or leaving them on the surface during that part of the year when critical periods of erosion usually occur.

(6) Mulching that involves the application of plant residues or other suitable materials not produced on the site to the surface of the soil.

(7) Pasture planting in which adapted species of perennial, biennial, or reseeding forage plants are established on new pasture lands converted from other uses.

(8) Tree planting that includes the planting of tree seedlings or cuttings in open areas to establish a stand of forest trees.

(9) Woodland interplanting that is the planting of tree seedlings in sparsely or inadequately stocked stands.

(10) Various management practices, such as the proper use of pastures and ranges, deferred grazing, stubble mulching, that are used to maintain protective cover to the land.

Other measures, similar to those just listed, are used, but the point for consideration here is that these are agronomic and management practices employed to establish or improve the protective cover afforded by vegetation as a means of reducing erosion.

In addition to and in conjunction with the practices just discussed, mechanical field practices are usually employed. While some of these practices are more pronounced in their effect on erosion than are others, all of them afford additional reductions in the rate of erosion. Some of the more common mechanical field practices recommended for use are:

(1) Contour farming which is the conduct of farming operations on sloping, cultivated land in such a way that plowing, land preparation, planting, and cultivation are done on the contour. Depending upon the steepness of slope, erosion from contoured fields may be from 100 percent to 50 percent of that expected from up

and down the slope tillage.[3] It is most effective during low-intensity storms.

(2) Contour stripcropping that involves the growing of crops in a systematic arrangement of strips or bands on the contour. The crops are arranged so that a strip of grass or close-growing crop is alternated with a strip of clean-tilled crop or fallow. This practice works well in conjunction with conservation cropping systems, especially where a grass or legume is included in the crop rotation, and is effective in reducing erosion and sediment yields. Erosion from contour stripcropped fields averages from 25 to 45 percent of that expected from up-and-down tillage (fig. 5).[3]

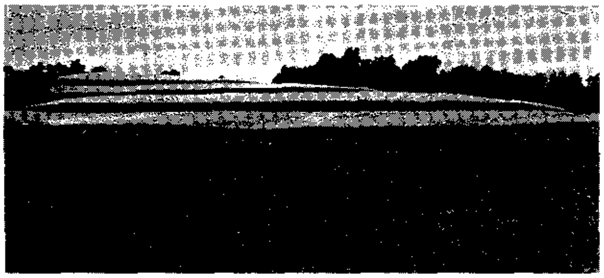

FIGURE 5. — Contour stripcropping.

(3) Contour furrowing on range or pasture land is accomplished by plowing furrows on the contour at intervals varying with the slope and ground cover.

(4) Gradient terraces are established by the construction of an earth embankment or a series of ridges and channels across the slope at suitable spacings and with accepted grades. These are applied to reduce erosion and sediment yield by intercepting surface runoff and conducting it to a stable-outlet at a nonerosive velocity. Contour farming goes hand-in-hand with terracing (fig. 6), and stripcropping often is used in conjunction with gradient terraces.

(5) Level terraces are also a series of ridges and channels constructed across the slope at suitable spacings, but they have no grade.

(6) Diversions are graded or dug channels, with a supporting ridge on the lower side, across the slopes and are used to divert water from areas where it is in excess to sites where it can be used or disposed of safely. This mechanical aid is often used to intercept water from higher elevations before it can reach and erode cultivated fields.

(7) Grassed waterways are natural waterways or depressions that are reshaped or graded and on which suitable vegetation is established. They provide for the disposal of excess surface water from terraces, diversions, or from natural concentrations without damage by erosion.

All of the foregoing discussion of the land treatment measures for controlling erosion has been concerned with those measures aimed primarily at sheet erosion, although the control of minor gullies can be accomplished through their use. The control of channel-type erosion, which would include larger gullies, streambank cutting, valley trenching, etc., usually requires more than the establishment of vegetation. Structures needed may involve earthwork, or the construction of works built of concrete, masonry, metal, or other materials as listed below.

(1) Check dams can be placed in active gullies to reduce downcutting and widening. The effect is accomplished by providing areas of deposition behind the structures, thus reducing the bottom gradient. The structures can be of a temporary nature, constructed of brush or logs, until permanent vegetation finally heals the gully, or

FIGURE 6. — Gradient terraces and contour farming.

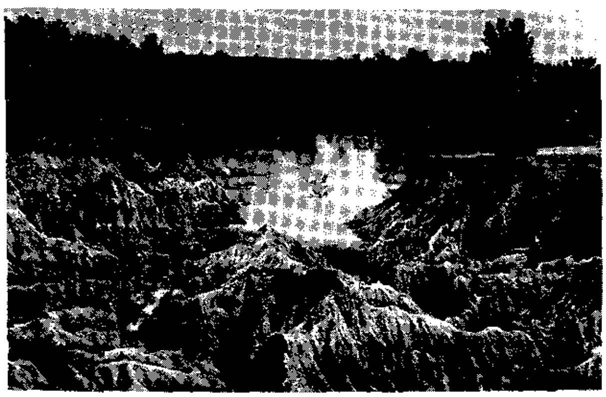

FIGURE 7. — Process of gully stabilization by the construction of a dam (in background) and the planting of bermudagrass (in foreground).

[3] AGRICULTURAL RESEARCH SERVICE. A UNIVERSAL EQUATION FOR PREDICTING RAINFALL-EROSION LOSSES. U.S. Dept. Agr., ARS 22-26, 11 pp., Washington, D.C. 1961.

they can be of a more permanent nature, constructed of masonry or concrete, if it is believed vegetation will be too long in establishing itself. Figure 7 shows a gully in which a dam has been constructed to reduce the bottom gradient and to assist in stabilization until the grasses planted on the actively eroding areas provide protection. Not only do the areas of deposition afforded by the structures aid in the control of the gully, but they also are quite effective in reducing the sediment yield from the gullies by trapping the greater part of the eroded material.

(2) Where tributary streams or ditches convey water into larger streams or canals, headward erosion often occurs. In order to reduce the erosion and possible loss of agricultural land, drop structures can be used. Such structures, of concrete, masonry, cribbing, or sheet piling, provide the means of conducting the water through differentials in elevation without downcutting in the tributaries.

(3) Streambank stabilization is sometimes required when the loss of productive flood plain land is occurring. Some of the means employed to prevent this erosion are bank sloping, riprap, deflectors, and jetties.

(4) Gradient control structures have been employed to reduce the upstream migration of valley trenches, thus eliminating the loss of land caused by such erosion. To be effective, this type of structure should be constructed so that the active headcut of the valley trench is covered by the impounded water.

That the management and agronomic practices enumerated earlier are effective in reducing the rate of accelerated erosion is well borne out by research. Crop rotations that include a grass or legume have been shown to reduce the rate by about 70 percent of that experienced under fallow or completely unprotected conditions. The establishment of dense hay and pasture grasses can similarly reduce the rate of soil loss to practically nothing.

Depending upon the steepness of the slope, the addition of mechanical field practices will reduce the rate still further. Contouring, alone, will afford a reduction in erosion rates from 10 percent on the steeper slopes to 40 percent on the flatter slopes. Contour stripcropping on terraced land will accomplish reductions of 55 to 70 percent in soil loss, again depending upon the steepness of the slope.[4]

It follows, quite properly, that if the rate of erosion in an area is altered, the rate of sediment yield from that area will also be changed. An example of what conservation can do in reducing sedimentation was experienced in Lake Issaqueena, S. C., where it was found [5] that the establishment of conservation measures and increased vegetation resulted in a decrease of 37 percent in the rate of sheet erosion and of 52 percent in the rate of sediment inflow. The reduction in the amount of sheet erosion was responsible for a large part of the reduction in the sediment inflow, the remaining reduction being due to the stabilization of gullies and eroding roadbanks.

It is upon this basic premise of reducing sediment yield through the application of proven conservation measures that the Soil Conservation Service predicates its sediment design for structures requiring sedimentation features. Not only is sedimentation reduced, but also our irreplaceable soil resource is maintained to continue its role of producing our needed food and fiber.

[4] U.S. DEPARTMENT OF AGRICULTURE. SOIL LOSS ESTIMATION IN THE SOUTHEAST. Agricultural Research Service — Soil Conservation Service Workshop, Athens, Ga., Apr. 12-13, 1960, 38 pp., mimeo. 1960.

[5] NOLL, J. J., ROEHL, J. W., and BENNETT, JACKSON. EFFECTS OF SOIL CONSERVATION ON SEDIMENTATION IN LAKE ISSAQUEENA. U.S. Dept. Agr., SCS-TP-95, 20 pp. 1950.

SOME INTERPRETATIONS OF SEDIMENT SOURCES AND CAUSES, PACIFIC COAST BASINS IN OREGON AND CALIFORNIA

[Paper No. 2]

By HENRY W. ANDERSON, *project leader*, and JAMES R. WALLIS, *research forester, Water Source Hydrology Project, Pacific Southwest Forest and Range Experiment Station, Forest Service*

Differences in sediment discharges from watersheds can be attributed to differences in erosion from watershed slopes and channels and to differences in the transport of eroded material from the watersheds. The rates of sediment discharge from watersheds represent an integrated average of the sediment discharge from all parts of the watershed. The rates from the individual parts of the watershed — the sediment sources — may be evaluated by analyzing data from many watersheds. Between watersheds, the discharges of sediment vary in response to differences in streamflow, soils, topography, and land use. Within the parts of single watersheds, similar responses occur. Thus, sediment sources and causes can be expressed in terms of sediment production from whole watersheds as related to variables of the meteorological potential, topographic potential, soil erodibility, and land use and condition.

This paper reports the differences in sediment discharge associated with specific measures of these potentials largely from our studies of sedimentation in the Pacific coast basins of western Oregon and California.

In making these evaluations, the measures of sedimentation used were the average annual suspended sediment discharge from watersheds, the seasonal or annual catches of erosion from slopes, or reservoir deposition measurements. Average annual suspended sediment discharge for a watershed was obtained from suspended sediment samples, relating suspended sediment to stream discharge, then obtaining from streamflow discharge frequencies sediment discharge frequencies and finally average annual suspended sediment discharge (table 1). Seasonal or annual catches of erosion from slopes were measured by means of half-round steel troughs placed on contour along slopes or in debris chutes or channels (*6*). Reservoir deposition was determined by measuring changes in reservoir capacity resulting from sediment deposition.

TABLE 1.—*Average annual suspended sediment and discharge from sediment sampling and streamflow duration before and after logging of 1-square-mile of the 4-square-mile Castle Creek, Yuba River headwaters, Calif., 1958 and 1959*

Discharge class	Mean discharge	Streamflow frequency	Relative volume	Sediment samples	Streamflow in various sediment concentration classes, p.p.m.						Average sediment concentration [1]
					< 12.5	13–27	28–72	73–142	143–400	>400	
BEFORE LOGGING, 1958											
	C.f.s.	*Percent*		*Number*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*P.p.m.*
< 1	0.2	44.0	0.006	2	44.0						7
1–10	4.1	30.0	.089	15	26.0	4.0					9
11–40	20.2	14.00	.200	14	7.0	6.0			1.0		36
41–100	60.0	8.8	.380	6		7.3	1.5				25
101–200	125.0	2.8	.258	15	.2	.4	.6	1.4	.2		104
201–250	210.0	.25	.038	0					.25		(190)
>250	270.0	.15	.029	6						0.15	(430)
Total		100.00	1.000	58							
Average	14.7				7	20	50	108	270	430	[2]64
AFTER LOGGING, 1959											
< 1	0.2	44.0	0.006	11	36.0	4.0	4.0				12
1–10	1.0	30.0	.089	13	23.1			4.6	2.3		43
11–40	21.0	14.0	.200	18	7.8	4.7	1.5				16
41–100	63.0	8.8	.380	12	2.2	2.2	.7	2.2	1.5		83
101–200	130.0	2.8	.258	3					1.9	0.9	413
201–250	216.0	.25	.038							.25	(1,700)
>250	280.0	.15	.029							.15	(3,200)
Total		100.00	1.000	57							
Average	15.3				7	20	50	108	210	980	[3]303

[1] Values in parentheses were taken from sediment concentration-discharge curve.
[2] 935 tons sediment per year per square mile.
[3] 4,600 tons sediment per year per square mile.

The measures of the meteorologic potential used were storm rainfall intensity and snowmelt characteristics of unit areas, antecedent precipitation, and rain-snow characteristics of the precipitation. In some studies, these variables were used directly; in others, these variables were used to predict two characteristics of the runoff: total volume and peakedness or intensity of runoff.

The topographic potential was assessed from variables of elevation, slope characteristics, and channel patterns and characteristics. Elevation was usually not expressed explicitly, but in terms of how it affected rain-snow distribution of the precipitation, precipitation amounts, and soil formation. Slope characteristics were indexed by the slope of streams of 1-mile mesh length (*4*), thus largely eliminating problems of mapping scale. Channel patterns and characteristics were determined by using Horton's (*10*) procedures.

The sediment associated with the soil potential was determined by taking soil samples under standard conditions and relating their physical characteristics to soil formation factors. The physical erodibility factors — surface-aggregation ratio (*4*) and dispersion ratio (*14*) — were related to rock type, vegetation type, and climatic variables by regression analysis.

The effects of land use and condition on sedimentation were determined for variables by indexing the type and degree of forest land cutting, forest fires, broad categories of cultivation, extent of road development, length of unstable stream banks, and condition of geologic instability.

Analytical Methods

In studies using many watersheds, we determined the relation of sediment discharge of each to its watershed characteristics by multivariable analysis. Specific variables were chosen to give quantitative expression to the watershed characteristics. A variable had to meet two requirements: (1) It should be related to sediment discharge, and (2) it could be expressed in terms applicable to individual land areas within watersheds. The value of a variable for an entire watershed was obtained by averaging the value of the variables — taken from maps — for the individual land areas within the watershed.

Results of analysis in half a dozen groups of watersheds along the Pacific coast and some recent additional studies of soil erodibility were used to interpret and give quantitative expression to the principal sediment sources and causes in western Oregon and California. In other areas, the results will have quantitative meaning only if climate, topography, and geology are similar, but the variables themselves may be useful in studies of sedimentation in many areas.

The results of analysis of measured sediment production to the various cause-variables are summarized in table 2. Shown are the specific measure of sediment discharge involved, the general analytic model, the specific analytic model, and a definition of variables, together with a regression coefficient giving the independent effect of that variable on sediment discharge. These results were used to interpret and infer the differences in sediment discharge associated with differences in cause-variable.

TABLE 2.—*Regression models and results relating sedimentation to variables of streamflow, topography, soil, and land use and condition potentials*

Models and results	Explanation	
(1) Sedimentation model $SS = f\ (Sf, T, S, Lu)$	Suspended sediment discharge (tons/sq. mi./yr.) equals function of streamflow (Sf), topography (T), soil (S), and land use (Lu) (*4*).	
(2) Log SS = −4.721	Regression constant.	
+1.244 log MAq	Mean annual runoff, c.f.s./sq. mi.; range, 1.09–7.48.	Sf
+1.673 log FQp	Discharge peakedness, based on a separate regression analysis which related peak discharges from water sheds to: geologic rock types, the area receiving rain during storms, and the area in which snow was ripe during the storms (*7*); range, 1.98–4.30.	Sf
+0.116 log A	Area of watershed; unit, sq. mi., range 56–7,280.	T
+0.401 log S	Slope of stream of 1-mile mesh length after method of Horton (*10*) (see derivation in section on topographic potential); unit, ft./mi.; mean, 910; range, 210–1,510.	T
+0.0486 SC	Silt and clay; fraction of top 6 inches of soil with particle sizes less than 0.05 mm. in diameter; unit, pct.; mean, 23.0; range, 19.1–32.0.	S
+0.482 S/A	Surface aggregation ratio; surface area on soil particles of sand and coarser size (>0.05 mm. diameter) divided by the aggregated silt plus clay, $cm.^2/mg.$ pct.; range, 0.26–1.78.	S
+0.942 R	Roads; part of watershed area in roads, percent; mean, 0.30; range, 0.05–0.60.	Lu
+0.0086 RC	Recent cutover; part of watershed area cutover in last 10 years, percent; mean, 6.0; range, 0–30.4.	Lu
+0.0280 BC	Bare cultivation; part of watershed in row crops and small grain, percent; mean, 4; range, 0–22.	Lu
−0.0036 OC	Other cultivation; part of watershed area in cultivation other than bare cultivation, percent; mean, 12; range, 0–48.	Lu
(3) Log e_D = 2.161	Sedimentation of reservoir during a single year (and regression constant); unit, acre-ft./sq. mi.; range, 0.3–36.0.	
+0.071 log A	Area of the watershed; unit, sq.mi.; range, 1.5–202.	
+1.619 log P_{24}	Maximum 24-hour precipitation for the watershed during the storm; unit, inch; range, 1.5–20.0.	
+0.410 log aP	21-day precipitation antecedent to the maximum 24-hour for the storm; unit, inch; range, 1.0–23.0.	
+0.370 log A_{Ch}	Area of main channel of the watershed; unit, acre/sq.mi.; range, 7–9.7.	
−1.974 log C	Cover density on the watershed; unit, pct.; range, 2.0–72.4.	
(4) Log q = 1.3383	Maximum yearly peak discharge; unit, c.f.s./sq.mi.; range, 10–550.	
+0.060 log A	Area of the watershed; unit, sq.mi.; range, 1.5–202.	
−0.975 log C	Cover density on the watershed; unit, pct.; range, 2.0–72.4.	
+0.863 log PE_3	Precipitation effectiveness (see equation 3 above).	
+0.360 (log PE_3 x $r_b r_s / r_l$	Defined above and on following page.	
−0.477 log $r_b r_s / r_l$	Watershed physiography expressed as the ratios, by stream order numbers, of stream numbers, slopes, and lengths, after Horton (*10*) (r_b, r_s, and r_l were expressed as ratios of larger numbers to smaller numbers); unitless; range, 1.1–4.2.	

TABLE 2.—*Regression models and results relating sedimentation to variables of streamflow, topography, soil, and land use and condition potentials*—Continued

Models and results	Explanation
(5) Log PE_3 = 1.188 log P_{24}	Maximum 24-hour precipitation for the watershed during the storm; unit, inch; range, 1.5–20.0.
+0.516 log aP	21-day precipitation antecedent to the maximum 24-hour for the storm; unit, inch; range, 1.0–23.0.
+0.985 log P_1	Maximum 1-hour precipitation for the watershed during the storm; unit, inch; range, 0.2–2.1.
(6) Log e_D = 1.041	Sedimentation of reservoir during a single year (and regression constant); unit, acre-ft./sq.mi.; range, 0.3–36.0.
+0.866 log q	Maximum yearly peak discharge; unit, c.f.s./sq.mi.; range, 10–550.
+0.370 log Ac_h	Area of main channel of the watershed; unit, acre/sq.mi.; range, 7–9.7.
−1.236 log C	Cover density on the watershed; unit, pct.; range, 2.0–72.4.
(7) Log Es = 3.073	Average suspended sediment content of streamflow in p.p.m.
−2.430 log C	Average cover density on watershed, pct.
+3.427 log DR	Dispersion ratio.
(8) DR = 5.7	Dispersion ratio.
+1.6 Kw	Dissociation constant of water (summed for 12 monthly values of $Kw = 0.2681(1.048F)$, in which F is mean monthly temperature in degrees Fahrenheit.
−0.014 Kw^2	Square of previously defined variable.
(9) S/A = 319	Surface aggregation ratio.
−6.39 P	Average annual precipitation, inches.
−7.52 Kw	(Same as in equation 8).
+2.42 KwP	Summation of 12 monthly products of Kw and P.
+0.0404 $(P)^2$	Square of previously defined variable.
+0.0553 Kw^2	Square of previously defined variable.
−0.00693 $(KwP)^2$	Square of previously defined variable.
(10) Log E = 1.115	Total deposition of sediment in individual reservoir and debris basins as the result of the storm; unit, acre-ft.; range, 1.2–74.0 acre-ft./sq.mi.
+0.619 log A	Area of the watershed; unit, sq. mi.; range, 0.1–202 sq. mi.
+1.688 log P	Maximum 24-hour precipitation falling on the watershed during the storm; unit, inches; range, 5.8–15.1 inches.
+0.191 log B	Barren area on the watershed; unit, acres; range, 0.8–83.0 acre/sq.mi.
+0.255 log F	Old fire area—area of fires multiplied by the number of times burned, for fires occurring more than 15 and less than 60 years before the storm; unit, acres; range, 8–1, 810 acres/sq.mi.
−1.316 log C	Average cover density on the watershed; range, 18.5–88.6 pct.

Meteorologic or Hydrologic Potentials and Their Effects

Differences in sedimentation resulting from the differences in the meteorology of unit areas may be related to either meteorological variables or to hydrologic consequences of the meteorology. We may take the volume of runoff and the intensity of runoff as hydrologic consequences. Differences in the volume of runoff may be rather easily appraised by referring to runoff maps, such as those published by the U.S. Army Corps of Engineers for Oregon and California. Differences in the peakedness or intensity of runoff may be appraised in several ways. For example, we have used the relative frequency of rainfall and snowmelt contributions to peak runoff. These have been determined by elevation zones for western Oregon (*7*) and have been extended to California by Wallis (*16*). Table 3 summarizes the frequency of rain and snowmelt by elevation zones for various latitudes on coastal Oregon and California.

The effects on sedimentation of differences in hydrologic potential were appraised for western Oregon watersheds. Differences in the total volume of runoff between watersheds produced differences in sediment production between watersheds by a factor of 11.7. Differences in the runoff intensity produced differences in sedimentation between watersheds by a factor of 3.6. Watersheds with large contrast in both the volume and peakedness of runoff (Wilson watershed as compared with Big Butte watershed) showed a difference in sediment production of 36 times attributable to the difference in hydrologic potential alone. The actual contrast in measured sediment per unit area was almost 70.

Frequencies for the combinations of the two variables, precipitation intensity and antecedent precipitation, have been worked out for southern California watersheds (*1*). Association between these variables and measured sediment deposition in reservoirs is shown in equation 3, table 2. For the same general storm, on March 1, 1938, differences in the hydrologic potential of two watersheds, Cucumonga and Thompson Creek, caused a 3.4 difference in the sediment production (*8*).

Topographic Potential

Slope of the land is closely related to the slope of the minor channels, according to Horton (*10*). He also presented some relation between

TABLE 3.—*Relative rain area, and snowmelt frequencies for latitudes listed*

RELATIVE RAIN AREA FREQUENCIES[1]

Elevation (feet)	Latitude									
	44°	42°	41°30′	41°	40°30′	40°	39°30′	39°20′	39°	38°30′
0–1,000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1,000–2,000	.96	.99	.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2,000–3,000	.87	.92	.93	.94	.95	.96	.97	.97	.97	.98
3,000–4,000	.75	.81	.83	.84	.86	.87	.88	.88	.89	.90
4,000–5,000	.59	.68	.70	.72	.73	.74	.76	.77	.77	.79
5,000–6,000	.39	.50	.52	.54	.56	.58	.60	.61	.62	.64
6,000–7,000	.17	.29	.32	.34	.36	.38	.41	.42	.43	.45
7,000–8,000	.00	.06	.09	.12	.14	.17	.19	.20	.21	.23

Elevation (feet)	Latitude									
	38°	37°30′	37°	36°30′	36°	35°30′	35°	34°30′	34°12′	34°
0–1,000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1,000–2,000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2,000–3,000	.98	.99	.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3,000–4,000	.91	.92	.93	.94	.94	.95	.96	.96	.97	.97
4,000–5,000	.80	.81	.82	.83	.85	.86	.87	.88	.88	.89
5,000–6,000	.65	.67	.69	.70	.72	.73	.75	.76	.77	.77
6,000–7,000	.47	.49	.51	.53	.54	.57	.58	.60	.61	.62
7,000–8,000	.25	.28	.30	.32	.34	.36	.38	.41	.41	.42

RELATIVE SNOWMELT FREQUENCIES[2]

Elevation (feet)	Latitude								
	44°	42°	41°30′	41°	40°30′	40°	39°30′	39′	38°30′
0–1,000	1.00	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1,000–2,000	.99	.993	.995	.998	1.000	1.000	1.000	1.000	1.000
2,000–3,000	.92	.939	.941	.953	.969	.989	.999	1.000	1.000
3,000–4,000	.82	.840	.846	.866	.889	.921	.967	.991	.999
4,000–5,000	.69	.712	.720	.745	.772	.819	.883	.935	.967
5,000–6,000	.54	.570	.574	.604	.634	.688	.770	.837	.881
6,000–7,000	.38	.410	.416	.449	.481	.539	.631	.711	.768
7,000–8,000	....	.242	.299	.288	.318	.379	.475	.564	.629

Elevation (feet)	Latitude								
	38°	37°30′	37°	36°30′	36°	35°30′	35°	30°30′	34°
0–1,000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1,000–2,000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2,000–3,000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3,000–4,000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
4,000–5,000	.983	.992	.997	.998	1.000	1.000	1.000	1.000	1.000
5,000–6,000	.912	.937	.950	.969	.968	.972	.976	.978	.980
6,000–7,000	.807	.840	.860	.873	.885	.893	.900	.904	.908
7,000–8,000	.674	.714	.740	.755	.772	.780	.789	.796	.800

[1] Values taken from a smoothed curve through Anderson and Hobba's (*7*) relative rain area frequencies for the central Willamette Valley.

[2] Values taken from a smoothed curve through Anderson and Hobba's (*7*) relative snowmelt frequencies for the central Willamette Valley area.

channel lengths, channel slopes, and channel order number. His studies make possible a valid determination of slope that is independent of map scale. The slope of streams of 1-mile mesh length, for example, can be derived from simultaneous plotting of stream slopes and stream lengths against order number, and reading the slope of a stream whose length is 1-mile (*4*). To compute sediment discharge, we used the relation of sediment discharge to slope of the streams given by equation 2 in table 2. For a range in slopes from 210 to 1,510 feet per mile, sediment discharge differed by a factor of 2.2.

Channel patterns and characteristics that affect sedimentation include channel areas, which affect the availability of material for transport and channel drainage patterns that affect the hydrologic potential and, hence, affect sediment production. For many watersheds of southern California these effects were summarized by Anderson (*1*).

The relation of channel area to sediment production, from table 2, equation 3, can be used to compute the effect on sedimentation of differences in channel area. Thus, Tujunga has a sediment potential 98 percent higher than

Big Santa Anita because of channel area alone.

The effects of channel patterns may be trivial for a small storm or years with small discharges, yet of considerable importance in the large events that produce most of the sediment discharge from watersheds. Horton's (*10*) bifurcation, slope, and length ratios have been found to affect the hydrologic potential (*2*, *8*). The definition of a composite variable and its relation to discharge is shown in equations 4 and 5 of table 2, and the relation between discharges and sedimentation is shown in equation 6. In a large storm, 50 percent greater sediment production from the San Gabriel watershed is expected than from the Santa Anita watershed because of the differences in the channel pattern alone. But in a small storm, only about 20 percent increase in sediment would be expected (*2*).

Soil Potential

Soils — the primary material of sedimentation — vary in their resistance to erosion. Sediment discharge from watersheds is related to the lack of resistance.

Sediment discharge from watersheds has been related to the dispersion ratio (*14*) and the surface-aggregation ratio (*4*) indexes that measure variation in soil stability. The wide differences in these properties of watershed soils can be determined by relating them to map characteristics, such as geologic type and vegetation type, and to climatic variables, such as temperature and precipitation. Thus, we introduce the submodel: Soil erodibility = function (rock type, vegetation type, climate, and topography), and evaluate this model.

Sediment discharges vary with erodibility in the south coastal watersheds of California (*3*) and the west coastal watersheds of Oregon (*4*). These variations are illustrated in equations 2 and 7, table 2. Sediment production from watersheds of western Oregon differ by a factor of 5 because of variation in the soil erodibility. In the south coastal watersheds even greater variations were found. For example, in the watersheds of the Cuyama badlands, the Miocene Continental deposits had a sediment potential 75 times as great as the marine shales of nearby watersheds.

The variation of these erodibility indexes with the soil-forming factors of rock type, vegetation, and climate (*11*) has progressed through a succession of refinements (*3*, *4*, *9*).[1] Highly significant and useful relations of soil erodibility to rock type were found. Table 4 summarizes the relation of two erodibility indexes to rock types.

[1] WALLIS, J. R., and WILLEN, D. W. SOME HYDROLOGIC CHARACTERISTICS OF SURFACE SOILS TAKEN FROM CALIFORNIA'S WILDLANDS AND RELATED TO VEGETATION, CLIMATE AND GEOLOGY BY REGRESSION ANALYSIS. Paper presented 2d Western National Meeting, Amer. Geophys. Union, Stanford, Calif., Dec. 28, 1962.

TABLE 4.—*Relation of soil erodibility indexes—dispersion ratio (DR) and surface-aggregation ratio (S/A)—to geologic-rock type*

Rock type	DR[1]	DR[2]	S/A[2]	DR[3]	S/A[3]	DR[4]	S/A[4]
Recent volcanics		60	275				
Young volcanics		56	204				
Acid igneous		54	164	52	120		
Granite and rhyolite						51	149
Quartz diorite						56	132
Grano-diorite						57	112
Diorite						48	71
Cenozoic nonmarine sed.						48	80
Miocene continental	50						
Schist and phylite				40	99	52	76
Metamorphics				49	47	48	67
Cenozoic marine sed.				47	68	40	58
Miocene marine	23	27	26				
Oligocene		28	41				
Eocene	16	30	62				
Quaternary terraces	42						
Upper Cretaceous sed.	37	50	57				
Lower Cretaceous mar.	14						
Basalt and gabbro		34	59	53	51	46	57
Jurassic Triassic		31	53				
Carboniferous volcanic		44	68				
Pre-Cenozoic marine				47	61	47	52
Carboniferous		57	60				
Devonian		23	23				
Peridotite and serpentine				39	42	37	43
Andecite						44	42
Eocene volcanic		25	17				

[1] Reference (*3*).
[2] Reference (*4*).
[3] Reference (*9*).
[4] See Wallis and Willen, footnote 1.

André and Anderson (*9*) concluded that variation in the erodibility of soils develops under different cover types. But now this does not appear to be generally true; when more sensitive climatic variables are included in the analysis, only for a few combinations of rock types and cover types do differences in erodibility occur. Under brush, high erodibility is associated with both marine and nonmarine soft Cenozoic sediments (table 5). Under grass, the granitic rocks display high erodibility, and this also seems to hold for the quartz sericitic schists that are common in the California coast range. Under Douglas-fir forests, the dispersion ratio and — to a lesser degree — the surface-aggregation ratio are low.

TABLE 5.—*Coefficients of interaction of cover type and rock type on surface aggregation ratio, northern California*[1]

Cover type	Rock type											
	Granite and rhyolite	Grano-diorite	Quartz diorite	Diorite	Andecite	Basalt and gabbro	Peridotite and serpentine	Schist. and phylite	Meta-morphic	Cenozoic non-marine sediments	Cenozoic marine sediments	Pre-Cenozoic marine sediments
Fir	....	+11	+10	−3	....	+2	+12	−8	−3	....	....	+2
Pine	−50	+4	+14	....	+26	+16	+16	−1	−23	−15	....	+2
Brush	−10	−21	−18	+12	+7	+11	−11	−14	−10	+32	+54	+3
Grass	+45	+1	0	−12	−33	−18	−7	+29	+19	−9	−16	−4

[1] Surface-aggregation ratio for a rock-type deviate by the amounts shown for the different cover types.

The relation of erodible soil development to climate is of most interest to the soil morphologist, and certainly is of some interest to the sedimentationist. Some schools of soil morphologists would have us believe that climate was the sole control of soil development. We have seen that the rock type is the dominant influence — at least for the young residual soils of the Pacific coast mountains.

But climate is important. Early studies showed differences in soil erodibility with simple climatic segregations of elevation and geographic zone (*9*). More recent studies[2] have shown that a climatic factor can be expressed from the amounts and temperature of the percolating rainfall. The dispersion ratio is related to the dissociation constant of water (equation 9, table 2); the surface-aggregation ratio of the soil is related to the amount of precipitation, the dissociation constant of water for that precipitation, and their joint product (equation 9, table 2). Variation in soil erodibility between areas of northern California associated with these climatic variables is by a factor of 1.4.

Soil Supply Factors

Depending on the particular sedimentation product under study, soil characteristics other than erodibility become important in predicting sedimentation. When suspended sediment discharge is being evaluated, the supply of silt and clay in the soil becomes important (equation 2, table 2). When the effect of sediment on water quality in terms of the number of days per year with turbid streamflow ($>$ 27.5 p.p.m.) is being tested, the percentage of coarse gravels in the watershed soil becomes important. Streams in areas of gravelly soils cleared up sooner after storms; hence, had fewer days with turbid flow. Soil texture may cause reservoir deposition to vary even though total sediment discharge is the same; reservoir trap efficiency is greater for watersheds with coarse-textured soils. When we sedimentationists find it desirable to consider separately the effects of the soil on runoff and the effects of runoff on sedimentation, other soil characteristics and their formation will become important.

Land Use and Condition Potential

Wide differences in sediment discharge are associated with differences in land use and condition — both past and present. Factors include forest fires, logging, road building, cultivation, and natural geologic instability.

Logging of forest lands changes the sediment discharge. In Oregon, studies have shown 80 percent greater sediment discharge in one watershed than another, associated only with logging during the previous 10 years (from equation 2, table 2). The first year after one-fourth of a watershed in the Sierra Nevada was logged, sediment discharge increased by a factor of 6 (table 1); the second year, the factor fell to 2 (*15*).[3] For the logged area the rates were 17 and 5 times the prelogging rate.

Forest fire effects on sediment discharge have depended on the sequence of storms that followed the fire and the rate that vegetation recovered. For 10 years after a fire that burned

[2] See footnote 1, p. 27.

[3] ANDERSON, H. W. and RICHARDS, L. G. FOURTH PROGRESS REPORT, 1960-1961 COOPERATIVE SNOW MANAGEMENT RESEARCH. U.S. Forest Service, Pacific Southwest Forest and Range Experiment Station, pp. 142-204. 1961. [Processed.]

30 percent of the Santa Ynez watershed, sediment deposition averaged 5,400 tons per square mile per year, 3.3 times the prefire rate (*5*). In major floods, such as the 1938 flood in southern California, sedimentation increased by a factor of 3 for the flood occurring the first year after the burn; only a 16 percent increase was indicated 15 years after the burn (*8*).

Fire may affect erosion differently than it does sediment discharge. The burn in the Arroyo Seco watershed in 1956 produced erosion from watershed slopes in channels 4 to 17 times the prefire rate, yet no sediment discharge reached the downstream Devil's Gate Reservoir in that light runoff year (*12, 13*). Materials eroded from the slopes contribute sediment for years after a fire. Fires 15 to 60 years old still affected sediment discharge in a major flood (*8*). Differences in these old fires between watersheds produced differences in sediment discharge by a factor of 4 during a major storm (equation 10, table 2).

Roads in watersheds produce differences of a factor of 3 in sediment discharge between watersheds in western Oregon (equation 2, table 2). In southern California, roads were a major contributor to sediment discharge during the 1938 flood (*8*). Erosion from road fills for the period 1934-47 averaged from 6 to 10 times that from adjacent nonroad areas; about three-fourths of this eroded material came in the 1938 flood.

Cultivation effects differ markedly between bare cultivation, such as row crops, and other cultivation, such as grain. A difference by a factor of 5 in sediment production is indicated by the analyses in western Oregon (equation 2). That is, 80 percent reduction in sedimentation would be expected from a change from bare to nonbare cultivation.

Geologic unstableness is a major driving force in sedimentation. Where recent uplifts have rejuvenated mountain slopes, major changes in sediment discharge result. Rejuvenated slopes produced as much as four times as much sediment discharge as did similar nonrejuvenated slopes (*6*). When a fire destroyed the vegetation, a larger contrast occurred — the rejuvenated slope produced 11 times as much sediment discharge as that of the nonrejuvenated (*12*).

Application of Results

Differences in the hydrologic, topographic, and land use and condition potentials may be combined to estimate the sediment discharge potential for individual parts of watersheds (*4*). For the Willamette basin in Oregon, for example, a map of the sediment potential was prepared and major sediment-producing areas delineated. Sediment sources were:

	Sediment discharge (Tons per year)	Sediment discharge (Percent)
Source:		
Forest lands (5,460 square miles)	470,000	24
Agricultural lands (1,120 square miles)	430,000	22
Main channel banks (39 miles)	1,055,000	54
Total	1,955,000	100

By combining the effects of all the various sediment potentials, we have found that the sediment potential for nonagricultural lands varies by a factor of 100 and from agricultural lands by a factor of 7. From these results, areas where caution in management may be needed can be determined and the effectiveness of certain types of management can be estimated.

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RESIDENTIAL CONSTRUCTION AND SEDIMENTATION AT KENSINGTON, MD.

[Paper No. 3]

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Abstract

Sediment transported in storm runoff near Kensington, Md., during the transformation of part of a 58-acre area from rural to residential land use was measured for 25 storm events from July 1959 to January 1962. These data were used with the water discharge record of nearby Rock Creek in a multiple regression analysis to show the magnitude and trend of sediment movement with time.

Total sediment discharged from the area affected by urbanization was 189 tons per acre for the entire period of construction and the subsequent return to a reasonably stable residential area. The high yield of sediment from the Kensington area is attributed to (1) the rolling topography, 3 to 25 percent slope, (2) a very friable soil and subsoil, (3) the construction of a street in the major drainage channel, (4) a tendency for construction methods to expose extensive areas of the soil for a long period of time, and (5) a substantial amount of the 42 inches of annual rainfall occurring at a rate in excess of the infiltration capacity of unprotected soil.

Introduction

Population pressure in and around cities causes much urban construction that is tied to the mantle of soil and subsoil. This includes all the construction for the industrial, commercial, and residential developments and the necessary highways, streets, and utilities. Some of the impact of urban growth on the general water regime was discussed by Savini and Kammerer.[1] The impact of urbanization on sediment accumulation in small reservoirs has been discussed by Guy and Ferguson.[2]

The population growth of our cities and the pressure to occupy extensive land areas around them are mostly attributed to advances in agricultural technology and private transportation. Thus, the relatively high economic status of the urban population and relatively cheap transportation have combined to "price" the farmer off the land adjacent to cities. In many instances the use of more single- instead of multiple-family dwellings, larger parking lots, and one-level school and commercial buildings causes an increase of urban land use per capita.

This paper gives an example of the effects of residential construction on the sediment transported from a 58-acre drainage area at Kensington, Md. — a part of the metropolitan area of Washington, D.C. The duration of the study is from July 1957 to April 1962.

The soil at Kensington contains a considerable amount of sand and silt. The average size distribution of two subsoil samples in the basin is 14 percent clay, 30 percent silt, 43 percent sand, and 13 percent gravel. Thus, the soil is very friable when acted upon by the erosive forces of raindrops and by the surface runoff flowing in sheets, rills, and larger channels. Under rural or natural conditions, the soil is usually well protected by vegetative cover.

The slope of the land surface in the construction area ranges from 3 to 10 percent. Artificial slopes may be much steeper. The layout of streets in the basin is irregular. One of these streets is in the principal drainageway in the upper part of the basin.

The average annual precipitation on the area is about 42 inches. The average amount of stream runoff is about 16 inches, of which about 4 inches is overland or surface runoff. Areas with little or no vegetative cover usually have a higher portion of the precipitation leaving the basin as surface runoff.

Basic Measurements

The determination of the amount of sediment

[1] SAVINI, JOHN, and KAMMERER, J. C. URBAN GROWTH AND THE WATER REGIMEN. U.S. Geol. Survey Water-Supply Paper 1591A, 39 pp. 1961.

[2] GUY, H. P., and FERGUSON, G. E. SEDIMENT IN SMALL RESERVOIRS DUE TO URBANIZATION. Amer. Soc. Civil Engin., Jour. Hydr. Div. 88 (HY2): 27-37. 1962.

FIGURE 1. — Photograph taken August 28, 1957, on which the construction area in the basin is outlined. Scale, 303 feet per inch.

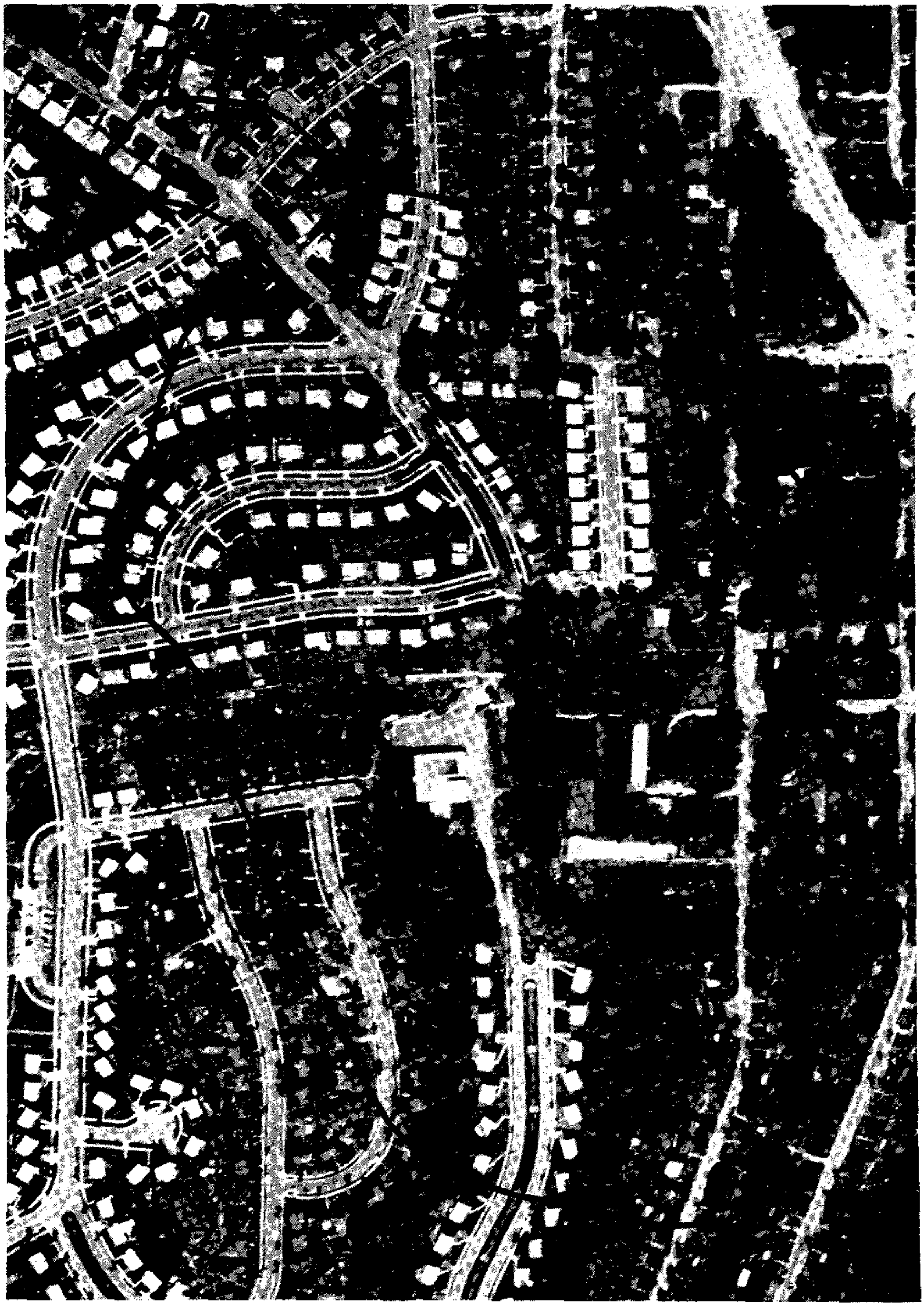

FIGURE 2. — Photograph taken May 7, 1961, on which the completed residential construction is shown. Stabilization of the construction area and the drainage channels caused a diminution of sediment outflow for many months. Scale, 317 feet per inch.

transported from the basin was accomplished by use of a combination of actual observations and a system of computation through correlations. The sampling was done on only selected storm events, because the small size of the basin caused the surface runoff from the construction area to drain from the basin within a few minutes of the rain. Generally, several samples were obtained for the selected storms in order to define the variation of sediment concentration in transport. The samples were velocity-weighted over the cross section of flow moving through a drop spillway, and therefore, except for particles too large to enter the nozzle of the sampler, represent the total sediment discharge.

Sediment concentration and water discharge data were collected for 25 storm events plus some miscellaneous single observations during other storm periods. The first observations were made in July 1959 about the time of maximum construction in the basin. The sediment transport determinations for the unmeasured storms was accomplished through correlation with water discharge of nearby Rock Creek on which a continuous record is available.

The water discharge for the storms having sediment measurements was computed from hydrographs drawn from instantaneous observations of flow depth in the notch of the drop spillway. The stage-discharge relation was established by measurements with a pigmy current meter. The unmeasured water discharge from the basin was determined by correlation with water discharge from nearby Rock Creek. All correlative relations for both sediment and water were made on the storm event basis.

A precise record of the environmental conditions of the basin during the period of record was not attempted, because of the effect of the varying stage of construction of a group of houses on the amount of sediment yield for a given storm characteristic and given season of the year. It is logical to assume that the maximum sediment yield would occur when the maximum 10 acres of construction was exposed. The total area exposed during the period of record can, however, be measured quite precisely from aerial photographs. (See figs. 1 and 2.) The total construction was for 89 single dwelling houses on 20½ acres.

Results for a Single Storm

The water discharge hydrograph and sediment concentration curves are shown in figure 3 for one of the larger storms (August 4, 1960). The streamflow hydrograph was drawn on the basis of four observations of water stage and the stage-discharge curve. The discharge near the peak rate of flow was checked by observations of float velocity moving through an 80-foot reach of the channel immediately upstream from the drop spillway.

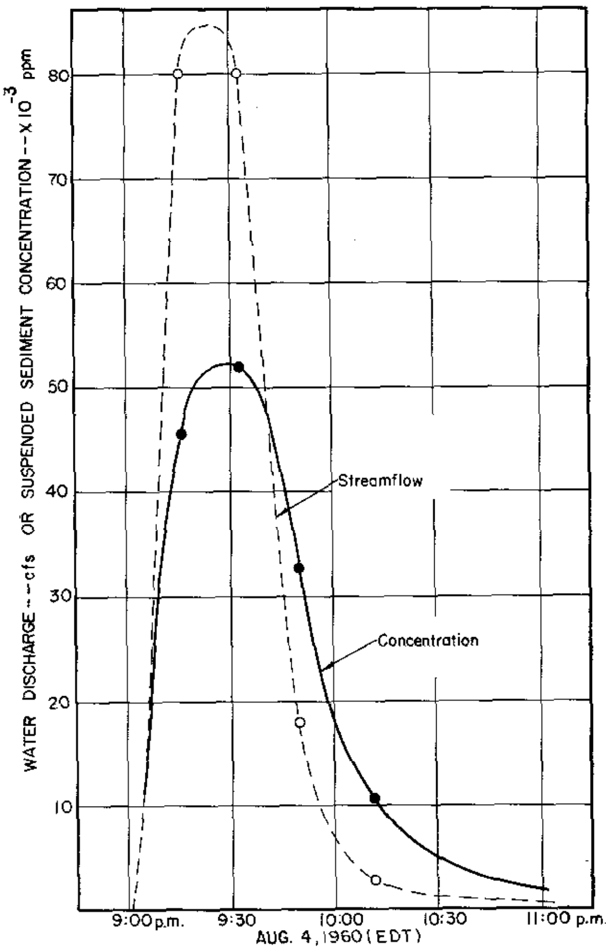

FIGURE 3. — Runoff hydrograph and suspended-sediment concentration graph for storm of August 4, 1960, on a 58-acre area at Kensington, Md.

Four depth-integrated suspended-sediment samples were obtained at the time of the water discharge measurements. A concentration graph was drawn on the basis of these data and the concentration data for other storms. The relative amount of sand in each concentration sample was determined by wet sieving the sediment. The percentage of sand in each consecutive sample during the storm is 67, 80, 77, and 44. The amount of coarse sediment as contrasted with the amount of fine sediment in transport is considered indicative of the relative amount of sediment derived from channel erosion as contrasted with sheet erosion.

The hydrograph and concentration graphs were subdivided as shown in table 1 for computation of water and sediment discharge. The table, the graphs, and the basic data provide information for summarizing the total and the peak intensity of rainfall, streamflow, and sediment as shown in table 2. This table allows more meaningful comparison of this storm with other storms and with other drainage areas.

TABLE 1.—*Subdivision and computation of water and sediment discharge for storm the evening of Aug. 4, 1960*

Time (p.m.)	Interval	Runoff discharge	Sediment	
			Concentration	Discharge
	Hour	*C.f.s.*	*P.p.m.*	*Tons*
9:00–9:06	1/10	6.5	7,000	0.5
9:06–9:12	1/10	39	28,000	12.3
9:12–9:18	1/10	74	43,000	37.1
9:18–9:30	1/5	84	51,200	100.3
9:30–9:36	1/10	79	51,700	47.7
9:36–9:42	1/10	56	49,000	32.0
9:42–9:48	1/10	34	41,500	16.5
9:48–10:00	1/5	13	27,000	7.9
10:00–10:12	1/5	4.7	14,400	1.5
10:12–10:42	1/2	1.7	6,000	.5
Total	—	[1]50.04	—	256.3

[1] In c.f.s. = hours.

TABLE 2.—*Summary of rainfall, streamflow, and sediment discharge, both total and peak intensity, for storm of Aug. 4, 1960*

Storm items	Total	Peak rates for maximum 12-minute period
Rainfall	1.82 inches from 9 to 11:20 p.m. 1.68 inches from 9 to 9:33 p.m.	Estimated 4 inches per hour.
Streamflow	2.1 c.f.s.-days 0.87 inch.	84 c.f.s. (from 58 acres) 927 c.f.s. per sq. mi. 1.44 inches per hour. 51,200 parts per million.
Sediment	260 tons.	8.4 tons per minute for 58 acres. 12,000 tons per day for 58 acres. 132,000 tons per day per sq. mi.

Analysis of Data

The quantity of sediment discharged from the basin during the period of construction was computed by the following generalized steps:

(1) The amount of water and the sediment discharged for each of the 25 sampled storm

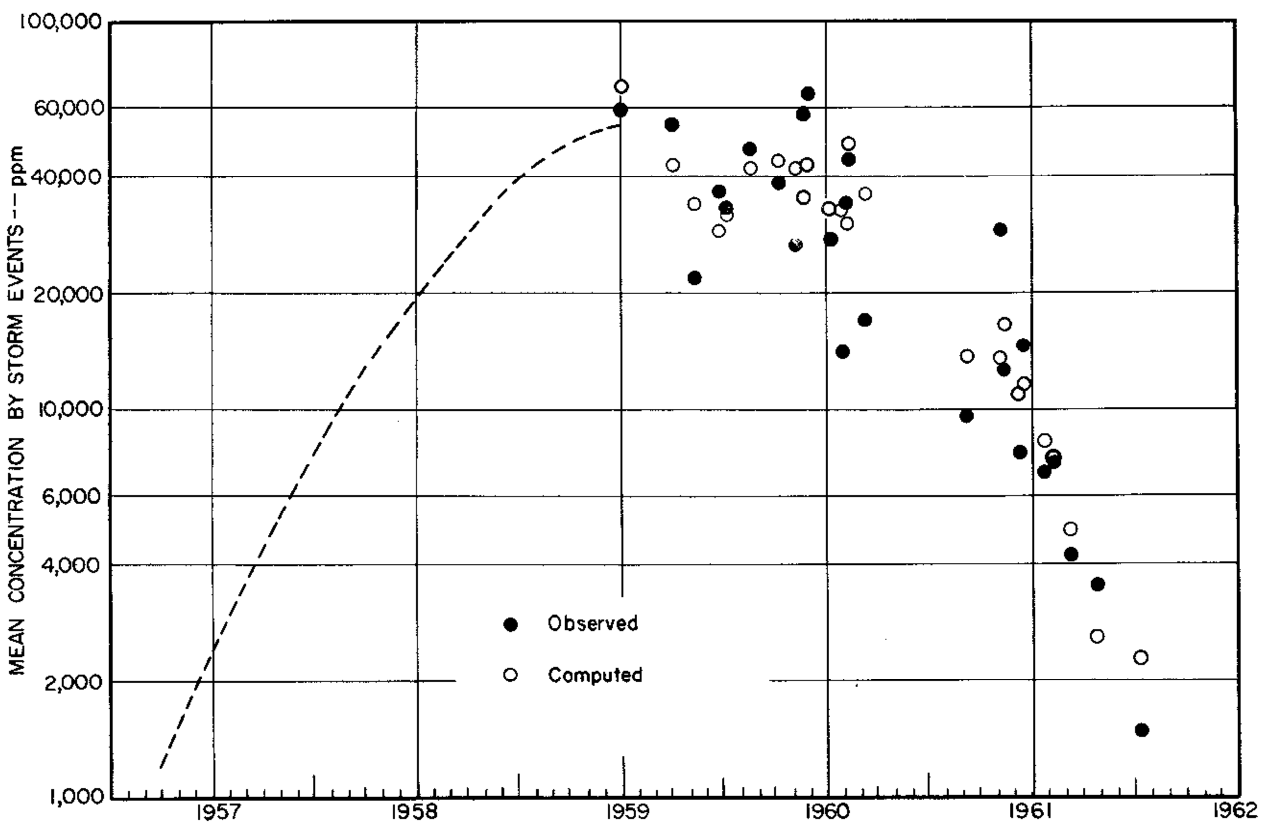

FIGURE 4.—Variation of mean sediment concentration of storm runoff from an area of residential construction at Kensington, Md., 1957-62. The line to July 1959 is estimated on basis of visual observations of construction area and the drainage channels.

events were computed from sketches of the hydrographs and sediment concentration graphs. Figure 3 and table 1 provide an example for one of the 25 storms.

(2) The second step consists of listing variables associated with the storm-to-storm variation of sediment concentration or discharge. Due to the drastic changes of environment in the drainage basin, the effects of which cannot be evaluated numerically, a measure of time (M_t) from the beginning of the record is essential (fig. 4).

Some of the remaining storm-to-storm variation can be related to (a) the magnitude of the storm measured in terms of runoff quantity (Q_w) or rainfall quantity (R_q), (b) the season or time of year which can be evaluated in terms of the mean air temperature (T_a), (c) the storm intensity determined from the relative peakedness of the hydrograph (P_n), and (d) the antecedent condition of the basin measured in terms of the base flow in nearby Rock Creek.[3] Tables 3 and 4 summarize the data for these variables for each of the 25 storms for the construction basin and for the Rock Creek basin (values with subscript r), respectively.

(3) Graphical correlation was used in the third general step to determine the necessary transformation of the variables to yield linear relationships. The values of T_a can be used directly. The function (f) for transformation of M_t is

$$f(M_t) = \log\left(\frac{M_t - 5}{1.5}\right)^{\left(1+\frac{M_t-5}{10}\right)}$$

All other variables are transformed with log base 10. The values for Q_w are multiplied by 100 and the values for R_q and R_{qr} are multiplied by 10.

TABLE 3.—*Hydrologic and sedimentologic data by storm events from a drainage area affected by residential construction*

Date	Precipitation (R_q)	Water discharge (Q_w) C.f.s.-days	Water discharge (Q_w) Inches	Sediment Discharge (Q_s)	Sediment Concentration (C)	Peak flow (P_n)	Mean air temperature (T_a)
1959	*Inches*			*Tons*	*P.p.m.*	*C.f.s.*	*°F.*
July 1	1.7	0.81	0.332	128	59,200	25	74
Oct. 1	.9	.39	.160	60	54,500	9.0	61
Nov. 7	.8	.25	.103	14.7	21,800	1.8	48
Dec. 28	.44	.048	.020	5.0	37,200	2.0	35
1960							
Jan. 3	.8	.156	.064	14.3	32,800	5.0	33
Feb. 18	.7	.59	.242	73	46,700	11.1	34
Apr. 3	.4	.194	.080	20.3	38,700	1.6	49
May 8	1.5	.76	.312	55	26,800	6.0	61
May 21	.6	.23	.094	37	57,300	12	64
May 22	.6	.39	.160	72	65,300	15	64
July 11	.7	.158	.064	11.7	27,400	5.0	75
July 30	1.0	.53	.218	20.2	14,000	3.1	75
Aug. 3	.8	.52	.213	48	34,000	13	74
Aug. 4	1.8	2.08	.854	256	44,000	84	74
Sept. 12	4.1	2.68	1.102	123	17,000	20	68
1961							
Mar. 8	.4	.233	.096	6.0	9,600	7.8	41
May 7	.6	.149	.061	11.7	29,000	13.5	61
May 12	.3	.37	.152	12.6	12,700	9.0	61
June 9	.22	.032	.013	.7	7,700	2.1	69
June 14	1.0	.48	.197	18.9	14,600	22	70
July 24	.30	.042	.017	.8	6,900	3.3	75
Aug. 9	.6	.21	.086	4.1	7,350	12.9	74
Sept. 3	.30	.125	.051	1.4	4,200	12.3	70
Oct. 21	.5	.45	.185	4.4	3,550	3.4	54
1962							
Jan. 6	.6	.23	.094	.9	1,490	3.9	33

(4) Multiple regression analysis by computer was then used to obtain equations having a minimum standard error of estimate for predicting log C and log Q_w. These are:

1. Log $C = 4.935 - 0.506\ f(M_t) + 0.317$ log $P_n - 0.294$ log 10 R_q (Standard error = 0.141 log units.)
2. Log $C = 3.741 + 0.109$ log $Q_{wr} - 0.429\ f(M_t) + 0.0062\ T_a + 0.325$ log Q_{br} (Standard error = 0.172 log units.)
3. Log 100 $Q_w = -0.579 + 0.896$ log $Q_{wr} + 0.0103\ T_a - 0.345$ log Q_{br} (Standard error = 0.271 log units.)

The first equation is mostly of academic interest because water discharge and precipitation data were collected for only 25 storms during the period of observation; however, it does

[3] GUY, H. P. AN ANALYSIS OF SOME STORM-PERIOD VARIABLES AFFECTING STREAM SEDIMENT TRANSPORT. U.S. Geol. Survey Prof. Paper 462-E, 46 pp. 1964.

TABLE 4.—*Hydrologic data for Rock Creek for storm events listed in table 3*

Date	Precipitation (R_{qr})	Water discharge (Q_{wr}) C.f.s.-days	Water discharge (Q_{wr}) Inches	Base flow (Q_{br})	Peak flow (P_{nr})
1959	*Inches*			*C.f.s.*	*C.f.s.*
July 1	0.8	170	0.102	18	840
Oct. 1	1.0	135	.081	21	396
Nov. 7	.6	55	.033	33	164
Dec. 28	.6	65	.039	49	121
1960					
Jan. 3	.8	205	.123	41	443
Feb. 18	1.3	895	.536	75	1,080
Apr. 3	1.2	286	.171	110	330
May 8	1.9	323	.193	36	418
May 21	.8	128	.077	35	131
May 22	.5	175	.101	53	401
July 11	1.5	166	.099	19	386
July 30	1.5	171	.102	22	450
Aug. 3	.9	111	.066	18	890
Aug. 4	1.6	522	.312	30	1,750
Sept. 12	3.2	791	.473	28	1,200
1961					
Mar. 8	.3	124	.074	76	99
May 7	.5	160	.096	60	374
May 12	.4	215	.129	57	325
June 9	.2	35	.021	43	283
June 14	.5	148	.089	35	650
July 24	.6	34	.020	34	90
Aug. 9	.4	50	.030	21	194
Sept. 3	.2	12	.007	18	48
Oct. 21	1.8	268	.160	6	531
1962					
Jan. 6	.8	360	.216	28	480

give a basis for evaluating the effectiveness of the other equations when used for determining sediment discharge of the unsampled storms.

From the time of the first observation in July 1959 to the end of the record in April 1962, the continuous recording from the Rock Creek gaging station shows a total of 124 storm events that could result in at least 0.011 inch of runoff or at least 0.2 ton of sediment. The sediment discharged from the drainage basin for each of the 124 storm events was computed by

$Q_s = 0.0027\ C\ Q_w$ when $C < 32{,}000$ p.p.m.
and

$Q_s = 0.0028\ C\ Q_w$ when $C > 32{,}000$ p.p.m.
where C and Q_w are computed from the multiple regression equations 2 and 3. The computed results for C are presented for comparison with the measured values of C in figure 4 for the 25 storms for which data were obtained.

From July 1957, the beginning of construction, to the observation of the first storm event in July 1959, the data from Rock Creek show an additional 63 storm events important to the determination of the sediment contribution from the construction area. The sediment discharged for these events was computed by use of the same formulas for Q_s, the third regression equation for Q_w, and the use of an estimated value for C from figure 4. During the period of record for these 63 events, the value for Q_w was decreased by a factor to compensate for the trend of increasing storm runoff as the 20-acre construction area was cleared of it natural vegetative cover. The factor was varied with time from 0.62 in July 1957 to 1.00 in July 1959. During the sampling period from July 1959 to April 1962 no significant change in the relation of runoff in the test basin Q_w to runoff in Rock Creek Q_{wr} took place.

The computations show that 4,000 tons of sediment in 22 inches of runoff was discharged from the 58-acre basin during the 4¾-year construction period from July 1957 to April 1962. The actual construction area on which 89 single family dwellings were built is 20½ acres. The remaining 37½ acres is mostly a residential area, which was completed prior to this study, and some undeveloped area. A liberal estimate of sediment discharge for the 37½-acre part of the basin would be three-quarter ton per acre per year, or a total of about 130 tons. The net is then 3,880 tons from the construction area, which is equivalent to 189 tons per acre, or 121,000 tons per square mile.

Figure 5 shows the trend of cumulative sedi-

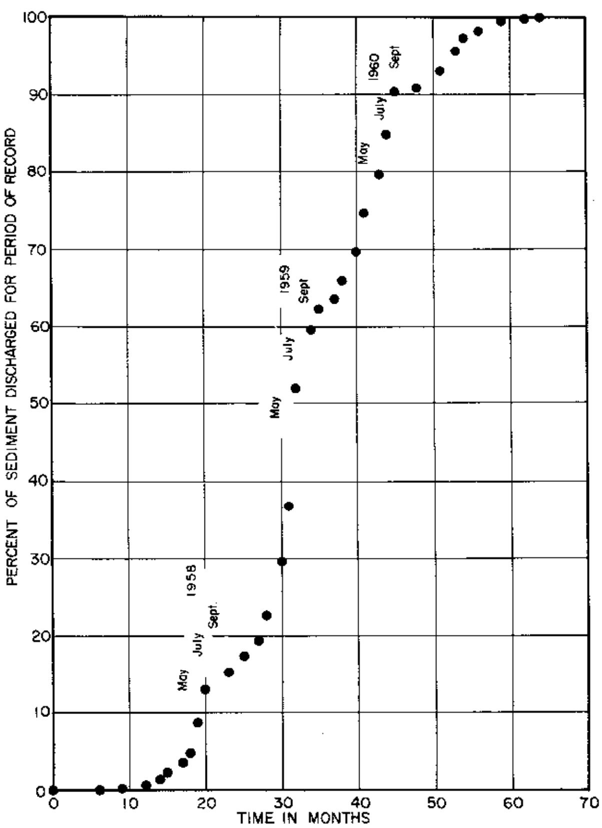

FIGURE 5. — Cumulative sediment discharged from the construction area with time. Note the higher rates of yield during summer months.

ment discharge from the area during the construction period. The rate of sediment discharge yield was more during the summer months than during the remaining months of the year. The maximum year of accumulation was during 1959 when the average concentration of sediment in the runoff was a maximum (fig. 4).

Discussion and Summary

Most of the construction in the 58-acre basin was located on or near the upper part of the basin. As noted in the introduction, one of the streets was built over the principal drainageway. The construction followed a pattern of development in subareas ranging in size sufficient for 5 to 20 houses with as many as 3 subareas exposed at one time. The lack of vegetative cover reduces the infiltration rate and hence causes an increase in surface runoff. Some of the subareas were exposed for as long as 2 years while others were exposed for only about 8 months. The relatively great areas of exposed slopes and channels, therefore, cause intensive sheet, rill, and channel erosion of sediments.

In the early stages of construction in 1957 and 1958, much of the sand eroded from the construction areas was deposited in the downstream channels, giving them the appearance of a true sand-bed stream. In the last year of the record, most of the sand was transported from the channels. Thus, the channels returned to the more natural state with rock and gravel armoring of the bed and with heavy vegetative growth on the banks.

The 189 tons per acre, or 121,000 tons per square mile, determined from the Kensington area may be considerably greater than may be expected for average urbanization around Washington. Measurements of sediment accumulated in Lake Barcroft, also a part of the metropolitan Washington, near Fairfax, Va., between 1938 and 1957 show an average of about 25,000 tons for each of the 9½ square miles urbanized. The Lake Barcroft yield may be low, since much of the housing development, at least in the vicinity of the lake, is "custom built," that is, only the small area for a single home is exposed at a given time and each area has little likelihood of being connected by direct channel to the natural surface drainage system. Also, in the Barcroft area, some sediment is stored in the channels and on the flood plains that drain the area to the lake.

It is reasonable to assume that the streams draining the area around metropolitan Washington will transport 20 million tons of sediment to the Potomac River in the next 20 years given the following:

1. That the population increases by 2 million.
2. That the present population density of 4,000 per square mile will continue.
3. That 500 square miles of rural area will therefore be urbanized.
4. That the sediment discharged to the streams will be 40,000 tons per square mile, or about one-third that measured at Kensington and yet more than that measured at Lake Barcroft.

The results of urbanization under these conditions amount to the movement by streams of 10 tons of sediment for each person added to the city. Such intense movement causes the streams to be muddy part of the time and may cause considerable stream aggradation. The sediment will be deposited in small reservoirs in some cases, but mostly in the navigation and recreation area of the Potomac estuary.

FACTORS RELATED TO GULLY GROWTH IN THE DEEP LOESS AREA OF WESTERN IOWA

[Paper No. 4]

By Craig E. Beer, *assistant professor*, and Howard P. Johnson, *professor, Agricultural Engineering Department, Iowa State University, Ames*

Introduction

Soil erosion became a serious problem in America soon after the beginning of modern agriculture. One type of erosion was the formation of gullies. In 1939, Bennett (*2*) stated there were more than 200 million active gullies in the United States. Since 1939 more gullies have developed. Although progress has been made in the control of gullies, the process of gullying has not been defined by quantitative relationships. In many cases today, the quantitative prediction of gully development is needed for the cost-benefit analysis of structural measures in the Public Law 566 Watershed Program. Since little has been done in research to aid the geologists and engineers to improve their estimates, gross errors may be made in prediction of gully growth. The need for further research is emphasized by a quote from Lueder (*4*):

> It is rather unfortunate that no quantitative observational data, prepared upon a comparative base, have yet been amassed regarding the relationships among length, texture, erodibility, age and hydrology. It is possible

that such data would prove so complex as to defy other than general analysis. Even general analysis would be of value, however.

The objective of this paper is to present part of the results of a study[1] that was designed to meet the following objectives.

1. To select active gullies in the loess soil area and determine, as accurately as possible, the amount of gully growth for a given period in the past by the use of land surveys and aerial photography with ground control.
2. To relate the gully growth in the given period to hydrologic, gully geometry, and watershed variables.
3. To define relationships between factors that are associated with the geometry of the gully.

Investigation

Selection of Gully Study Area

The area used for the gully study was Steer Creek Watershed located in Harrison County, Iowa. This watershed covers approximately 14 square miles. The main gully extends upstream for 10 miles and has many laterals and sublaterals that are active gullies. The gullies in Steer Creek Watershed were well suited for the study and met the following criteria for the selection of a study site.

1. Data must be available to determine accurately the gully development for a 20-year period. It would be desirable to divide the 20-year period into two or three intervals that would increase the number of samples.
2. The land treatment and watershed cover must be available for a 20-year period.
3. Recording rain gage records should be available from a station located near the gullies to be studied.

Methods of Obtaining Data

Aerial flights for 1938, 1949, and 1961 were obtained for Steer Creek Watershed. Contact prints of the 1938 and 1949 flights were obtained from the U.S. Department of Agriculture Commodity Stabilization Service. The 1961 flight was contracted by the Iowa Agricultural and Home Economics Experiment Station. Before the 1961 flight, targets were placed on the ground at right angles to the flight line and were visible on the photographs. The distance between the targets was chained, which made it possible to determine the exact scale of any photograph along the flight lines. In all cases where aerial photographs were available, diapositives of each negative were made and used in a Kelsh Plotter to obtain a topographic map with four- to five-fold enlargement. Thus, it was possible to delineate on the topographic map the gully outlines, land treatment measures, land use, subwatershed outlines, and the natural drainageways from the gully overfalls to the subwatershed divides. The map scale for the 1961 flight was 1 inch equal to 200 feet and, for the 1938 and 1949 flight, 1 inch equal to 500 feet.

A ground survey of Steer Creek Watershed was made by Soil Conservation Service personnel in 1942. This survey provided means for determining gully outlines, gully cross sections, gully profiles, and land use that existed in 1942. The scale of the 1942 topographic map was 1 inch equal to 200 feet. Thus, it was possible to obtain the 1942 and 1961 data from the same map scale.

The choice of weather stations with appropriate precipitation records was limited. The nearest station to Steer Creek Watershed that had recording rain gage records prior to 1938 was the airport at Omaha, Nebr. Therefore, the precipitation records from Omaha were used in this gully study.

Interviews were conducted by the authors with farmers who had been residents in the Steer Creek Watershed during the period 1900-30. From these interviews, it was possible to correlate landmarks with stages of gully development in some areas during this period. Further information on the stage of development of the drainage system in Steer Creek was obtained from the original land surveyors' notes (*1*).

During a 20-year period, many changes, either natural or induced by man, can occur that render some gully growth data unusable. Many cases were encountered in this study where the gully growth had been altered by roads, by installation of land treatment measures, and by excessive timber growth in the gully. It is also extremely difficult to determine the magnitude of some variables related to gullying. In most cases, no continuous record of either land cover or volume of runoff is available. Thus, the validity of any quantitative relationship for gullying is dependent on the quality of the available data.

Analyses

The records (*1*) of 1851 showed no major gully development in Steer Creek. There were three developed laterals averaging 3 feet in width. Information obtained from interviews showed active gullying around 1900 in the laterals that were shown on the 1852 map. However, the development of the remaining 26 major lateral gullies has occurred from 1915 to 1963. The maximum width of the main gully in 1852 was 7 feet at the outlet. As late as 1932, the depth and width of the main was such that it could be crossed easily by livestock and horse-drawn vehicles at many locations. The depth

[1] BEER, C. E. RELATIONSHIP OF FACTORS CONTRIBUTING TO GULLY DEVELOPMENT IN LOESS SOILS OF WESTERN IOWA. 1962. [Unpublished Ph.D. thesis. On file, Iowa State University Library, Ames.]

of the main gully today exceeds 30 feet and the width 50 feet at most locations.

The major part of this gully study was devoted to relating the growth of lateral gullies to hydrologic, gully geometry, and topographic variables. The hydrologic variables that were evaluated for the period of gully growth were precipitation depths and an index of surface runoff. An equation derived by Gray [2] that predicts volume of runoff on a per storm basis was used to evaluate the total runoff for a given gully growth period. The equation expresses the volume of runoff as a function of depth and intensity of precipitation, percentage of watershed area in meadow, and the antecedent precipitation index.

The gully geometry and topographic variables were evaluated from the topographic maps. The geometry variables included the length of the gully from the outlet to the overfall and the surface area of the gully contained within the gully outline on the maps. The topographic variables were evaluated for each gully and included the watershed area and the length along the drainageway from the outlet to the watershed divide.

Regression Analysis With Linear Model for Change in Gully Area

A regression analysis was made on the data of lateral gully development from 1938 to 1961. The data were from 61 samples. One gully could provide three samples by dividing the period from 1938 to 1961 into three intervals. All gully samples had one overfall and were continuous from the outlet to the overfall.

Since regression analysis may be defined as the estimation or prediction of the value of one variable from the values of other given variables, the practical application presents a number of problems. First, there are the problems of estimating the constants of a regression when the form of the relationship is given and the testing of the concordance of some preassigned regression relation with the data. There is also the question of which variables should be included in the relationship. Since the functional relationship or model for predicting gully growth and the variables that should be included were not known, a model that expressed gully growth as a linear function of the variables was assumed for the preliminary analysis.

Table 1 includes five equations derived by using the linear model. These equations were obtained by programming the data for the IBM 650 computer. Five combinations of variables represented by equations 4, 5, 6, 7, and 8 in table 1 were investigated.

Statistically, the equations in table 1 fit the data reasonably well. The R^2 statistic, which according to Snedecor (*5*) measures the fraction or percent of total deviation that is attributed to regression, is 0.70, 0.89, 0.73, 0.89, and 0.89 respectively for equations 4, 5, 6, 7, and 8. Each regression coefficient of the variables in equations 4, 5, 6, 7, and 8 was tested to determine if the value was significantly different from zero. This test of significance is based on the *t*-distribution, and, in a given equation, one considers a regression coefficient to be tested independently of the remaining coefficients. Those coefficients that were significant at the 95 percent level or greater are shown in table 1 by boldface figures. The failure of a regression coefficient to be significant does not necessarily mean that the associated variable should be omitted from the equation. Yates, as quoted by Williams (*6, p. 5*), has the following to say about tests of significance:

TABLE 1.—*Regression equations to predict change in gully area using a linear model* [1]

No.	Equations[2]
4....	$X_1 = -0.906 + \mathbf{0.0022}X_2 - \mathbf{0.0484}X_3 + 0.0098X_4 + 0.0308X_5 - 0.0271X_6 + \mathbf{5.5209}X_7$
5....	$X_1 = -0.324 - 0.0006X_2 - \mathbf{0.0435}X_3 + 0.0063X_4 + 0.0453X_5 - \mathbf{0.0355}X_6 + 0.0013X_8 - 0.00008X_9$
6....	$X_1 = -1.665 - 0.0019X_2 - \mathbf{0.0495}X_3 - 0.0143X_4 + 0.0431X_5 - 0.0814X_6 + \mathbf{5.5576}X_7 + \mathbf{0.0003}X_9$
7....	$X_1 = -0.526 - 0.0017X_2 - \mathbf{0.0465}X_3 + 0.0069X_4 + \mathbf{0.0533}X_5 - 0.0506X_6 - 0.2172X_7 + \mathbf{0.0013}X_8$
8....	$X_1 = -0.240 - 0.0428X_3 + \mathbf{0.0057}X_4 + 0.0443X_5 - 0.0286X_6 + \mathbf{0.0012}X_9 - \mathbf{0.0013}X_{14}$

[1] Coefficients in **boldface** in this table indicate a significant level of 95 percent or greater.
[2] X^1 = Change in gully surface area (acres);
X_2 = Watershed area (acres);
X_3 = Deviation of precipitation from normal (inches);
X_4 = Index of surface runoff (inches);
X_5 = Length of period (year);
X_6 = Terraced area of watershed (acres);
X_7 = Ratio of gully length (L_1) at beginning of period to total length (L) from outlet to watershed divide;
X_8 = Gully length (L_1) at beginning of period (feet);
X_9 = Total length (L) from outlet to watershed divide (feet);
X_{14} = Length from end of gully to watershed divide (feet).

[2] GRAY, D. M., and JOHNSON, H. P. RAINFALL AND RUNOFF RELATIONSHIPS FOR LOESS SOILS OF WESTERN IOWA. Iowa State Univ. Dept. Agr. Engin., Ames. 1961. [Unpublished paper presented at Amer. Soc. Agr. Engin. Meeting, Ames.]

The emphasis on tests of significance, and the consideration of the results of each experiment in isolation, have had the unfortunate consequence that scientific workers have often regarded the execution of a test of significance on an experiment as the ultimate objective. Results are significant or not and that is the end of it. Research workers, therefore, have to accustom themselves to the fact that in many branches of research the really critical experiment is rare, and that it is frequently necessary to combine the results of numbers of experiments dealing with the same issue in order to form a satisfactory picture of the true situation.

On the basis of the preceding discussion, there is no evidence to reject any of the equations in table 1. However, a further check on the validity of equations 4, 5, 6, 7, and 8 was made by substituting the original data into the equations and examining the predicted value of change in gully surface area. All equations gave some predicted values that were negative or less than zero. This result is not desirable and limits the usefulness of the linear model equations. Also, computations from the linear analysis revealed correlations of 0.80 to 0.92 between the following variables:

1. Watershed area and watershed length;
2. Length of period and index of surface runoff; and
3. Length of period and deviations of precipitation from normal.

Regression Analysis With Logarithmic Model for Change in Gully Area

To avoid the problem of negative-predicted values and reduce the interdependence of variables, a logarithmic model with different variable combinations was tried. This model forced the curve through the origin, and no negative predicted values would result from the use of the equation. In the logarithmic model, the logarithm of the predicted variable equals the logarithm of a constant plus the sum of the products of the coefficients times the logarithms of the respective variables. Since the variable X_3, which represented the deviation of precipitation from normal, could be either positive or negative, it was not possible to include this variable in the logarithmic form; the product of X_3 and its coefficient were added to the logarithmic terms. Thus, after taking the antilogarithm of both sides of the model, the equation is of the form represented by equations 9, 10, and 11 in table 2.

TABLE 2.—*Regression equations to predict change in gully area using a logarithmic model* [1]

No.	Equations[1]
9...	$X_1 = 0.013\ X_2^{0.0790}\ X_5^{\mathbf{1.314}} X_6^{-0.0708}\ X_{10}^{\mathbf{0.500}}\ e^{-\mathbf{0.0783} X_3}$
10...	$X_1 = 0.01\ X_4^{0.0982}\ X_6^{-0.0440}\ X_8^{\mathbf{0.7954}}\ X_{14}^{-0.2473}\ e^{-0.0360 X_3}$
11...	$X_1 = 0.549\ X_2^{-0.1314}\ X_4^{0.0411}\ X_6^{-0.0575}\ X_{10}^{\mathbf{0.6775}}\ e^{-0.0304 X_3}$

[1] **Boldface** coefficients in this table indicate a significance level of 95 percent or greater.
[2] X_1 = Change in gully surface area (acres);
X_2 = Watershed area (acres);
X_3 = Deviation of precipitation from normal (inches);
X_4 = Index of surface runoff (inches);
X_5 = Length of period (year);
X_6 = Terraced area of watershed (acres);
X_8 = Gully length (L_1) at beginning of period (feet);
X_{10} = Gully surface area at beginning of period (acres);
X_{14} = Length from end of gully to watershed divide (feet);
e = 2.71828 (base of natural logarithm).

With the information gained from the linear analysis, the combinations of variables for the logarithmic model were chosen to satisfy the following conditions:

1. One variable would be used to measure the watershed area contributing runoff at the overfall;
2. One variable would be used to measure the length along the gully where growth in surface area results from increased width in the present length of the gully;
3. A lesser number of variables would be used to measure the hydrologic and period-of-time factors; and
4. The remaining variables would be the same as in the linear analysis.

Although the R^2 values for equations 9, 10, and 11 are lower than for the linear model equations, the sign of most of the exponents is the same as if the sign had been determined by reasoning. The watershed area variable becomes positive in equation 9 with the omission of the watershed length variable. However, the sign of the watershed area variable is reversed in equation 11. In equation 9 the period of time (X_5) was used instead of the runoff index (X_4). With a high correlation between X_4 and X_5, the change in sign for the watershed area would not be expected. Since this result is not explainable, equation 10 is preferred over equations 9 and 11.

In equation 10 the length from the overfall to the watershed divide has been used to measure the effect of the watershed area above the overfall; this watershed area contributes runoff for the elongation of the gully. The gully length (X_8) has been included in equation 10, which is a measure of the watershed area contributing runoff to the perimeter of the gully. This length also gives an indication for potential gully growth through widening of the gully. With an increase in area terraced, the terrace variable reduces the gully surface area. This would be expected, since level terraces reduce the volume of runoff. The two remaining variables — X_{14} and X_3 — are both negative. Every regression that was made in the gully study shows X_3 to be negative. Engelstad (*3*) has given a possible explanation of the negative sign. He has observed large cracks in the areas of loess soil during extremely dry periods. Shrinkage cracks that form parallel to the gully sides would intercept surface runoff and tend to increase the rate of gully bank caving. Also, land cover is poorer, particularly in pastures, during periods of rainfall deficiency. The variable for the length from the gully overfall to the watershed divide, with its negative sign, is a subtractive factor that reduces the effect of X_8 when the gully is starting. As the gully length (L_1) increases, the value of X_{14} increases and approaches a maximum value equal to one.

In addition to statistical parameters and tests, it is possible to examine the predicted values and use them as a guide in selecting the most appropriate equation. The predicted values are obtained by substituting the original sample values of the independent variables into a given equation. In figure 1, the predicted value ($\hat{y}$) has been computed for equation 8. Since the original value of the dependent variable is represented by y, a value of 1 for the ratio $\hat{y}/y$ represents a perfect fit for a given sample value. In figure 1, a perfect fit for all sample values would be represented by a vertical line from the abcissa value of one. However, a perfect fit was not obtained and lines have been drawn on figure 1 to bracket the percentage of the sample

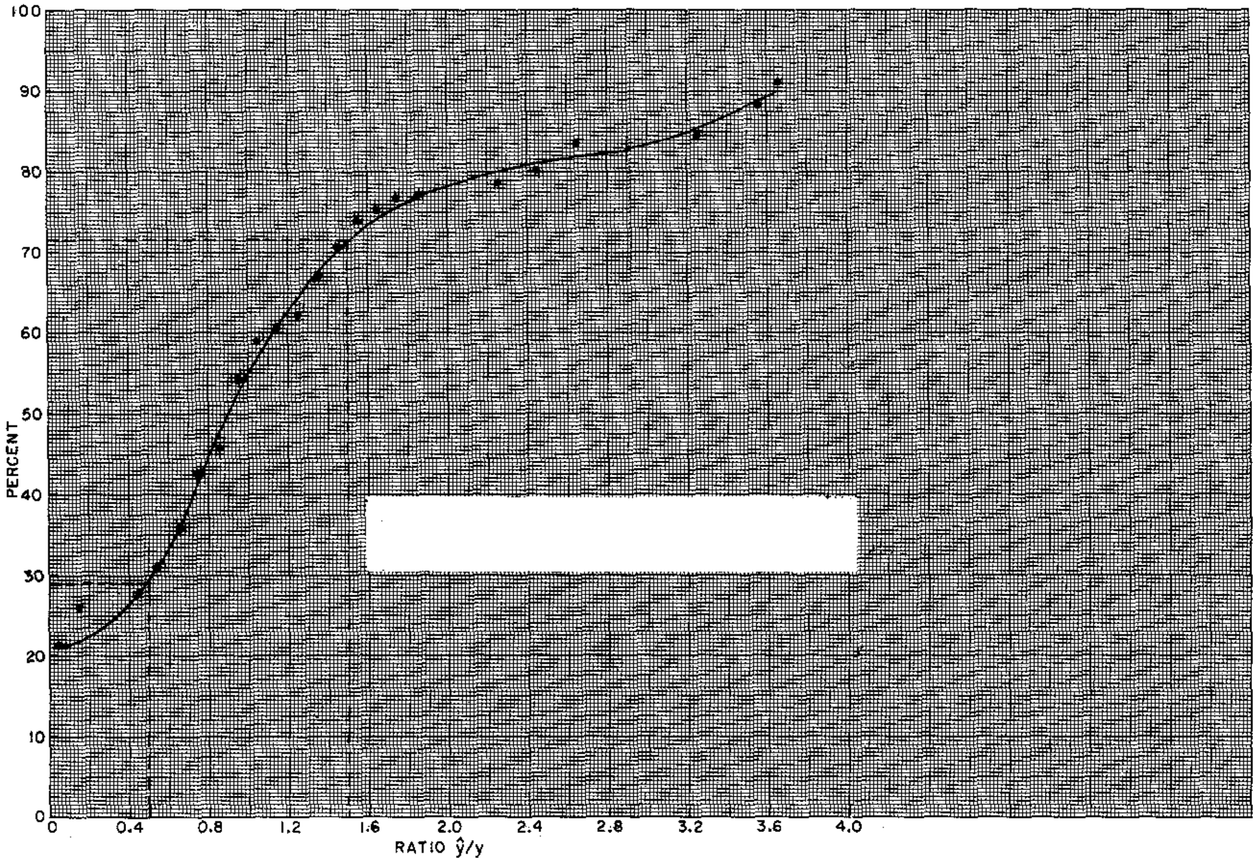

FIGURE 1. — Cumulative-distribution of the ratio of predicted value ($\hat{y}$) to original value (y) for linear equation No. 8.

values that were predicted within one-half of the original value. With the linear equation (equation 8) about 42 percent of the samples were predicted within 50 percent of the actual original value. The curve also shows that about 20 percent of the sample values were predicted with a negative value.

A similar comparison for the logarithmic equation (equation 10) is shown in figure 2. With the logarithmic equation, the percentage of samples predicted within 50 percent is increased to about 50 percent; an increase of 8 percent over the linear equation. It is also shown that no negative predicted values were obtained with the logarithmic equation.

Summary and Conclusions

The major objective of this study was to define a functional relationship that describes the gully development phenomena in western Iowa. Since no controlled studies of individual components responsible for the gullying process have been made, this study was based on a historical approach where all variables were evaluated from the past growth of gullies. Steer Creek Watershed, a gullied area in Harrison County, Iowa, was used for this study. The rates of gullying were determined with the use of controlled aerial flights, supplemented with a topographic survey that was made on the watershed 20 years ago. The hydrologic and watershed factors that were postulated to effect gullying were evaluated for the same period as for the gully growth.

The major emphasis in this study was directed to the evaluation of the lateral gully development since 1938. The gully, hydrologic, and watershed data were programmed for the IBM 650 computer. From the programmed data, prediction equations based on two models were obtained for the change in gully surface area. These models were the characteristic linear model and a logarithmic model where the independent factors are multiplied in the prediction equation. Although different hydrologic, gully, and watershed variables and combinations

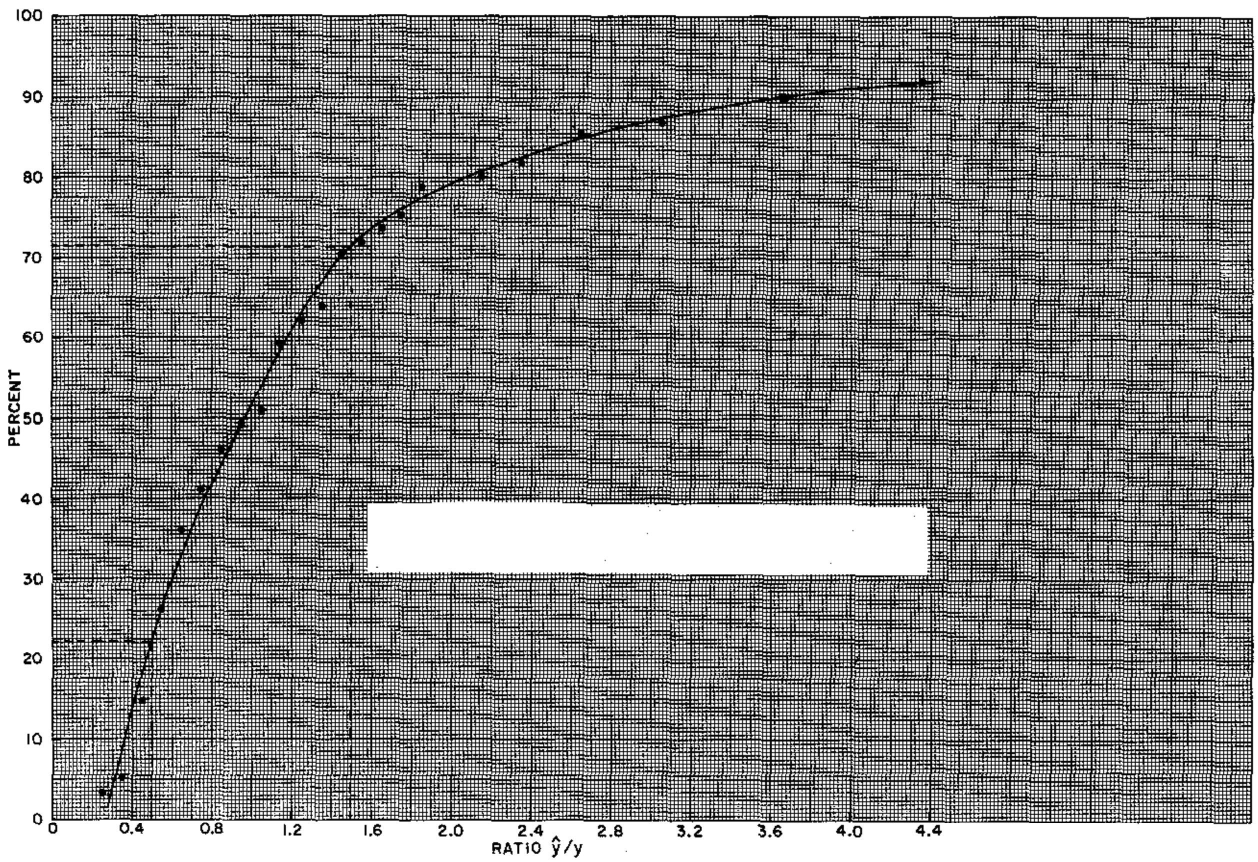

FIGURE 2.—Cumulative-distribution of the ratio of predicted value ($\hat{y}$) to original value (y) for logarithmic equation No. 10.

of these variables were used, the prediction equation for change in gully surface area that most nearly represented the gully development phenomena was:

$$X_1 = 0.01\ X_4^{0.0982}\ X_6^{-0.0440}\ X_8^{0.7954}\ X_{14}^{-0.2473}\ e^{-0.0360x_3}$$

Where X_1 = Change in gully surface area, in acres;
X_3 = Deviation of precipitation from normal, in inches;
X_4 = Index of surface runoff, in inches;
X_6 = Terraced area of watershed, in acres;
X_8 = Gully length (L_1) at beginning of period, in feet;
X_{14} = Length from end of gully to watershed divide, in feet.

The conclusion that the functional relationship for the gullying process is a logarithmic relationship was supported by the fact that the average deviations from the fitted curve were smaller for the logarithmic model than for the linear model.

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LOGGING AND EROSION ON ROUGH TERRAIN IN THE EAST

[Paper No. 5]

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During the past 150 years the forest lands in most of the southern Appalachian, Allegheny, White, and Green Mountains in the eastern United States have been cut over one, two, or more times. In the New England mountains, extensive operations began after the introduction of the steam-powered sawmill around 1850. Cutting reached a peak around 1880. The Allegheny and southern Appalachian forests were cut over somewhat later, and production reached its peak there about 1900. Cutting in virgin stands often followed a two-step procedure in which selected valuable species were cut first, followed by a second cutting a few years later in which everything salable was taken. Generally most of this forest land has been cut over every 30 to 60 years.

The results of the several cuttings are evident; forests now covering the Eastern mountains are second or third growth, and little remains of the original cover except isolated stems that, at time of logging, were either too hard to get to or were not worth cutting. A few scattered tracts of virgin timber are so rare that they have become tourist attractions, and well-worn paths attest to the popularity of these areas and portend their probable eventual demise due to soil compaction.

To the trained eye, evidences of the original logging are still visible in the occasional opening that bears the remnants of a logging camp, and, most of all, in the overgrown but still traceable logging roads that crisscross these areas and are now traveled only by the occasional hunter. These roads and the associated skid trails may well have occupied 10 to 20 percent of the logged-over area. Their aggregate length is great; in the upper Potomac river watershed, for instance, there is an estimated 1,620 miles of abandoned logging roads.

Logging Erosion

What has been the effect of this logging on erosion? General observation indicates that forest areas that have not been cut over in the past 20 or more years rarely show any signs of active erosion. The forest floor is covered with an inch or two of litter overlying 1 to 3 inches of humus (*6*). Even on steep slopes the litter shows no evidence of disturbance by overland flow, which strongly suggests that infiltration rates exceed rainfall intensities.

Most abandoned logging roads are stabilized. Generally they bear a mixed cover of seedlings, saplings, shrubs, herbs, moss, and litter; and some have an erosion pavement.

Streamflow from the forested headwaters is generally clear and prized for its purity; the second- and third-growth forest apparently is an excellent guardian of our water supplies. Under heavy rainfalls, the water becomes discolored — but more by organic debris or from bank cutting than by sediment from the tree-covered slopes.

For example, turbidities of streamflow from the second-growth forested watersheds of the Coweeta Hydrologic Laboratory in western North Carolina are generally less than 2 p.p.m. (parts per million) during nonstorm periods and they range well under 11 p.p.m. (the drinking water standard) during most storm periods. Extreme conditions may produce turbidities as high as 80 p.p.m., most of it organic matter picked up by the high flow (*1*). Streamflow from second-growth watersheds at the Fernow Experimental Forest in West Virginia has an average turbidity under 5 p.p.m. (*8*). At the Hubbard Brook Experimental Forest watersheds in New Hampshire, turbidities during nonstorm periods are less than 1 p.p.m.; during an unusually heavy storm they have ranged from 4 to 11 p.p.m. These forested watersheds have not been disturbed by logging for several decades.

Such conditions are somewhat difficult to square with an opinion held by many that forest cutting leads to erosion, sediment in the streams, and associated land ills. Forest watershed research results back up this opinion with some evidence. For instance, at the Coweeta Hydrologic Laboratory, exploitative logging resulted in a maximum turbidity of 5,700 p.p.m. (*1*); and at the Fernow Experimental Forest, a maximum turbidity of 56,000 p.p.m. (*8*). Keys to this paradox may lie in certain relationships recently observed on the Fernow Experimental Forest where four small forested watersheds were logged according to four different practices.

The Fernow Studies

The Fernow experimental watersheds, ranging in size from 38 to 96 acres, had before treatment a forest cover of second-growth hardwoods about 50 years old interspersed in places with a large number of old residuals left from original logging. Principal species were red and chestnut oaks, black cherry, yellow-poplar, sugar maple, beech, birch, and basswood. The soils of these watersheds are strongly acid (pH 4.5 to 5.0) silt loams, primarily of the Calvin series. Soil depth to bedrock ranges from 25 to 48 inches with an average depth of 30 inches. Stone content is moderately high. Bedrock consists of interbedded red shales and sandstones of the Catskill series. Slopes are steep, averaging 40 to 65 percent, and logging is difficult.

After a calibration period, four of these watersheds were cut over in 1957-58, and a fifth was left uncut as a control. Turbidity samples were collected before, during, and after logging; and ring-infiltrometer tests were made on and off the skidroads.

Watershed treatments ranged from a commercial clear-cutting with logger's choice skidroads to a conservative selection cutting with carefully planned and constructed skidroads (table 1). Logging was done with a TD–9 crawler tractor equipped with a rubber-tired sulky and winch. Generally the tractor stayed on the skidroads and winched up the material in tree lengths. Tractor skidroads — but no truck

TABLE 1.—*Forest practices applied to Fernow experimental watersheds*

Practice	Timber cut	Period of logging	Maximum [1] of grade skidroads	Water bars	Other requirements
Commercial clear-cut	Everything merchantable: 8.5 M bd.-ft. per acre.	May 1957 to June 1958.	No restrictions	None	None.
Diameter limit	All marketable trees over 17 inches d.b.h.[2]: 3.9 M bd.-ft. per acre.	June to Aug. 1958.	No restrictions	At 2-chain intervals.	None.
Extensive selection	Selected trees above 11 inches d.b.h.: 2.3 M bd.-ft. per acre.	Aug. to Nov. 1958.	20 percent	As needed	No skidding in streams.
Intensive selection	Selected trees above 5 inches d.b.h.: 0.9 M bd.-ft. per acre.	Oct. 1958 to Feb. 1959.	10 percent	As needed	No skidding in stream. Skidroads located away from streams. Grass seeding for soil stabilization where needed.

[1] To be exceeded only for short distances when necessary.
[2] D.b.h. = diameter at breast height (4.5 feet above ground).

roads — were constructed on the watersheds. Area and grade of bulldozed skidroads are given in table 2. Greater care in planning reduced both the area of skidroads and their grades.

TABLE 2.—*Proportion of skidroad, by area and grade*

Practice	Percentage of watershed in—		Percentage of bulldozed skidroad, by grade class—			
	Bulldozed skidroads	Bulldozed and non-bulldozed skidroads	0–10 percent	11–20 percent	21–30 percent	31–40 percent
Commercial clear-cut	3.6	7.3	22	32	35	11
Diameter limit	2.5	6.2	20	72	8	0
Extensive selection	2.1	5.8	36	57	7	0
Intensive selection	.8	1.9	68	31	1	0

Maximum turbidities occurred during the logging operation, and they ranged from 56,000 to 25 p.p.m. (table 3). The range of values and the frequency distribution of samples are clearly related to logging practices. Before logging, streamflow from all the watersheds had average turbidities less than 5 p.p.m.

TABLE 3.—*Maximum turbidities measured and frequency distribution of turbidity samples during the logging operation*

Cutting practice	Maximum turbidity	Samples in turbidity unit classes				
		0–10 p.p.m.	11–99 p.p.m.	100–999 p.p.m.	1000+ p.p.m.	Total
	P.p.m.	*Number*	*Number*	*Number*	*Number*	*Number*
Commercial clear-cut	56,000	11	7	11	11	40
Diameter limit	5,200	5	5	8	7	25
Extensive selection	210	14	0	1	0	15
Intensive selection	25	22	1	0	0	23

Here we should note that some logging operations, using different equipment and methods, result in much greater skidroad area and greater disturbance of the forest floor than occurred even on the clear-cut watershed on the Fernow Forest.

Sources of sediment at the Fernow Forest were improperly constructed skidroads and skidroads located too close to the streams. Ring infiltrometer tests made both on and off these roads (table 4) indicated limited infiltration only in the tread area of bulldozed skidroads. However, the large amount of soil moved from the skidroads suggested that overland flow was greater than a comparison of rainfall and infiltration rates would lead one to expect. Subsurface flow, intercepted at the road cut, may have been a major contributor. Also, logging debris in the stream diverted stormflow from the channel to the road and this resulted in excessive erosion.

TABLE 4.—*Infiltration rates, in inches per hour, on and off skidroads*

Area and location No.	Infiltration rate in—		
	Tread area	Center, between treads	Adjacent undisturbed area
Bulldozed skidroad:			
1	6.4	5.1	96.8
2	.5	11.3	260.9
3	2.4	39.7	89.6
Mean	3.1	18.7	149.1
Non-bulldozed skidroad:			
4	37.3	15.2	49.6
5	5.7	11.5	109.1
6	9.8	18.5	66.7
Mean	17.6	15.1	75.1

Erosion from Roads

Apart from logging and water-quality studies, a few other studies indicate the amount of erosion-on-site connected with logging operations. For instance, in the Ouachita Mountains of Arkansas, a survey of skid trails, logging roads, and concentration yards showed that a commercial clear-cutting operation laid bare at least 2.5 percent of the area and caused 3.6 tons of topsoil to be eroded per acre; on a selectively cut area, 1.2 percent of the watershed was affected, and less than 1.5 tons of soil per acre was lost (*3*).

A study at Coweeta showed an average soil loss of 1.3 inches in a 3-month period from a road with an average grade of 30 percent (*4*). This loss is of the same general magnitude as first-year erosion losses reported from skidroad studies at the Fernow Forest (*11*).

Thus, extensive erosion *can* result from logging, and it has so resulted in the past. However, erosion from a logging road and damage to water quality are not one and the same. For, when the road is located some distance from a stream, turbid road runoff usually does not reach the channel; the water sinks into the forest floor, leaving the sediment on the surface. But, located close to the stream, the road can feed sediment directly into the channel. Road location obviously is the most important factor in water-quality control during logging.

After-Logging Erosion

After logging on the Fernow Forest, water-quality measurements indicated a rapid reduction in erosion (table 5). An important cause

TABLE 5.—*Percentage of samples by turbidity classes*

Cutting practice	Period	Turbidity classes: 0–10 p.p.m.	11–99 p.p.m.	100–999 p.p.m.	1,000+ p.p.m.	Samples
		Percent	*Percent*	*Percent*	*Percent*	*Number*
Commercial clear-cut	During logging	27.5	17.5	27.5	27.5	40
	After logging:					
	1st year	53.5	31.4	12.8	2.3	86
	2d year	90.9	6.8	2.3		87
	3d year	95.1	4.9			81
	4th year	94.4	5.6			72
Diameter limit	During logging	20.0	20.0	32.0	28.0	25
	After logging:					
	1st year	87.8	12.2			81
	2d year	100.0				79
	3d year	100.0				79
	4th year	100.0				57
Extensive selection	During logging	93.3		6.7		15
	After logging:					
	1st year	96.3	3.7			81
	2d year	100.0				84
	3d year	98.8	1.2			80
	4th year	100.0				37
Intensive selection	During logging	95.7	4.3			23
	After logging:					
	1st year	100.0				85
	2d year	98.8	1.2			84
	3d year	100.0				81
	4th year	100.0				15

was the cessation of skidding that heretofore had loosened the surface soil of the skidroad and had compacted the soil below the surface. The development of an erosion pavement was another factor: the soils contained about 50 percent stone fragments by volume and quickly developed a protective stone cover. The rapid development of vegetation, woody and herbaceous, coupled with leaf fall, served further to reduce erosion.

Of these several factors, the formation of erosion pavement was the most important. Grant and Struchtemeyer (*2*) have attributed three beneficial effects to erosion pavement in promoting infiltration and reducing runoff and erosion: erosion pavement acts as a rock mulch by intercepting and dispersing rain-drop energy; it reduces the detaching action of flowing water; and it is associated with an increased noncapillary porosity.

Where soils are not stony, erosion can continue for some time, as at Coweeta where for several years clay subsoil from skid trails and roads continued to move into streams after every storm. Three years after the eroding areas were stabilized by seeding, the water was still slightly murky during normal flows.[1] As a general condition, however, soils of the Allegheny Mountain region, and particularly in the glaciated regions, are stony or have a high content of coarse fragments.

This combination of factors — erosion pavement, rapid invasion by vegetation, leaf fall — and the facts that only a small proportion of any logging operation has exposed soils and that the naturally high infiltration rates of forest soils are not affected by logging are probably the reasons why the forested watersheds of our eastern mountains, though heavily cut over in the past, can generally still provide adequate water-quality protection.

Watershed-Management Applications

This self-healing process however, may be effective only after considerable damage to water quality has been done; and in some areas, such as the Coweeta example, the reduction of water quality may continue for some time. This need no longer be; for from studies at the Fernow Forest and at other areas, a number of principles and practices for water-quality protection have been developed.

For instance, excessive damage to water quality from roads running close to the stream can be avoided by careful road location. As a general rule, the minimum distance of logging road from a stream should be 25 feet plus 2 feet for each percent of slope between road and stream (*10*).

Also important is the grade and drainage of the road. On a steep road without provision for drainage, accumulated surface runoff carrying

[1] Personal communication from John D. Hewlett, project leader, Coweeta Hydrologic Laboratory, Jan. 8, 1963.

a high proportion of soil may discharge directly into the stream at the bottom of the slope. Even if discharge is not directly into the stream, the volume and sediment content may be such that the water cannot infiltrate into the forest floor over any reasonable distance.

If the roads in the two Fernow watersheds that produced the highest sediment yields had been properly located and drained, maximum turbidities in parts per million would have been in the low hundreds rather than in the 5 to 50 thousand range. Care in location and construction should not burden the logger, for it pays off in efficiency and reduced logging costs (*5, 7, 9*).

Most of the erosion from logging roads occurred during the logging operation. This suggests:

1. That the operation in any one area should not be prolonged, but should be completed as soon as possible.
2. That more attention should be paid to preventing erosion during the operation. It is not enough to limit erosion control measures to afterlogging care. Perhaps the most practical measure is to cut and maintain broad-based outsloped drainage dips across skidroads. This is not always easy, and the idea will often be resisted by loggers.

This study points up again the fact that erosion from only a fraction of the logging area can pollute a lot of water. Hoover (*4*) has pointed out that a short stretch of logging road can produce much more sediment than occasional patches of steep land in cultivated crops. The forester who might not permit clearing a piece of forested municipal watershed for a row crop because of the erosion hazard should feel just as much concern over the location of logging roads.

Finally, observations in many areas indicate that continuously used permanent road systems in the forest can create serious water-quality problems. Standards for constructing and maintaining such roads should be even higher than for logging roads that are used for only short periods of time.

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SEDIMENT YIELDS FROM SMALL WATERSHEDS UNDER VARIOUS LAND USES AND FOREST COVERS[1]

[Paper No. 6]

By S. J. URSIC, *research forester, Southern Forest Experiment Station, Forest Service,* and FARRIS E. DENDY, *agricultural engineer, USDA Sedimentation Laboratory, Soil and Water Conservation Research Division, Agricultural Research Service*

Reported here are 3-year results of studies that two agencies of the U.S. Department of Agriculture are conducting on small upland watersheds in northern Mississippi. The Agricultural Research Service has installations on crop and pasture lands. The U.S. Forest Service is studying lands that are now in forest or which, because of progressive erosion, have been retired from agriculture and are suited only for forests that will protect watersheds and produce timber.

Description and Methods

The hill lands of the upper Coastal Plain in northern Mississippi were originally forested

[1] Research cooperative with the University of Mississippi and Mississippi State University.

with pine and hardwoods. When cleared for agriculture, most of them eroded severely. Erosion is now so widespread that hydrologic studies of specific soil–vegetation combinations must be confined to small headwater catchments. The 16 watersheds in this study were selected to represent prevailing conditions of soils, slopes, erosion, land use, and plant cover.

Land Uses and Cover Types

The watersheds include one in pasture and three replications each of lands in cultivation, abandoned fields reverting to native grass, depleted stands of upland hardwoods, abandoned lands planted to loblolly pine, and forests of mature shortleaf pine and hardwoods. The drainages range from 1.5 to 4.5 acres (table 1).

TABLE 1.—*Physical characteristics of study watersheds*

Land use or cover type	Drainage area	Soils: Loessial[1]	Soils: Coastal Plain[2]	Range in elevation
	Acres	*Percent*	*Percent*	*Feet*
Corn	3.88	100	0	27
	1.61	100	0	18
	1.45	58	42	21
Pasture	3.01	62	38	28
Abandoned fields	2.65	100	0	37
	2.62	64	36	44
	2.43	25	75	49
Depleted hardwoods	2.56	65	35	49
	2.12	34	66	58
	2.13	100	0	44
Pine plantations	3.35	29	71	68
	3.58	46	54	60
	2.60	100	0	40
Pine–hardwoods	3.31	16	84	74
	4.56	6	94	99
	4.01	4	96	95

[1] Providence, Lexington, Loring, and Grenada series.
[2] Principally Ruston soils (Wilcox on pine–hardwood watersheds).

The pasture has been heavily grazed since 1957.

The three cultivated watersheds are planted to corn each year. One receives preferred management practices consisting of high rates of fertilization, high plant populations, and cultivation on the contour.

The abandoned fields support a grass-herbaceous cover dominated by broomsedge (*Andropogon* spp.). Once planted continuously to cotton, they were abandoned as a result of progressive erosion and waning production. They have not been burned or grazed in recent years; cover is near maximum for the type and site.

The upland hardwood forests, depleted by a century of overcutting, grazing, and frequent wildfire, now are sparse stands of poor quality and low commercial value. Blackjack oak (*Quercus marilandica* Muenchh.), post oak (*Q. stellata* Wangenh.), and hickory (*Carya* spp.) are the principal species. The forest floor lacks the high degree of biotic activity that creates desirable hydrologic properties in some hardwood soils.

The loblolly pine plantations were established in 1939 on fields from which erosion had removed an estimated 2 feet of the surface and had cut gullies 5 feet below the level of the remaining soil. Loblolly pine is the main species for erosion-control planting in northern Mississippi. It has been established on 350,000 acres; planting the pine on abandoned land and to convert stands of depleted hardwoods to pine continues at the rate of 40,000 acres a year.

The pine–hardwood forests are on land too steep for cultivation, but for many years they were subjected to grazing, heavy cutting, and frequent wildfire. Since 1936 they have been protected from these influences as part of the Holly Springs National Forest; their stocking now averages about 5,000 board feet of shortleaf pine and 600 board feet of hardwoods per acre.

Soils

Two major groups of Red-Yellow Podzolic soil are represented: Loring, Providence, and Lexington series derived from wind-deposited loess; and Ruston and closely allied series developed from Coastal Plain materials. The loess soils are primarily silt loams; the Coastal Plain soils, sandy loams. On two of the cultivated fields and on one each of the abandoned fields, depleted hardwood stands, and pine plantations, all soils are loess. The remaining watersheds representing these covers, together with the pasture watershed, have Coastal Plain soils on the lower slopes and loess on the upper slopes and ridges.

Ruston soils are important agricultural and forest soils in all the Atlantic and Gulf Coast States. Loessial soils are prevalent in all States bordering the Mississippi River from Illinois southward.

Soils on the pine–hardwood watersheds are primarily Wilcox sandy loams shallowly underlain by a layer of firm mottled clay that restricts internal drainage. Because of this layer, the soils are hydrologically shallow and are not comparable to those on the other watersheds. Total runoff is greater than from the other forest covers, but it is released gradually so there is measurable flow for up to 6 months each year.

Instrumentation

Runoff from the pasture and cultivated watersheds is measured with modified Parshall flumes. Sediment is collected in concrete boxes equipped with slot-type samplers for sampling overflows.[2] Quantities of sediment are determined monthly.

Runoff from the abandoned fields and forested watersheds is measured with 3-foot H-type flumes. Sediment yields are determined for individual storms. Deposited sediment is collected in a concrete approach section. Samples for suspended-sediment determinations are obtained with a Coshocton wheel sampler.[3] All flumes are equipped with FW–1 water-stage recorders.

Precipitation

Average annual precipitation in the study region is 52 inches. Average rainfall on the watersheds was 50, 44, and 61 inches in 1959, 1960, and 1961, respectively. Sixty-one inches is exceeded only about once in 5 years. The 3-year period provided opportunity to observe the interplay between cover, soils, runoff, and sediment production under a representative range of precipitation.

Results and Discussion

Sediment production decreased in the order: corn > pasture > abandoned fields and depleted hardwoods > pine plantations and mature pine-hardwoods (table 2). The maximum annual yield of sediment from a single watershed among the 12 representing forest land covers was 0.54 ton per acre. The minimum from the pasture exceeded this amount by a factor of 2, that from the cultivated fields by a factor of 6. Although comparisons between the abandoned field-depleted hardwood types and the two pine covers were less clear-cut, differences in mean annual sediment yields were significant in 1960 and highly significant in 1961. In 1959 differences in yield between the two cover groups were not significant; the lack of significance was due largely to sediment from a single storm in which 5 inches of rain fell on the pine plantations but less than 3 inches on the other covers.

TABLE 2.—*Sediment and surface water yields*[1]

Land use or cover type	Average annual rainfall	Average annual runoff	Annual sediment yields	
			Means	Ranges
	Inches	*Inches*	*Tons per acre*	*Tons per acre*
Open land:				
Cultivated	52	16	21.75	3.28– 43.06
Pasture (one unit)	51	15	1.61	1.19– 2.03
Forest land:				
Abandoned fields	51	7	.13	.01– .54
Depleted hardwoods	51	5	.10	.02– .32
Pine plantations	54	1	.02	.00– .08
Mature pine–hardwoods[2]	51	9	.02	.01– .04
Gullies[3]	53	—	182.	84.3 –399.3

[1] Data are means of 9 values, 3 replications of each cover for the 3 years, 1959–61 except pine–hardwoods (1960–61).

[2] These watersheds are on hydrologically shallow soils.

[3] Average annual rainfall and sediment outflow from 7 gullies for the 5 years, 1956–60. (See text footnote 4.)

Annual sediment yields from pine plantations and pine-hardwoods averaged less than 50 pounds per acre. This amount is probably not in excess of the geologic norm for undisturbed native forests of the area.

Loessial soils, although highly erosive, did not consistently yield the most sediment. Of the pine plantations, the one on loess soil had the highest sediment rate, but the all-loess abandoned field had the lowest rate in its group. The highest yield from the depleted hardwoods was from the watershed that had the highest proportion of sandy soils. On the cultivated watersheds, soil losses were highest from the two all-loess units, but soil effects were confounded with the improved practices on the unit having both types of soil.

Added to table 2 for comparative purposes are data from seven individual gullies studied by Miller and others.[4] The gullies, which have drainage areas of 0.32 to 0.64 acre, are within a few miles of the small-watershed installations and are formed on similar soils. Annual sediment yield from the gully with minimum erosion was twice the maximum from the cultivated fields and 156 times greater than the maximum from the forest watersheds. The gully with maximum erosion was annually losing soil at the rate of 400 tons per acre, or 2.36 area inches.

Contributing to differences in sediment yields among covers were varying amounts of annual runoff and sediment concentrations.

Precipitation-Runoff Relationships

The effect of land use and cover types on annual runoff is shown in figure 1. The data indicate discrete populations with runoff decreasing in the order: corn and pasture > abandoned fields and depleted hardwoods > pine plantations. As the pine-hardwood watersheds are on entirely different soils, they are not represented in figure 1. If plotted, their values would fall within the range shown for abandoned fields and depleted hardwoods.

For each cover type, runoff was greatest from the watershed with all loess soils. Despite variation due to soils, however, runoff from the cultivated and pasture watersheds and from the abandoned field and depleted hardwood covers

[2] BARNES, K. K., and FREVERT, R. K. A RUNOFF SAMPLER FOR LARGE WATERSHEDS. PART I. LABORATORY STUDIES. Agr. Engin. 35: 84–90, illus. 1954.

BARNES, K. K., and JOHNSON, H. P. A RUNOFF SAMPLER FOR LARGE WATERSHEDS. PART II. DESIGN OF FIELD INSTALLATION. Agr. Engin. 37: 813-815, 824, illus. 1956.

[3] PARSONS, D. A. COSHOCTON-TYPE RUNOFF SAMPLERS. U.S. Dept. Agr., Agr. Res. Serv. ARS 41–2, 16 pp., illus. 1955.

[4] MILLER, C. R., WOODBURN, RUSSELL, and TURNER, H. R. UPLAND GULLY SEDIMENT PRODUCTION. *In* Symposium of Bari, Internatl., Assoc. Sci. Hydrol. Pub. 59. 1962.

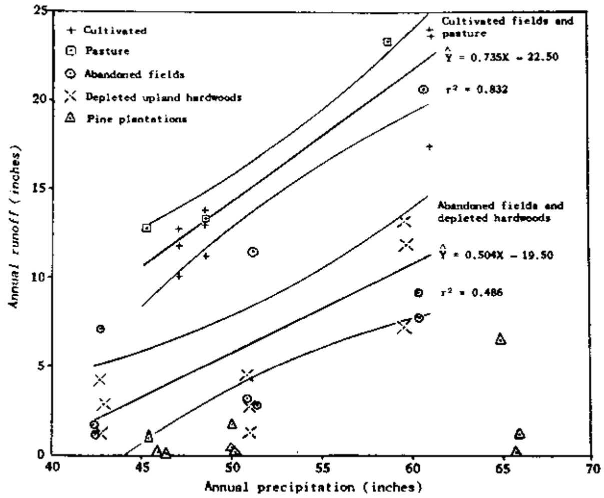

FIGURE 1. — Effect of land use and cover types on the precipitation-runoff relationship for small watersheds in northern Mississippi. Plotted points are annual values for individual watersheds for 3 years, 1959-61. Regressions for the cultivated fields and the pasture, and for the abandoned field and depleted hardwood covers, are shown with 95-percent-confidence limits.

was significantly correlated with annual precipitation.

While runoff from the pine plantations was not significantly correlated with annual precipitation, this cover represents a third population of runoff potential. Mean annual runoff from the pine plantations was significantly less (5-percent level) than from the abandoned fields and the depleted hardwoods, despite higher rainfall on the plantations than on the other covers.

Sediment Concentrations Varied by Cover Types

Sediment concentrations also decreased in the order: corn > pasture > abandoned fields and depleted hardwoods > pine plantations and pine-hardwoods. The minimum average concentration per acre-inch of annual runoff from a cultivated watershed was 0.32 ton. The maximum from the pasture was 0.12 ton.

The lowest annual average concentration from the pasture (0.087 ton) exceeded the maximum of the 18 values for abandoned fields and depleted hardwoods (0.084 ton).

Since runoff amounts from the cultivated fields and pasture were similar (table 2), differences in sediment yields from the two covers were due largely to sediment concentrations. The grass cover reduced soil movement. Runoff from the pasture, however, was higher than from the watersheds in native grass; and the excess contributed to higher sediment yields. This was perhaps the result of the accumulation of less litter on the pasture, and the compaction of soils by animals, which reduced infiltration and caused higher rates of overland flow.

Average annual sediment concentrations per acre-inch of runoff from the abandoned field-depleted hardwood watersheds (0.022 ton) were twice as great as from the pine plantation and pine-hardwood covers (0.011 ton). The difference fell short of statistical significance. Since three-fourths or more of the annual sediment yields came from a few key storms, seldom more than 5, concentrations from these storms were compared. It was first established that sediment concentrations were not significantly correlated with amounts of overland flow on either of the two cover groups. Overland flow rather than total runoff was used in this comparison because of the very low concentrations of sediment during protracted periods of low flow. Such flows occurred on watersheds with a high proportion of loessial soils and on watersheds covered with pine-hardwoods. Overland flow for individual storms was estimated as that part of the hydrograph above a straight line connecting the beginning of the rise to the point of maximum curvature on the recession. The mean concentration of sediment per acre-inch of overland flow from the abandoned fields and depleted hardwoods for these storms was 122 pounds, as compared to a mean concentration of 46 pounds from the pine and pine-hardwood areas. The difference between these means was significant at the 1-percent level.

Sediment-Precipitation Relationships

General trends, although they did not achieve significance, indicated that annual sediment yields from various covers increase directly with annual precipitation. Future studies of individual storms should help remove the masking effect of varying runoff from individual watersheds, differing storm characteristics, and variations in sediment concentrations. Cover, however, because it directly affected both runoff and sediment concentrations, was the dominant influence in determining sediment yields (fig. 2).

Figures 1 and 2 indicate that considerable reduction in runoff and sediment can be achieved by changes in land use or cover types. In the future it is planned to change the cover on several of these watersheds to confirm and further refine these findings.

Summary

Data from small watersheds in the hilly uplands of northern Mississippi show large variations in annual runoff and sediment production attributable to land use and cover types. Runoff decreased in the order: corn and pasture > abandoned fields and depleted hardwoods > pine plantations. Annual sediment yields and average concentrations of sediment per unit of run-

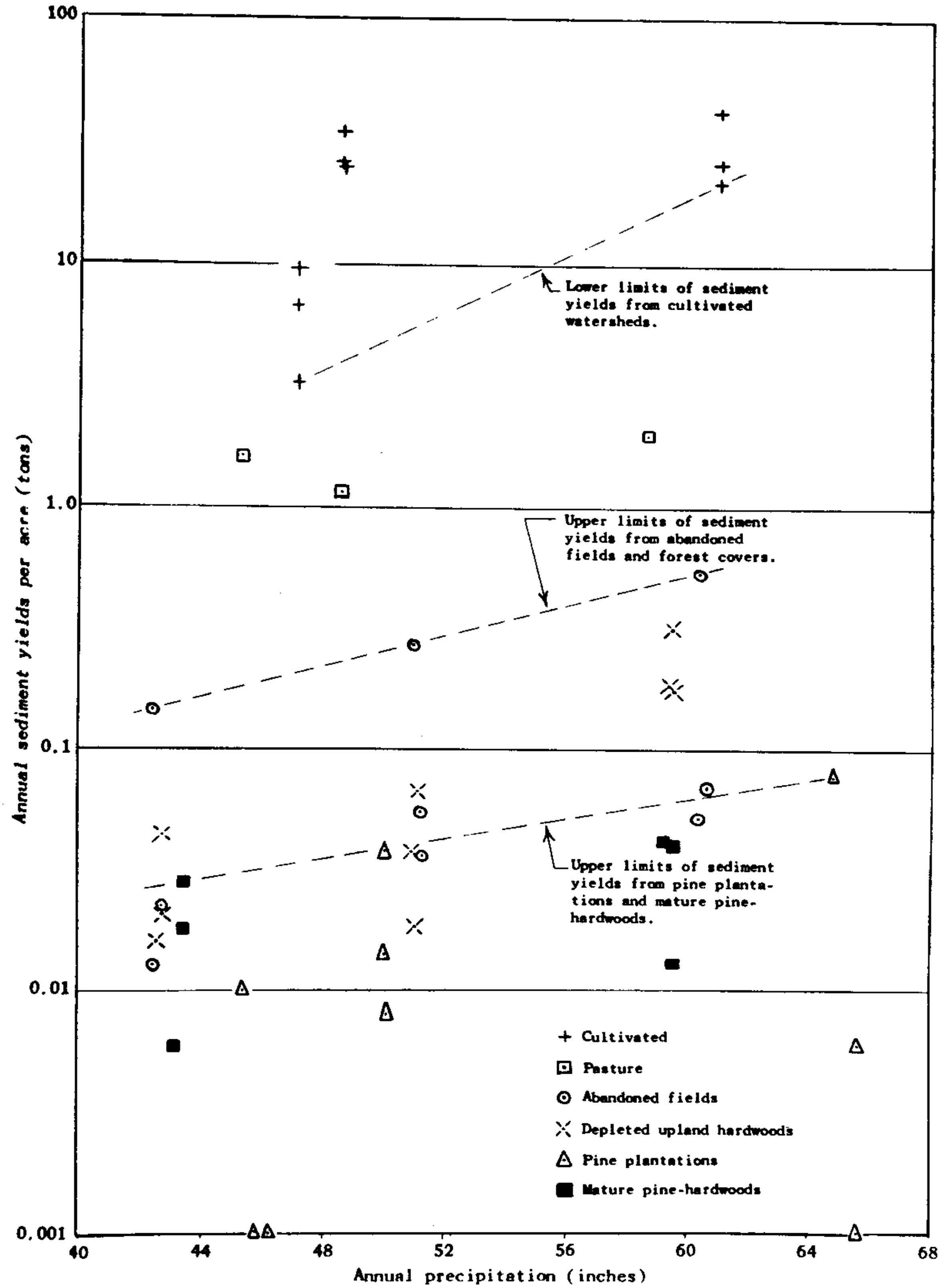

FIGURE 2.—Annual precipitation and sediment yield from individual watersheds in northern Mississippi, 1959-61.

off decreased in the order: corn > pasture > abandoned fields and depleted hardwoods > pine plantations and mature pine-hardwoods. These progressions represent discrete populations of erosion potential.

Runoff was greater from watersheds with loessial soils than from those with both loess and Coastal Plain soils, but the effect of soil on sediment yields was not consistent for all covers.

Extremes in annual sediment production ranged from 43 tons per acre from a cultivated watershed to a few pounds per acre from pine plantations. Sediment yields from abandoned fields with a dense cover of native grass and from forest covers did not exceed 0.5 ton per acre annually. By contrast, yields from gullies in the same locality have been reported as 84 to 400 tons per acre.

The studies are yielding data that should eventually allow prediction of sediment production from permanent covers. They suggest opportunities for reducing runoff and sediment by changing land use and cover types.

Establishing pine on actively eroding abandoned fields has in two decades reduced sedimentation to amounts probably not in excess of the geologic norm for undisturbed climax forests in this area.

EFFECT OF HIGHWAY CONSTRUCTION AND MAINTENANCE ON STREAM SEDIMENT LOADS

[Paper No. 7]

By W. E. BULLARD, *forester, Watershed Management, Division of Water Supply and Pollution Control, U. S. Public Health Service*

Thousands of miles of freeway, highway, country road, and forest access roads are built in the United States every year. Nearly every foot of this construction is in a watershed, and, except for overpasses and viaducts and bridges, nearly every foot of it involves soil disturbance. Whenever there is soil disturbance, there is a potential sediment source. Too often in highway construction this potential is realized; disturbed soil erodes and erosion products are carried to streams and become damaging sediments. Maintenance operations subsequent to construction often accelerate the process.

This paper describes the adverse effects of road construction and maintenance on stream sediment loads and points out how to avoid or reduce them.

Soil Disturbance

In more or less chronological order, the steps in building a road are clearing the right-of-way, bulldozing an accessory "shoo-fly" road, relocating stream channels, opening up the cuts, putting in culverts, hauling and dumping rock and soil in the fills, side casting or end hauling excess material not needed for fill, digging drainage ditches, smoothing and compacting the surface, and spreading and smoothing the final surfacing material. Each of these steps may, and often does, involve unnecessary soil disturbance and erosion. There are other changes: deep cuts may intercept ground water and dry out the slopes; imposition of a new drainage pattern may radically change local streamflow regime; and new openings in forest cover may modify the local ecology and microclimate.

Sidehill cuts and fill slopes are major sites for soil disturbance and erosion that provides stream sediments. On long, steep slopes directly above stream channels, the movement is immediate and rapid. End hauling is expensive and interferes with progress of the road; gravity is cheap and always ready to work. Solution of the sidehill-cut problem as a sediment source largely depends on avoidance. Sidehill locations, wherever possible, should be bypassed in favor of bench and ridge top locations that do not involve as much cut and fill. Or cribbing can be used to build up one side of the roadbed to reduce the volume of cut needed. Leaving a screen of brush and trees between the road and the channel below will trap much of the overcast debris that would otherwise become sediment.

Channel relocations that may appear necessary from the standpoint of road construction economics often initiate long-chain reactions that are felt for many miles downstream. Moving the stream to a rock cut may be perfectly safe; but changing its length and gradient on other than a solid bottom will inevitably start a cycle of bank cutting, meandering, and reworking of old deposits that adversely affect both water quality and aquatic habitat. Such upsets are particularly harmful in the upper reaches of streams, since these are usually the zones of supply and replenishment of food and fish populations for downstream reaches.

Where the road cut has removed the toe support to a slope, slides will occur until a new equilibrium is established on the slope. This can be avoided or reduced by draining the soil mass subject to movement or by providing cribbing or toe-wall support. Otherwise, maintenance is apt to be excessive for a considerable period; and since maintenance generally consists of shoving the unwanted excess over the side of the road, erosion and consequent sedimentation are apt to be excessive also.

A well-rocked road surface will prevent considerable sedimentation. Without a good rock surface, roads tend to become rutted with use; ruts erode, intercept drainage, and carry fine sediments to diversion points. Even the splash from rutted roads along streams has a noticeable effect on stream turbidity. The best surface is broken rock that packs well to support heavy loads and yet remains porous enough to drain readily. In regrading a road surface, the object should be to redistribute the surface material evenly, not to scrape it off and shove it over the edge.

The places where the needed fill material and surfacing material come from may also be involved in sediment production. When more fill is needed than the cuts provide, it is usually taken from borrow pits; these borrow pits may become sores on the landscape that erode and put muddy drainage into streams. Borrow pits should be planned and operated so that the areas of bare disturbed soil do not erode into stream channels. Surface soil should be stockpiled, and when the job is finished, spread over the abandoned borrow pit, graded, mulched, and seeded or planted to naturalize and stabilize it against erosion. The same process also serves to reduce accident hazards and clean up mosquito breeding places.

Sharp, crushed hard quarry rock makes the best surfacing material, but it is not always available. River gravel is often closer at hand and cheaper. But taking out river gravel disturbs the channel, often sufficiently to initiate a cycle of meandering and bank cutting, and directly muddies the water where bulldozer and dragline work in the river itself. In streams of the Northwest, these operations cause serious damage to fisheries if done at a season when eggs and young fry are in the stream bottom gravels. Where gravel dredging in a live stream is necessary, it should avoid the spawning season. It may also be necessary to avoid the extremely low water season, as sediments stirred up may adversely affect temperature and oxygen content of the stream.

Disruption of Drainage Patterns

Since roads tend to be horizontal rather than vertical, they cross the natural drainage channels on the land. The road cuts often intercept ground water and bring it to the surface and road fills often block intermittent drainage channels and obstruct — to a greater or lesser degree — the main drainage channels. Resurrected ground water and the flashy runoff from road surfaces can overload natural channels and start a cycle of bank cutting that loads the stream with sediment and affects the acquatic habitat for long distances below.

Channel obstructions may arise from encroachment of fill slopes, bridge piers, poor placement of culverts, or culverts of inadequate capacity. They may also arise from careless right-of-way clearing where debris that rolls or falls into channels is left untouched or from the blasting of rock points and ledges that dump tons of rock into channels. Obstructions change the streamflow regime and often cause the stream to seek a new channel, a process that involves bank cutting and channel bed reworking with consequent sedimentation and loss of aquatic habitat.

New drainageways provided by uncontrolled road drainage turnouts that gully their way to the nearest natural channel are always a dependable source of sediment. And as the gullies work headward, they can readily undermine the road and increase maintenance needs. Maintenance by dumping material into the gully only continues the sediment production and does not cure the erosion "sore" nor solve the maintenance problem. Any gully also tends to drain off ground water and dry out the slope; while this may sometimes be desirable to reduce slumping and sliding, it generally is adverse to production of tree, forage, or other crops on the land affected.

Overloading of natural channels by the rapid concentration of road drainage water may have serious consequences in sedimentation. Road surfaces may account for as much as 3 percent of the area of a small upstream watershed; this impermeable 3 percent sheds water as fast as it falls and can add an unnaturally heavy load to the small draws leading to the stream unless the road drainage is dispersed into infiltration ditches. Overloading the channels means high velocity flow and bank and bed erosion that put more sediment in movement in the main stream below.

Installations

Clearing the right-of-way may be done in any weather, but use of heavy dirt-moving machinery in opening up the location should be restricted to dry weather. If the machinery is used during wet weather, soil may be compacted or the mud may drain off to streams. Machinery also should be kept off streambanks and out of channels as much as possible. (A "shoo-fly" road on a temporary fill in the Umpqua River, built and used only a month or two in the low-water season, caused heavy sedimentation of the river and damage to aquatic habitat for 25 miles downstream.)

Culvert installations are often made in such fashion that they greatly increase soil erosion. The "cannon" culvert sticking out several feet above a steep fill slope is all too common a sight, as is the long gully below it. Too-short culverts sometimes are used in stream crossings; the fill slopes override the culvert ends to supply sediment to the stream. Buried culverts with unprotected inlets may induce erosion, too. Generally, the solution is to lay the culvert on the natural channel gradient, to make it long enough to extend well beyond the fill slopes, to protect the inlet and outlet with headwalls, and to provide a lined drainageway where a natural drainage route is not available. Drop inlets and protected outfalls will save many cubic yards of erosion sediments.

Drainage collection and disposal may also significantly affect soil loss and sediment contributions. Road ditches should be built so that they do not erode and undermine either the roadbed or the cutbank. Cross-drainage should be by means of structures that will not break down and permit escape of the water to gully out the road. Drainage should not be allowed to concentrate, but should be diverted at short intervals, depending on gradient and soil type. Disposal should be into natural channels of sufficient capacity to handle the maximum expected drainage flow without erosion, into infiltration ditches on contour, or onto areas of undisturbed cover where it can spread out and percolate into the soil. Drainage should never be turned loose to dig its own channel.

Maintenance

The major operations involved in maintenance are regrading the road surfaces to smooth out ruts and redistribute surfacing material, cleaning out soil and rock eroded and sluffed into ditches, and removing slides. Where there is surplus material to take care of, it generally is overcast onto the fill slope. This can nullify the effectiveness of any soil stabilization work done on the fill and may directly contribute to increased erosion and sedimentation.

Amount of maintenance necessary is related to many different factors — road location and design being two of them. Poor location and poor design can cause maintenance costs to rise almost to equal those of construction. Where unstable formations suffer recurrent slips and slides, where poorly placed ditches undercut steep side slopes, where unprotected drainage outfalls gully back into the road, both high sediment contributions and high maintenance costs will be the rule. To lower costs and cut down sediment contributions, maintenance should avoid undercutting the side slopes or plugging drainage ditches and should conserve surfacing material.

Effects

Three specific effects of sediment from roads might be named: (1) damaging the aquatic habitat, (2) degrading water quality, and (3) lowering the attractiveness of streams for recreation. Sedimentation damage to aquatic habitat arises from smothering of fish eggs and fry in stream bottom spawning beds, blanketing and smothering stream bottom plants and animals that make up the food chain, clouding the water and cutting off light from stream organisms, and at times even abrading the gills of adult fish. The damage to water quality arises from the presence of suspended material that prevents use of the water without treatment to remove the unwanted additions; the treatment is costly. Sediment in water decreases the efficiency of purification by chlorination, and increases the cost of even this simple treatment. Attractiveness of streams and lakes for recreation purposes is based on the preference people generally show for clear, clean water, whether for drinking or bathing, or just sitting beside. Turbid, sediment-laden waters are not attractive, are not very good for fishing, and may conceal safety hazards.

Evaluation of these effects in economic terms is difficult and unsatisfactory. Even such an apparently readily defined sediment damage as loss of reservoir storage space is not adequately evaluated in terms of cost of construction of that storage space, if we are concerned that no other storage space may be available. Damage to aquatic habitat may be measured in terms of loss of production of commercial fish; but what of the loss to the sports fisherman? Damage to water quality may be partially evaluated in terms of treatment costs; but what of water uses that perforce must be abandoned because they cannot afford this cost? No one yet has discovered how to evaluate esthetics; we know only that most outdoor recreation activity is tied to water, that we want the water clean and sparkling, and that we feel a loss when we can't find the conditions we like.

Solutions

A number of problem situations causing or affecting sedimentation have been cited, and it has been pointed out repeatedly that avoidance of sediment is the best treatment. It is always easy, after the fact, to say, "You shouldn't have done it in the first place." But, before the fact, there are certain useful tools available.

Informed land management is based on full knowledge of what is being managed, the objectives and main direction of management, and possible side effects. The full knowledge of what is being managed refers to the land itself — the soil, the underlying rock, topography and land forms, the hydrologic regime, the plant cover, and accessory factors such as climate and land use. This means that soil maps, geologic maps, land form maps, topographic maps, or any other source of information should all be used in laying out the preliminary road location. Since land-form maps are available in few places (in some parts of the State of Washington, in the Northwest), aerial photographs can be used for the same purpose. Even with these aids and with a ground check, it is not possible to miss every unstable area; some will show up only when cut into.

Planning road layout together with planning of the uses and developments it is to serve will enable construction of the most efficient road system for an area, with compromises recognized as such and adequately allowed for. If water quality and aquatic habitat are considered when planning the layout, erosion and sedimentation hazards can be greatly reduced. Although such planning is possible and desirable for the local forest access or mineral access or farm-to-market road, it may not be possible for the interstate expressway. Still, the local needs and local disruptions (including water quality and aquatic habitat) should be considered and any needed compromises in the highway plans made accordingly.

The planning should include the stabilization work needed not only to protect the road itself but also to safeguard the streams and water resources. The stabilization job can be done more efficiently and with better chance of success if it is made a part of the construction job. This stabilization work may include terracing the cut slopes; staking and wattling and mulching both cut and fill slopes; seeding and planting all bare soil areas; installing drop inlets and protected outfalls on culverts; diverting drainage above cuts and away from fills; and cleaning out carefully and completely any material put into streams. The material to be removed would include temporary fills and culverts as well as refuse inadvertently dropped into the streams.

We might summarize the road problems and solutions as follows:

Construction:	*What To Do About It*
Planning	Integrate considerations of road location, design, and use with considerations of all resources and uses affected, including water resources and aquatic habitat in streams.
Location	Avoid unstable soil and rock, choose bench locations, avoid encroachment on or interference with streams, limit cut and fill.
Clearing right-of-way	Preserve low cover for soil protection as long as possible, keep ash and soil and debris away from channels.
Cuts	Provide drainage diversion at top and in the cut as needed, leave support for the toe; fix slope according to local soil and topography; build terrace as needed; stake, mulch, and revegetate.
Fills	Divert drainage away from fills and protect drainage on fills, don't overcast excess material where it will roll or erode into natural channels, stabilize bare soil surfaces to avoid erosion, install toe structures as needed to support the fill, end haul rather than overcast excess material.
Channel relocation	Avoid where possible, or do it on solid rock bottom as far as possible.
Ditches	Cut ditches on regular grade, with sufficient capacity to carry greatest expected flow, and line against erosion; avoid undercutting side slopes.
Drainage turnout	Divert drainage at short intervals according to climate, soil type, and gradient; dispose into natural channels, into contour infiltration ditches, or onto permeable forest floor.
Culverts	Install on natural grade with minimum disturbance of channel and extend well beyond the fill; protect inlet and outlet against erosion; use drop inlets where fill can act as sediment trap or as necessary to prevent erosion; use no "cannon" culverts on steep slopes.
Shaping and surfacing	Carefully outslope and smooth the surface to reduce need for drainage structures and to keep erosion to minimum, round the surface to drain water to side ditches, apply sufficient rock course to provide a surface free of muddy ruts.
Maintenance:	
Regrading	Redistribute surfacing material without wasting or overcasting, fill ruts and leave berm to contain drainage as needed.
Drainage system	Keep ditches on even gradient and cleared to avoid overflow; do not undercut sides when cleaning ditches; see that clear drainage goes to natural channels where possible and muddy drainage to infiltration areas; keep culverts unplugged.

Slide removal..........	Rather than overcast excess material, end haul to safe disposal; cut diversion drains above wet cutbanks or insert French drains into the bank; build toe support as needed.
Repair	Fill and restabilize eroded or slumped areas.

Summary

The thousands of miles of new road built each year and the tremendous existing road network being maintained involve the disturbance of hundreds of thousands of acres of land and millions of tons of soil. Much of the disturbed soil erodes and becomes sediment in streams, damaging the aquatic habitat, degrading water quality, and lowering the attractiveness of the streams for recreation use. This is a situation that can be in large measure avoided. From planning the location and design of the road on through to care of the finished product, there are precautions to take; plus a number of positive actions that will enable holding soil disturbance and erosion and sedimentation to a minimum.

SEDIMENTATION AFTER LOGGING ROAD CONSTRUCTION IN A SMALL WESTERN OREGON WATERSHED

[Paper No. 8]

By R. L. FREDRICKSEN, *research forester, Pacific Northwest Forest and Range Experiment Station, Forest Service, Portland, Oreg.*

Abstract

During the summer of 1959, 1.65 miles of logging road were constructed in a 250-acre forested watershed that rises 2,000 feet in a distance of 1 mile. This study evaluates the change in sedimentation subsequent to road construction. Runoff from undisturbed watersheds in this area remains clear during the summer low-flow months and reaches concentrations of 100 parts per million during winter storm peaks. Runoff from the first rainstorms after road construction carried 250 times the concentration carried in an adjacent undisturbed watershed. Two months after construction, sediment had diminished to levels slightly above those measured before construction. Sediment concentrations for the subsequent 2-year period were significantly different from preroad levels. In about 10 percent of the samples, sediment concentrations were far in excess of predicted values, indicating a streambank failure or mass soil movement. Annual bedload volume the first year after construction was significantly greater than the expected yield, but the actual increase was small. A trend toward normalcy was evident the second year.

Introduction

Streams flowing from undisturbed mountain watersheds of western Oregon normally carry very small sediment loads. But when logging roads are built to harvest the old-growth Douglas-fir timber from these watersheds, the construction activities expose considerable raw soil, often resulting in increased sedimentation. In 1952, the Forest Service began a watershed experiment designed to measure the effect of intensive forest land management upon the sediment load carried by streams in the western Cascade Range of Oregon. The first treatment phase began in 1959 when logging roads were built in one experimental watershed. This paper presents an estimate of the change in suspended sediment concentration after construction of these roads.

Colby, Hembre, and Rainwater,[1] in a thorough investigation of the Wind River basin of Wyoming, found annual sediment yield ranged from 1.11 to 0.70 ton per acre during a 5-year period. They found large differences in the sediment load carried from watersheds draining different types of geologic materials. Care must be taken when projecting sedimentation rates from small watershed studies to larger watersheds, particularly where there is a change in geologic material.

Anderson[2] was able to segregate sediment load in the Willamette River basin of western Oregon into three sources: (1) 24 percent from forest lands comprising 77 percent of the drainage area, (2) 22 percent from agricultural land comprising 23 percent of the area, and (3) 54 percent from 205,000 feet of eroding main channel. He predicted that if forest land development continued at the rate existing at the time of the study, sediment discharge would increase to three times the rate that was estimated for the watershed condition in 1950.

The progress of erosion from a small watershed was measured for 3 years after logging in the Sierra Nevada of California. Here Ander-

[1] COLBY, B. R., HEMBRE, C. H., and RAINWATER, F. H. SEDIMENTATION AND CHEMICAL QUALITY OF SURFACE WATER IN THE WIND RIVER BASIN, WYOMING. U.S. Geol. Survey Water-Supply Paper 1373, 336 pp. 1956.

[2] ANDERSON, H. W. SUSPENDED SEDIMENT DISCHARGE AS RELATED TO STREAMFLOW, TOPOGRAPHY, SOIL, AND LAND USE. Amer. Geophys. Union Trans. 35(2): 268-281. 1954.

son and Richards [3] found that, once logging was completed and the area began to recover, mean sediment concentration during high streamflow decreased markedly. During the second and third years after logging, it decreased to about half what it had been the previous year.

The Study

On the H. J. Andrews Experimental Forest, located near Blue River, Oreg., three small, gaged watersheds (fig. 1) have been under study to evaluate the effects of logging on the quantity and quality of runoff.[4] In the 1 mile between the gaging site and the back ridge of the watersheds, the elevation increases from 1,500 to 3,000 feet. Topography is steep and broken with deeply incised stream channels that flow northwesterly. Geologic structures include basaltic-andesite ridges overdeposited with tuffs and breccias. Tuffs and breccias are parent materials for deep, heavy, and highly aggregated soils on benches and at the toe of slopes. Runoff in stream channels is rapid, though surface runoff has never been observed. The soil mantle is very permeable.

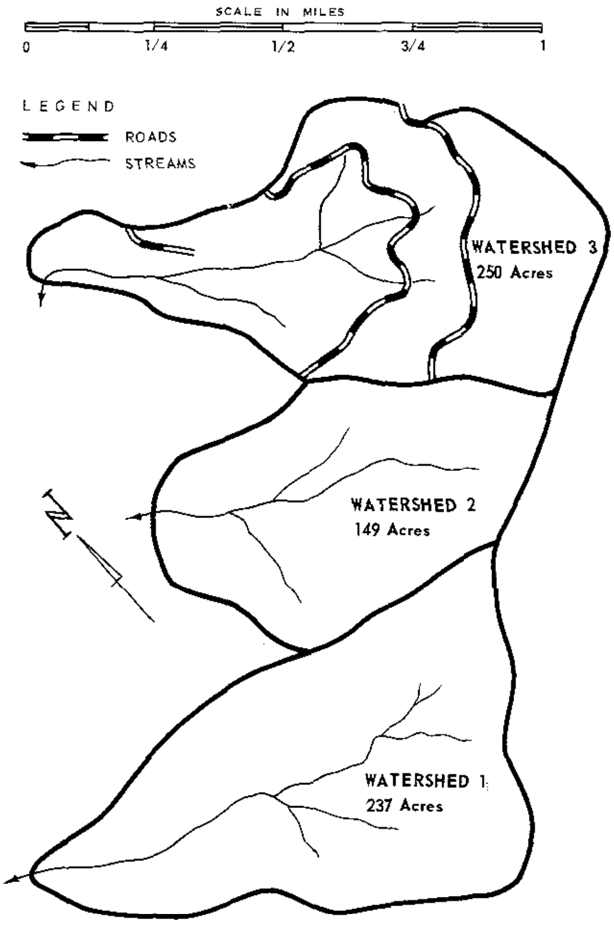

FIGURE 1. — Experimental watersheds.

Cover is predominately overmature Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], varying from 20,000 to 120,000 board feet per acre. The dense cover has remained essentially unbroken for a period of 450 years.

The maritime climate of western Oregon is typically dry in summer and wet in winter. Annual precipitation averages 91 inches but may vary from 56 to 114 inches, with 95 percent of the precipitation falling between October and May. Although large storms with 3 or more inches of precipitation per day may occur during this period, rainfall intensities seldom exceed 0.3 inch per hour. Snow may be present at this elevation from November through March, but only occasionally remains on the ground for more than two weeks at one time.

Road Construction

The experimental watersheds remain undisturbed until the spring of 1959 when construction of logging roads began in watershed 3. By October 1, 1.65 miles of all-weather logging road were completed with a 14-foot roadbed topped by a 10-foot, crushed-rock driving surface. This transportation system consists of three roughly parallel roads at elevations of 1,900, 2,400, and 2,800 feet. (fig. 1). Continuously flowing streams are crossed in two places by the middle road. No surface flow is evident at the lower or upper roads except during major storms.

Annual road maintenance, performed during the summer, consisted of removing several minor slumps along cut banks and clearing drainage ditches. During September 1959, all cut and fill slopes were seeded with grass, fertilized, and mulched with straw, but only a poor stand of grass resulted. No logging trucks used the roads during this phase of the study.

Methods

Beginning in 1955, suspended sediment was sampled at each stream gage (trapezoidal flume). Vertically integrated samples were taken in pint milk bottles from the upstream end of each flume. Results of analysis, by the Gooch filtration technique, are expressed in parts per million (p.p.m.). Bedload has been measured in catchment basins below the gaging sites since 1957. The basins, with 1,650 to 2,050

[3] ANDERSON, H. W., and RICHARDS, L. G. FOURTH PROGRESS REPORT, 1960-61, CALIFORNIA COOPERATIVE SNOW MANAGEMENT RESEARCH. U.S. Forest Serv., Pacific Southwest Forest and Range Expt. Sta. Study 112, pp. 154-155. 1961.

[4] BERNSTEN, C. M., and ROTHACHER, J. A GUIDE TO THE H. J. ANDREWS EXPERIMENTAL FOREST. U.S. Forest Serv. Pacific Northwest Forest and Range Expt. Sta., 21 pp., illus. 1959.

square feet of surface area, have a low trap efficiency. Bedload volume was calculated annually from the mean rise in pond-bottom elevation, measured on intersections of a 3-foot grid.

Results

Annual Sediment Distribution From Undisturbed Watersheds

Distribution of annual sediment concentrations measured in the experimental watersheds follows a pronounced cyclic pattern. Sediment concentration of samples plotted in figure 2 show considerable variation caused by major storms and the short 6-year period of record. But the figure shows clearly that sediment concentrations are small during low runoff summer months and rise in autumn to a peak during high runoff in winter months. Sediment seldom rose above 100 p.p.m. from these undisturbed watersheds, though greater concentrations have been measured. Localized failures of streambanks during storm peaks probably account for the short-lived surges to slightly over 200 p.p.m.

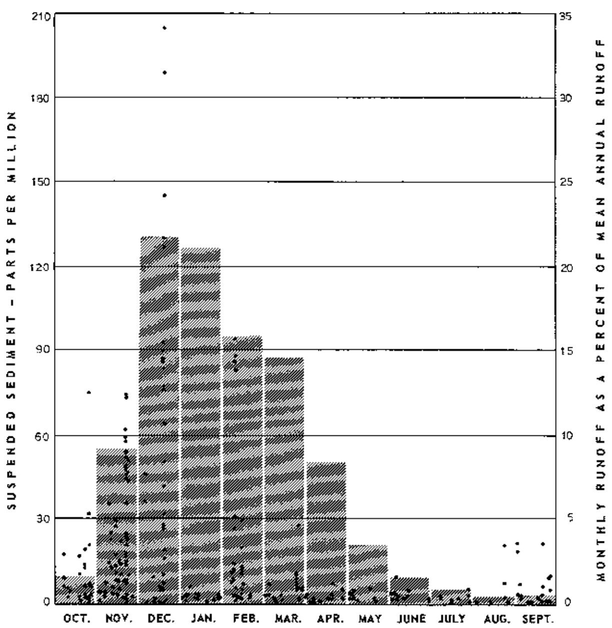

FIGURE 2.—Annual distribution of suspended sediment samples and monthly runoff from undisturbed watersheds, 1957-62.

Changes in Suspended Sediment After Road Construction

A drastic change in sedimentation was apparent immediately following road construction. The increase, measured when the rainy season began in autumn of 1959, compares with results reported by Guy[5] during the construction phase of urban development.

Sediment loads, when streams were near peak flows, are shown as ratios (watershed 3 to watershed 1) in figure 3. Before road construction, peak sediment loads in watershed 3 were 2.3 times those in watershed 1. During the first storm of September 21, 1959, when roads were nearing completion, sediment reached a maximum concentration of 1,780 p.p.m., 250 times the concentration in watershed 1. Two months later, the initial effect of road construction had apparently passed. By November 23, 1959, sediment concentrations in watershed 3 subsided to levels slightly above those measured before construction and remained at about these levels for the following 2 years.

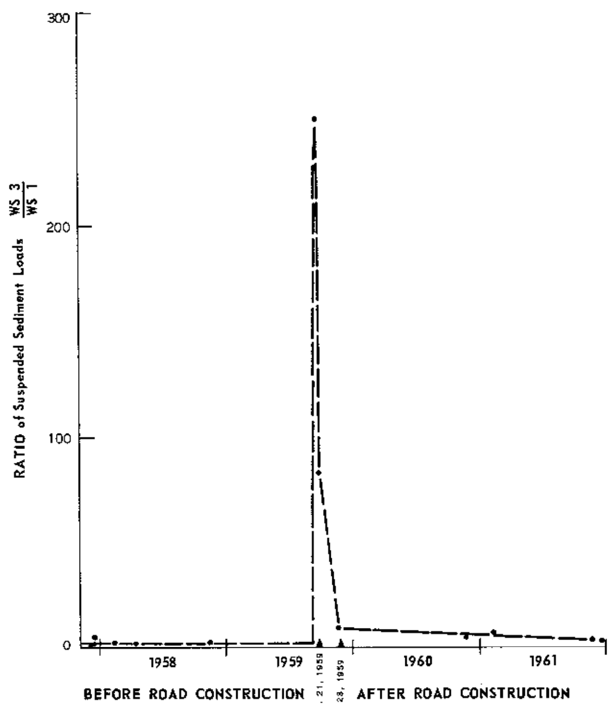

FIGURE 3.—Relative suspended sediment loads near peak flows: Watersheds 1 and 3, before and after road construction.

Data for this 2-year period after road construction were analyzed to determine their relation to data collected before construction. Two regressions of paired samples[6] from watersheds 1 and 3 were calculated and are compared graphically in figure 4. Sediment concentrations in watershed 3 were slightly more than twice

[5] GUY, H. P. EFFECTS OF URBANIZATION ON THE SUPPLY OF FLUVIAL SEDIMENT. U.S. Geol. Survey Res. Prof. Paper 424-A, p. 85. 1961.

[6] Samples were considered paired if both were collected within a 1-hour interval.

the corresponding concentration before construction. This increase proved highly significant.

Slides Add Unpredictable Quantities of Sediment

Relationships shown in figure 4 reflect only "normal" erosion of the soil mantel. The analysis does not include sediment concentrations caused by sudden movements of soil such as slippage of streambanks. In the period of observation, 8 samples out of 83 collected during major storms contained sediment contributed by these unpredictable events and were not included in the analysis.

The largest sediment concentration in watershed 3 during this period was caused by a slide that originated from the middle road and dammed a small tributary. When the dam was breached, a wall of water and debris scoured one-half mile of stream channel to bedrock. Two debris dams containing about 5,000 yards of rock, gravel, and logs were left in the channel. Within 20 hours after the slide, 260 tons of sediment passed the stream gage — many times the yield expected for this period had the slide not occurred.

Bedload

Annual accumulation of bedload material, normally very small, ranged from 1/4 to 3 1/2 cubic feet per acre of drainage for the period before road construction. The first year after road construction, bedload was significantly greater than expected (95-percent confidence level), although the actual volume was small during this low runoff year. A trend toward normalcy was evident by the second year. Bedload in significant quantities was deposited in the basin at watershed 3 after the slide described in the previous section. The volume of 10.84 cubic feet per acre was nearly 18 times the volume at undisturbed watershed 2.

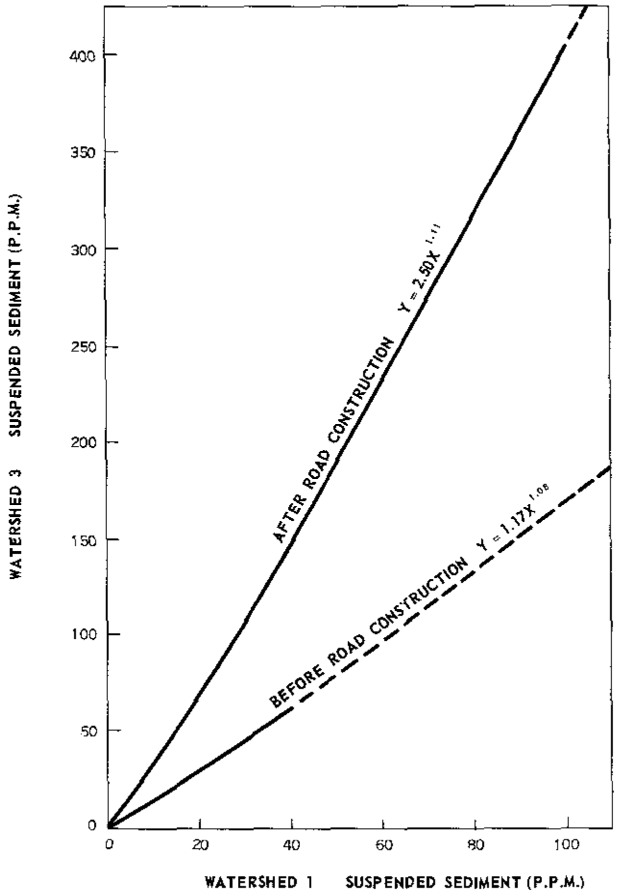

FIGURE 4.—Suspended sediment concentrations: Watersheds 1 and 3, before and after road construction.

Summary

Suspended sediment in undisturbed watersheds follows a cyclic concentration pattern largely influenced by the precipitation and runoff pattern in western Oregon. In these undisturbed watersheds, suspended sediment concentration seldom exceeded 100 p.p.m. Sediment concentrations were much higher for 2 months during the beginning of the 1959 autumn rainy season, immediately after road construction. Sediment concentrations during 1960 and 1961 continued at about twice the concentrations measured before road construction. A modest increase in bedload volume was noted during the first year after construction.

A slide in watershed 3 produced quantities of sediment far in excess of previous years. Slides play an important but unpredictable role in the rate of geologic erosion from this physiographic type.

EFFECTS OF WATERSHED CHARACTERISTICS ON RESERVOIR SEDIMENT DEPOSITION

[Paper No. 9]

By ROGER L. CORINTH, *assistant engineer, Illinois State Water Survey*

Scope

This paper attempts to set out a pattern of understanding of sediment movement in Illinois. Sediment measurements within the watershed and the reservoir are combined with knowledge of physical laws to gain understanding of happenings between the sediment-producing areas of a watershed and the deposition in the reservoir. In this "between" zone little or no data are available.

In Illinois, the terrain is flat and cultivated. The soil types range from moderately permeable soils developed from thick loess in the northwest quadrant of the State to very slowly permeable soils developed from thin loess in the southern half.

For the State of Illinois we have 126 reservoir sedimentation surveys, including 1,697 sediment samples, and complete gross erosion computations for 38 watersheds. The reservoirs range from 3 to 6,000 acres, with watersheds from ½ to 906 square miles. The percentages of clay (<2 microns), silt (2 to 30 microns), and sand (plus organic content) in sediments of these Illinois reservoirs are shown in figure 1 for three principal study areas in the State.

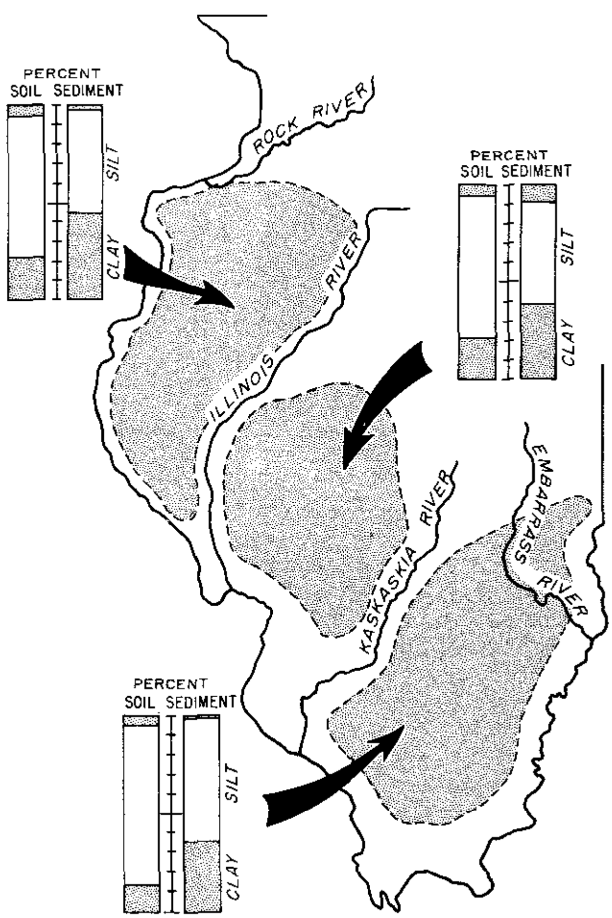

FIGURE 1. — Silt and clay content of sediment in Illinois reservoirs.

Principles of Sediment Movement

Soil erosion and the resulting reservoir sediment deposition are the composite result of a limited number of sequential processes out of many erosion and deposition processes, large and small. For the purpose of focusing our attention on reservoir sediment deposition, let's first clearly identify the elements of the problem and their interrelationship.

The problem has its beginning with the mechanism of soil erosion. Explanation of the movement of a unit mass as a process in soil erosion requires finding a source of energy. This obviously is an example of Newton's first law, "bodies at rest remain at rest until acted upon by some force." In most cases only one source of energy is considered dominant. In the Corn Belt States, the dominant energy source is derived from rainfall.

Three Sediment Movement Regimes

Regimes 1 and 2

From the definition of energy of a body as the amount of work it can do by virtue of its position or motion, the following two erosion regimes become apparent: (1) erosion resulting from kinetic energy [1] and (2) erosion resulting from the relationship of momentum and hydraulics. Regime 1 is a function of turbulence resulting from expenditure of the kinetic energy of rainfall and the turbulence inherent to open channel flow. The areal extent of this regime is a function of turbulence and depth of runoff.

The line separating regimes 1 and 2 is located where the runoff depth becomes such that the extreme turbulent energy per unit volume due to raindrop penetration does not reach through the depth of runoff, thus giving way to open channel flow with a far lesser amount of turbulent energy per unit volume. Beyond this point the turbulence characteristic of open channel flow minus the turbulence of the raindrop penetration must maintain the sediment load. This point of separation must be located in the search for watershed characteristics. This point may reach well up into the cultivated fields as opposed to its location in watersheds protected by cover such as forest.

The eroded soil carried as suspended load in the vicinity of the periphery of a cultivated field will very nearly appear in total at the reservoir head waters. Watersheds characterized by ephemeral streams appear quite stable, with little evidence of active degradation or aggradation. This means either that there is little or no

[1] WISCHMEIER, W. H., and SMITH, D. D. RAINFALL ENERGY AND ITS RELATIONSHIP TO SOIL LOSS. Amer. Geophys. Union Trans. 39: 285-291. 1958.

deposition in the watershed channels or that aggradation and degradation average out to a state of equilibrium. That is, sediment is alternately perched and transported with a like quantity replacing the unperched quantity. In either case the attenuation of watershed erosion (computed gross erosion by a soil loss equation)[2] caused by deposition in watershed channels is not supported by evidence, here in Illinois, of continued channel aggradation.

This precludes the consideration of regime 2 as a significant factor in attenuating gross erosion and suggests that the area of significant effect is in the zone of transition between regimes 1 and 2. However, regime 2 would be important where the overbank flooding produced by the larger storms gives rise to broad areas of temporary storage where considerable deposition may take place. This overbank storage would attenuate the total sediment load produced by the large storms. The inference here is that smaller watersheds are not likely to contain channels in broad U-shaped valleys, whereas large watersheds do contain broad U-shaped valleys. The same characteristics that differentiate a sharp-peaked, flashy hydrograph from one that is not would also attenuate the sediment load being transported through regime 2.

Supporting evidence of the effect of this potential overbank deposition is demonstrated by graphs of sediment production per acre of watershed vs. watershed area, which shows a general decrease in sediment production with increasing watershed size.

Support of regime 1 as being a dominant sediment source is borne out by the estimate that 90 percent of reservoir sediment in the United States is contributed by sheet erosion.[3] Also, in only 1 out of 38 Illinois watershed soil loss computations was channel erosion a significant percentage of the total erosion. Then, by default, the existence of regime 2 must be in the form of a nonsediment producing medium or as a sediment transport and deposition medium in equilibrium.

Regime 3

Regime 3 embodies the reservoir proper. Here the principles of fluid mechanics and Stokes law govern in relating sediment inflow to deposition. This completes the three divisions (1, 2, 3) shown in figure 2 representing the three regimes of sediment movement.

[2] VAN DOREN, C. A., and BARTELLI, L. J. A METHOD OF FORECASTING SOIL LOSS. Agr. Engin. 37(5): 335-341. 1956.

[3] GLYMPH, L. M., JR. RELATION OF SEDIMENTATION TO ACCELERATED EROSION IN THE MISSOURI RIVER BASIN. U.S. Soil Conservation Serv. SCS-TP-102. 1951. [Processed.]

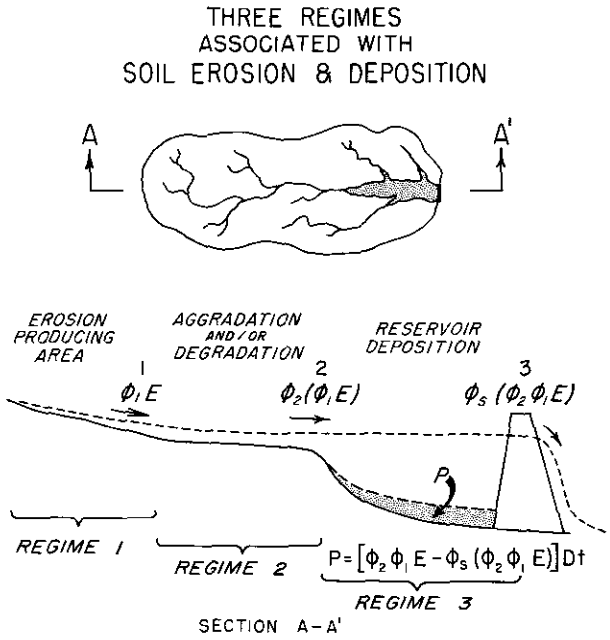

FIGURE 2.— Three regimes associated with soil erosion and deposition.

We next place some qualitative symbols on the three regimes as follows:

P = tons, reservoir deposition;
E = tons per acre-year, computed gross erosion;
D = acres, watershed area;
t = years;
ϕ_1 = coefficient of sediment discharge from regime 1;
ϕ_2 = coefficient of sediment discharge from regime 2;
ϕ_s = coefficient of sediment discharge from regime 3.

With reference to figure 2, the relationship of these mentioned seven variables in a sediment budget equation is as follows:

$$\phi_2 (\phi_1 E)\, Dt = P + \phi_s (\phi_2 \phi_1 E)\, Dt \quad (1)$$

$$P = \phi_2 E - \phi_s (\phi_2 \phi_1 E)\, Dt \quad (2)$$

$$P = \phi_2 \phi_1 E\, (1 - \phi_s)\, Dt \quad (3)$$

An overall pattern of understanding has now been laid out for sediment movement throughout the watershed and reservoir.

Physical Evaluation of Regimes 1, 2, 3

In the study of watersheds, assessing the sheet erosion contribution to sediment load has been very successful by evaluating on a watershed basis the universal soil loss equation.

Many recent authoritative articles have attacked the problem of isolating watershed characteristics that attenuate computed gross erosion to the extent that a quantitative prediction of

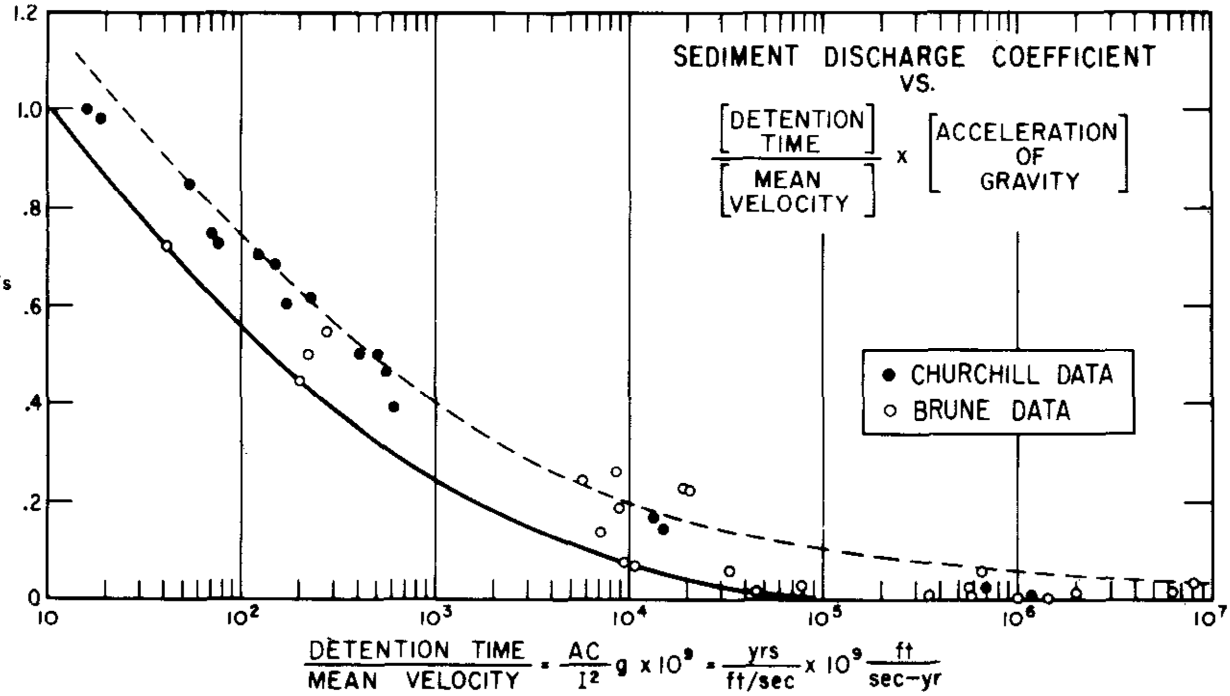

FIGURE 3. — Sediment discharge coefficient.

reservoir deposition is possible. In general, these studies have been on a macro scale in the watershed, thus encompassing regimes 1 and 2. Considerable success has been achieved under certain conditions, as in the case of Maner [4] who found, in the Rolling Red Plains area in Texas, a strong relationship between a relief-length ratio and sediment delivery rate.

Evaluation of regime 3 has commonly been by volumetric measurement of sediment deposited and in some cases by suspended load measurements at points 2 and 3 in figure 2.

Analysis of Interrelationship of Regimes 1, 2, 3

The area of primary interest to us in this system of regimes is the volume loss due to reservoir sedimentation. Thus, our program is oriented toward a reliable prediction of P in equation 3.

[4] MANER, S. B. A METHOD FOR ESTIMATING SEDIMENT YIELD IN THE ROLLING RED PLAINS LAND RESOURCE AREA. U.S. Soil Conservation Service, Fort Worth, Tex. March 1957. [Processed.]

[5] BRUNE, G. M. TRAP EFFICIENCY OF RESERVOIRS. Amer. Geophys. Union Trans. 34: 407-418. 1953.

[6] CHURCHILL, M. A. ANALYSIS AND USE OF RESERVOIR SEDIMENTATION DATA. Inter-Agency Sedimentation Conf. Proc. Washington, D. C. Discussion by L. C. Gottschalk, pp. 139-140. 1948.

Of the seven variables in equation 3, P, D, and t are readily obtainable, whereas E is a computed value. The term $(1 - \phi_s)$ corresponds to the commonly known reservoir trap efficiency relationships.[5]

Reservoir and river sedimentation is commonly a function of one-directional flow. Therefore, trap efficiency in terms of $(1 - \phi_s)$ affords perhaps a more logical explanation of the extremes in trap efficiency. In the particle size range associated with waterborne sediments, ϕ_s, the coefficient of sediment discharge from regime 3 would theoretically never be zero. At the other extreme, a ϕ_s value in the vicinity of 1.0 would be at the threshold of scouring conditions. A continuity in the expression $(1 - \phi_s)$ exists as reservoir size increases from impoundments created by submerged dams and channel obstructions to structures of large C/W ratios.

Data have been presented in a form corresponding to this relationship by Churchill,[6] who relates the sediment passing through a reservoir to a sedimentation index in units of the reciprocal of acceleration. For the reservoirs appearing in Brune's "Trap Efficiency of Reservoirs," detention time divided by mean velocity has been computed and plotted as shown in figure 3.

The introduction of acceleration of gravity makes the expression in figure 3 truly dimensionless as follows:

$$\frac{AC}{I^2} \times \frac{g}{1} = \frac{L^2 \times L^3}{(L^3/T^2)} \times \frac{L}{T^2} = \frac{L^6\,T^2}{L^6\,T^2}$$

This permits an equation for the curve to be written as:

$$\phi_s = f\left(\frac{AC}{I^2}\,g\right)$$

where

A = reservoir surface area;
C = reservoir capacity;
I = rate of average annual inflow;
g = gravitational acceleration;
ϕ_s = sediment discharge coefficient;
L = length;
T = time.

Accepting the sediment discharge coefficient relationship exemplified in figure 3 now makes the problem of interrelating regimes 1, 2, 3 determinant in that there remains only one unknown, the expression containing $\phi_2\,\phi_1$.

Thus, as is often done, the constants and knowns are divided out, leaving the unknown expression for sediment discharge from regime 2 on the right side of the equation; however, in accord with the preceding arguments, the composite unknown $\phi_2\,\phi_1$ remains on the right side as follows:

$$\frac{P}{D\,t\,E\,(1-\phi_s)} = f\,(\phi_2\,\phi_1) \qquad (5)$$

The left side is the dependent variable in evaluating watershed characteristics that are exemplified by $f\,(\phi_2\,\phi_1)$.

In our approach to the data contained in this equation we make certain necessary assumptions as to the rates of change for these factors on the left, namely, that their rates of change are negligible. However, as the quantity of data builds up, we will in time approach the realm of evaluating their rates of change.

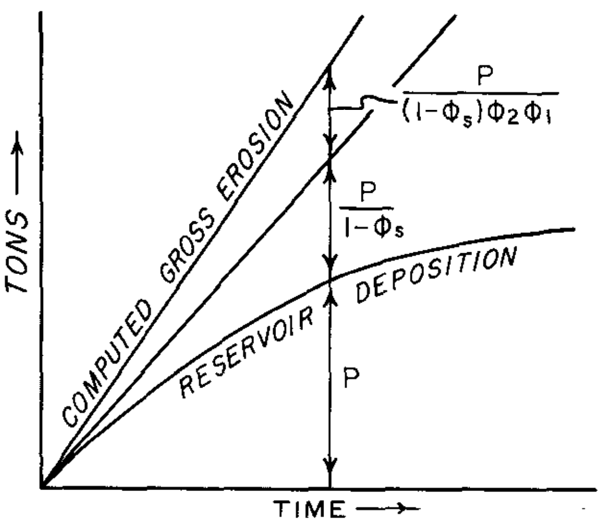

FIGURE 4. — Mass curves of erosion and deposition.

Of more immediate value is a consideration of the variation of ϕ_s with time. Reservoir capacity and ϕ_s, by comparison with all other factors at the present level of evaluation, have the most significant change with time. Plotting P against t from equation 3 gives a curve of the general shape shown in figure 4, which is a mass curve of sediment accumulation. The first derivative of equation 3 with respect to time then is interpreted as the instantaneous rate of change of the mass curve of P, or:

$$\frac{dP}{dt} = \phi_2\,\phi_1\,E\,(1-\phi_s)\,D \qquad (6)$$

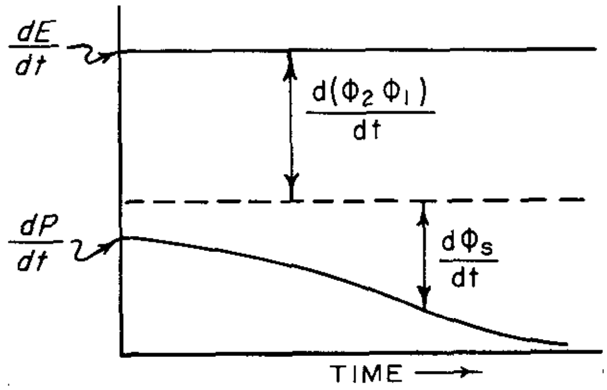

FIGURE 5. — Time derivative relationships.

Figure 5 shows the relationship of $\frac{dP}{dt}$ with time. Shown also is $\frac{dE}{dt}$, which through necessity is assumed to be constant. The horizontal dashed line represents $\frac{dP}{dt}$ corrected for trap efficiency, $(1-\phi_s)$. The ordinate then between $\frac{dP}{dt}$ and the dashed line is $\frac{d\,\phi_s}{dt}$, whereas the ordinate between the dashed line and $\frac{dE}{dt}$ remains to be explained by means of watershed characteristics. Figure 6 shows the relationship of ϕ_s with time.

Consider now the reverse case, where the mass curve of P is to be predicted for a proposed reservoir. The ordinate to the mass curve is now equal to the area under the $\frac{dP}{dt}$ vs. time curve shown again in figure 7 and is expressed as follows:

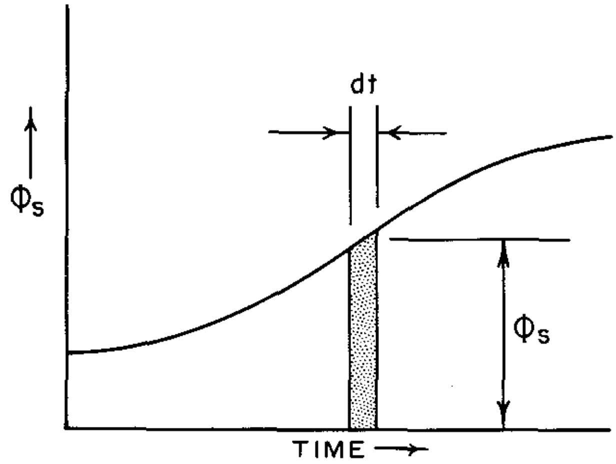

FIGURE 6. — Sediment discharge coefficient relationship.

$$P = \int_0^t \left(\frac{dP}{dt}\right) dt \qquad (7)$$

If we substitute equation 6,

$$P = \int_0^t [(\phi_2\ \phi_1\ E)\ (1-\phi_s)\ D]\ dt$$

The only variable we are presently capable of evaluating with respect to time is ϕ_s, and with all others being constant, then:

$$P = \phi_2\ \phi_1\ E\ D \int_0^t (1-\phi_s)\ dt \qquad (8)$$

$$P = \phi_2\ \phi_1\ E\ D \left[\int_0^t dt - \int_0^t \phi_s\ dt\right]$$

$$P = \phi_2\ \phi_1\ E\ D \left[t - \int_0^t \phi_s\ dt\right] \qquad (9)$$

The value of the integral in equation 9 is found to be the area under the ϕ_s vs. time curve shown in figure 6, and will be important in considering the life expectancy of a reservoir.

In data collection, the integral factor could be important where sedimentation surveys are made at a time in a reservoir's life, when the ϕ_s value is in the vicinity of rapid change. However, if conditions are such that ϕ_s may be assumed constant, equation 9 simply reverts to the form of equation 3, since the integral would then be $\phi_s\ dt = \phi_s\ t$.

When the effect of time on ϕ_s is considered in the analysis of watershed characteristics, equation 5 becomes:

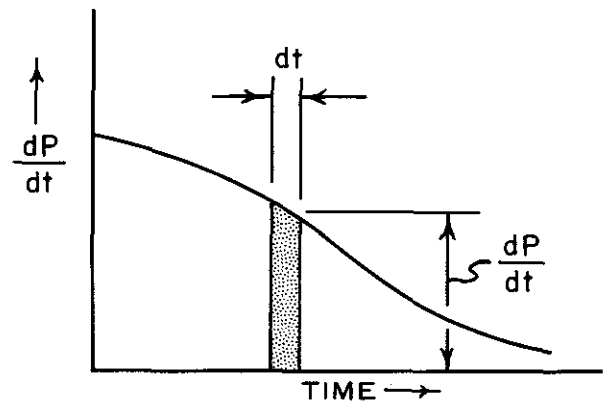

FIGURE 7. — Annual sediment deposition relationship.

$$\frac{P}{D\ E\left[t - \int_0^t \phi_s\ dt\right]} = f\ (\phi_2\ \phi_1) \qquad (10)$$

Conclusions

The problem of analyzing the watershed and reservoir as a unit is simplified by considering (1) the attenuation of gross erosion by factors on a macro scale that bridges regimes 1 and 2, and (2) the trap efficiency when it is analyzed as a constant with respect to time.

By the arguments set forth herein, the existence of regimes 1 and 2 is validated, giving rise to the concentration of effort on the evaluation of the zone of transition between regimes 1 and 2. Also the methodology for the evaluation of trap efficiency in its relationship to the sediment budget equation has been presented, which can be important in analyzing data and in designing reservoirs.

Thus, our approach to the interrelationship of the three regimes should use to the greatest extent possible our body of physical relations known to govern, and our findings should be in accord with other supporting evidence.

Advances on the zone of complexity, exemplified by $\phi_2\ \phi_1$, have been by way of making measurements of individual watershed characteristics. The pattern of understanding described in this paper is based largely on physical laws and is presented with the hope that it will allow all available reservoir and watershed information to be used to understand better the happenings in the void area between known watershed soil loss and known reservoir sediment deposition.

BUILDING A NONLINEAR SEDIMENT YIELD MODEL

[Paper No. 10]

By ROGER P. BETSON, *head, Statistical Analysis Unit, Hydrology Section, Hydraulic Data Branch, Division of Water Control Planning, Tennessee Valley Authority*

Abstract

Several examples are presented, illustrating the development and solution of a complex empirical sediment yield model utilizing nonlinear least squares techniques adapted for computer analysis.

Introduction

The suspended sediment transported from a watershed is a measure of the erodibility of the watershed. Changes in the yield of suspended sediment can provide a relatively sensitive index with which the effects of land use changes or changes in levels of land management can be evaluated.

The yield of suspended sediment, however, is a complex function of many hydrologic variables as well as the physical characteristics of the watershed. Large variations that are inherent in suspended sediment data tend to obscure any changes in the yield that may have resulted from land use changes. In order to make any quantitative analysis of sediment data, it is usually necessary to make some adjustment for the more important factors causing variation. Because of the large number of factors at work simultaneously, this adjustment is frequently achieved through multivariable regression analysis.

Prior to the advent of high speed electronic computers, devising mathematical sediment yield models and evaluating these models by regression analysis were tedious. The labor involved in analyzing data and solving a regression equation with a desk calculator precluded a trial and error approach to model building. The model itself, of necessity, had to be elementary and preferably with linear regression coefficients. Once the form of the equation was decided and the equation fitted to the data, extensive manipulation of the equation based on the results of the fitting were difficult to justify because of the expense and time involved.

Computers have changed this picture considerably. Computer programs are now available, or can be written, that will evaluate almost any equation that can be devised for data adjustment. This paper illustrates how a computer can be used in the analysis of a complex suspended sediment yield equation and how the model can be manipulated to yield certain desired results. The basic equation that is used in this study has been presented earlier.[1] No attempt has been made to drastically alter this basic equation by introducing different variables; nor has new data been introduced, although subsequent measurements have been made.

The Watershed

The Tennessee Valley Authority, as part of its regional resource development program, has recognized the necessity of giving appropriate attention to the solution of land use and water control problems on rural watersheds within the Tennessee Valley. Watershed projects have been included in the program to study the land use and land management problems. Some of these watershed projects are designed to promote basic hydrologic research, whereas others are concerned with demonstrating the effect of TVA's applicable regional development integrated on a single watershed. Hydrologic data on runoff and sediment loads are collected that serve as measures for determining the effect of changes in cover and land use. In the Chestuee Creek watershed, used for this study, TVA and other Federal, State, and local agencies worked with the people of the area in a program designed to promote efficient control and utilization of water and improved land use, including reduction of erosion and loss of valuable soil.

The Chestuee Creek watershed includes an area of 133 square miles located in the Great Valley of East Tennessee about midway between Knoxville and Chattanooga. Chestuee Creek is one of several streams that run in a northeast-southwest direction in this part of the Tennessee Valley, draining into the Hiwassee River arm of the Chickamauga Reservoir. In an 18-year period, 1944 through 1961, during which hydrologic measurements were collected on this watershed, annual precipitation ranged from 41.0 to 62.4 inches, averaging 52.8 inches, and annual runoff ranged from 14.2 to 28.3 inches, averaging 21.3 inches.

The stream pattern consists of the main Chestuee Creek and a nearly paralled tributary, Middle Creek, in the upper end of the watershed. Smaller creeks and branches drain the higher lands into Chestuee and Middle Creeks. Progressive deterioration of land cover on this watershed in the past century, with consequent accelerated erosion, has resulted in partial filling of the stream channels with resultant reduction in the floodwater carrying capacities.

Extensive hydrologic measurements of precipitation and streamflow were made over the

[1] COOPER, A. J., and SNYDER, W. M. EVALUATING THE EFFECTS OF LAND-USE CHANGES ON SEDIMENT LOAD. Amer. Soc. Civil Engin. Proc. Paper 883. 1956.

watershed during the period 1944 through 1961. Sediment measurements were made from 1944 through June 1955 and in the calendar year 1961. Considerable emphasis was placed in this early investigative work on monthly sediment load data because it was felt that this provided one of the better indices with which to measure the effects of improved cover and land use management on the hydrology of the watershed. All the sediment yield analyses were performed on data collected during the 10-year period, 1944–53. The data collected during the 18 months from January 1954 through June 1955 and calendar year 1961 were reserved for a check on the validity of the results. All the studies made in this paper were performed on this same 10-year data so that comparisons of results obtained using various techniques could be made. Studies are also limited to Chestuee Creek at Dentville, the largest gaged area in the watershed, totaling 114 square miles.

Estimating Sediment Yield

The original equation that was used to adjust the Chestuee Creek data was empirical, as are all of the subsequent modifications that were tried for this paper. All the equations studied for this paper, however, were the result of modifications of the original, which included, as the most important variables, current rainfall, antecedent rainfall, and a condition of the cover or season. The use of monthly data limited the available variables to those that could be given meaning over the span of a month. Also included in the eqaution was a time variable to enable the relationship to reflect changes in land use. The form of the equation was as follows:

$$Y = a + b P_1^m P_2^n + c P_1^m P_2^n (2 + \sin M) + de^{-fT}$$

where:

- Y = monthly sediment, in tons per square mile;
- P_1 = rainfall for current month, in inches;
- P_2 = rainfall for previous month, in inches;
- M = season, by months evaluated by arbitrarily setting January = 30°, February = 60°, etc.;
- T = time, by months (January 1944 = 0.01, February 1944 = 0.02, etc.);
- e = base of natural logarithms; and

$a, b, c, d, f, m,$ and n are constants to be evaluated.

Solution of this nonlinear equation directly by the use of only desk calculator techniques was virtually impossible, as the equation cannot be easily linearized. Therefore, the equation had to be simplified to reduce the exponents so that linear techniques could be used. Determination of the exponents of the rainfall terms in this equation was done by examining parts of the data in which the effects of the other variables were small. For example, the effect of rainfall on sediment load was studied for similar seasons of the year that also had similar antecedent conditions. The smallest simple integral root or power that seemed to express adequately the effect of that variable on the sediment load was chosen as the exponent of that variable.

Use of the exponential function as an additive parameter in the equation presented considerable difficulty, since with this term included the equation still could not be evaluated directly by the method of least squares. Consequently, an abbreviated form of the equation was used to evaluate the exponent on a trial and error basis. In this abbreviated form the first term of the equation after the constant was dropped to reduce the number of simultaneous equations that had to be solved. In order to evaluate the best value of the coefficient f, various values were assumed. The abbreviated form of the equation was then fitted to data by least squares, and the residual error of the regression computed. The trial values of f were plotted against the respective residual errors. The process was continued until the value of f, which gave the minimum residual error, could be determined from the plot. With the data used in this study, six separate solutions were necessary. After determination of the best value of the exponent f, the equation was fitted to the data by least squares to determine the best values of the other coefficients. Equation 1 shows the results obtained from this fitting.

$$Y = -8.696 - 0.03256 P_1^2 P_2^{1/3} + 0.4329 P_1^2 P_2^{1/3} (2 + \sin M) + 29.88e^{-2.800T} \quad (1)$$

Figure 1 shows the computed time regression for the average monthly sediment load, computed by assigning values to the two hydrologic terms corresponding to their mean. In the 10-year period since 1944, a reduction in the average monthly sediment load of 48 percent is indicated.

Solution of Equation by Computers

Earlier work in TVA has shown the feasibility of using the multivariate technique of component analysis in the solution of nonlinear least squares.[2] This technique for solution of nonlinear equations is found under the name "method of differential corrections." Whenever this technique has been tried in TVA,[3] using multivariate analysis for the solution, reason-

[2] SNYDER, W. M. SOME POSSIBILITIES FOR MULTIVARIATE ANALYSIS IN HYDROLOGIC STUDIES. Jour. Geog. Res. 67(2). 1962.

[3] NIELSEN, K. J. METHODS IN NUMERICAL ANALYSIS. pp. 309-313, New York. 1957.

PLATE I

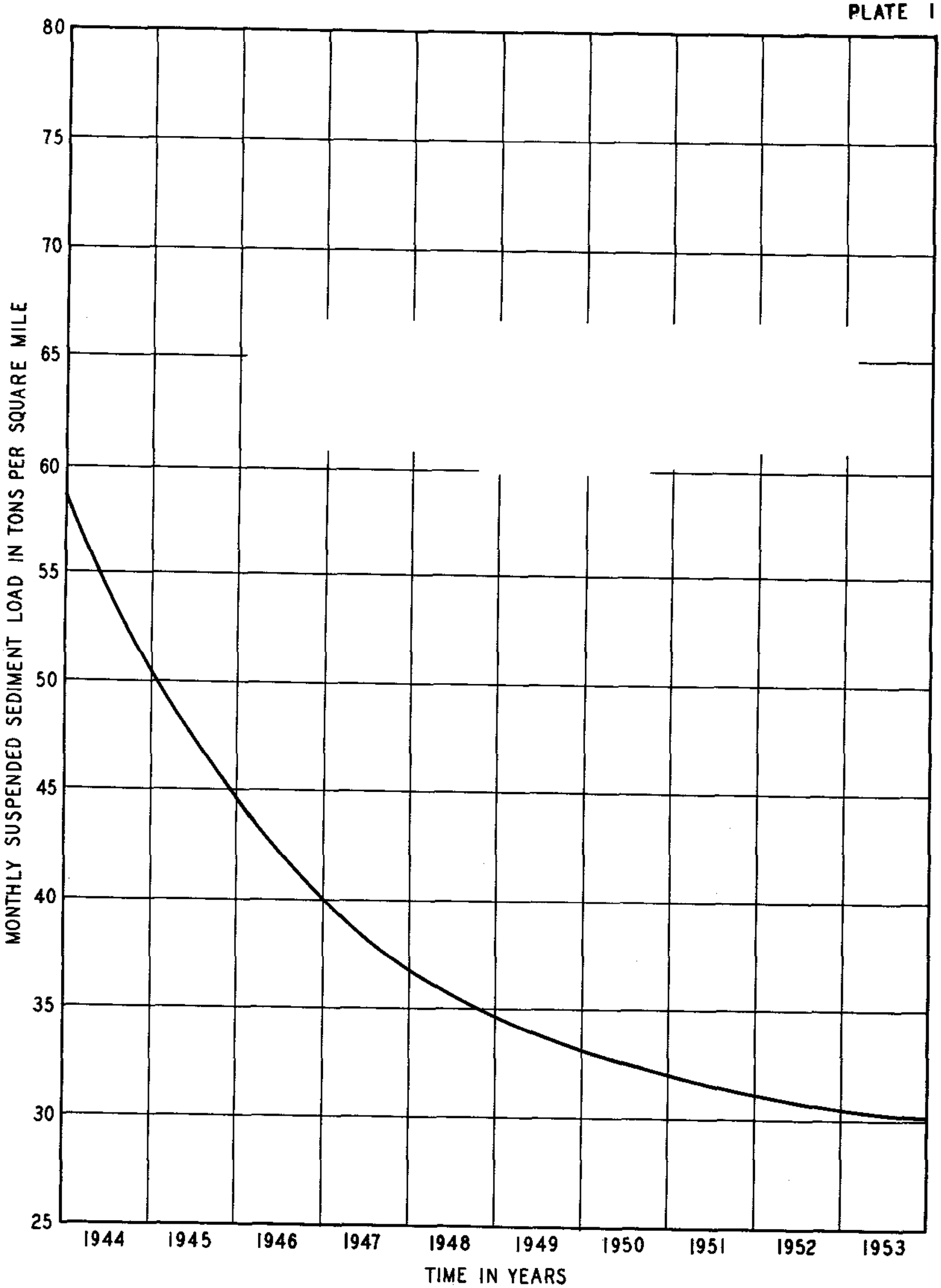

FIGURE 1. — Chestuee Creek Watershed: Average monthly sediment load — regression with time (equation 1).

ably rapid convergence of this iterative solution has been achieved consistently. All the equations that were developed for this paper were solved by this technique with an available master IBM 704 computer program. Operation of this program involves writing a short subroutine containing the partial derivatives of the equation to be solved.

Equation 2 shows the results obtained using the computer to solve for the same coefficients as in equation 1.

$$Y = -9.086 + 0.01625\, P_1^2\, P_2^{1/3} + 0.4204\, P_1^2\, P_2^{1/3}\, (2 + \sin M) + 30.77e^{-2.832T} \quad (2)$$

The comparability of the coefficients in equation 2 and equation 1 shows that the computer solution accomplished by simultaneous solution for all the coefficients supports the earlier solution achieved by manual trial-and-error regression analysis. The degree of comparability between these two equations is indicated by a comparison of the time regression functions as shown in figure 2. The difference between the amount of change indicated by equation 2, as compared with equation 1, is only 3 percent.

If the computer program is to be of any value, however, the real test is not its ability to reproduce results obtained by the use of desk calculator techniques; rather the test should determine its versatility in solving equations too complex to be attempted by hand solutions. To test the range of the program the sediment yield equation was revised slightly to the following form:

$$Y = a + b\, P_1^m\, P_2^n + P_1^m\, P_2^n\, (c \sin M + g \cos M) + de^{-fT}$$

In this equation all of the exponents as well as the coefficients are solved for by the program. In addition, the effect of using a sine + cosine term is to allow variation in both amplitude and phasing of the seasonal wave.

Equation 3 shows the results of fitting this equation to the Chestuee Creek data.

$$Y = -8.988 + 1.054\, P_1^{1.803}\, P_2^{0.4377} + P_1^{1.803}\, P_2^{0.4377}\, (0.5215 \sin M + 0.170 \cos M) + 31.90e^{-3.427T} \quad (3)$$

Again, the values of the coefficients, as well as the two exponents of rainfall, are in substantial agreement with the results obtained in equation 1. Because of the revision in form, the coefficients of the two terms that include the rainfall variables cannot be compared directly. However, if the rainfall variables are factored out of the two terms in which they appear, comparisons can be made.

Figure 3 shows that the variation of the seasonal terms for equations 1 and 3 throughout the year is similar. The two curves are phased within about one-half month of each other. The amplitude of the two seasonal curves differ by about 25 percent between the winter maximum and the fall minimum. The time-regression function, resulting when all of the coefficients and exponent terms in equation 3 are determined by the data, is shown in figure 2. This curve indicates that the suspended sediment transport rate in the watershed was reduced somewhat earlier in the period and also the total amount of the change during the 10-year period is about 9 percent larger than that indicated by equation 1.

One of the more tangible advantages of computer analysis of data is that "hindsight" can be used in the improving of a model to delineate adequately anticipated results. If a model proves inadequate, revisions can readily be made based on the results obtained from initial trials. Often the initial fittings of a model to actual data yield unexpected results, or, on the other hand, the results may be sufficiently encouraging that some sophistication in the model can be justified. An example of this latter case follows.

The time-regression function obtained fitting equation 1 to the Chestuee Creek data yielded desirable results; however, interpretation was difficult. If the two hydrologic terms are given values corresponding to their mean and the time-regression function allowed to vary over 120 months, the equation indicates a monthly reduction of 29 tons per square mile or about 48 percent of the initial rate. This reduction, of course, is an average, and a plotting of the prediction residual error with time would show a characteristic scatter with some months predicted high, others low. In general, the equation underpredicts during winter months and overpredicts during summer months. This seasonal distribution of the error pattern indicates that the change in sediment transport is not the same for all seasons. The time-regression function, in fact, indicates a reduction in the monthly sediment load that is larger than the total load experienced during many of the summer months, even early in the record. It is evident, then, that the amount of the change in sediment transport also varies with the season. Understandably, larger reductions can be expected during the winter months, when the sediment transport is high, than during the summer months. The model as originally constructed, however, allowed variation with time but not by season. To rectify this shortcoming, the following equation, an adaptation of equation 1, was fitted to the data:

$$Y = a + b\, P_1^2\, P_2^{1/3} + c\, P_1^2\, P_2^{1/3}\, (2 + \sin M) + de^{-fT} + ge^{-hT}\, (2 + \sin M)$$

In this form, the equation allows some seasonal variation in the time-regression function. The result obtained fitting this equation to the data is shown in equation 4.

PLATE 2

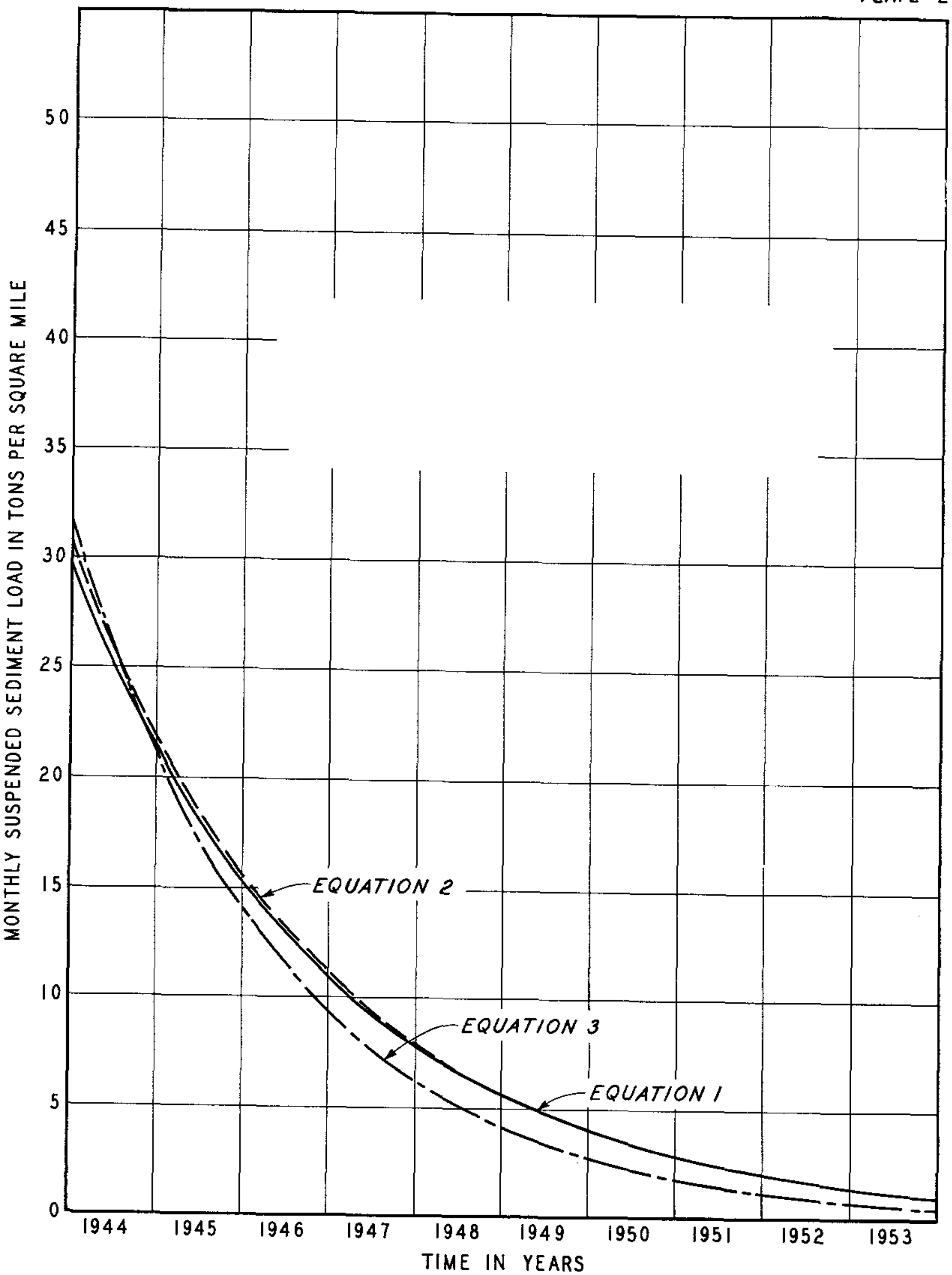

FIGURE 2. — Chestuee Creek Watershed: Suspended sediment prediction by time regression function.

PLATE 3

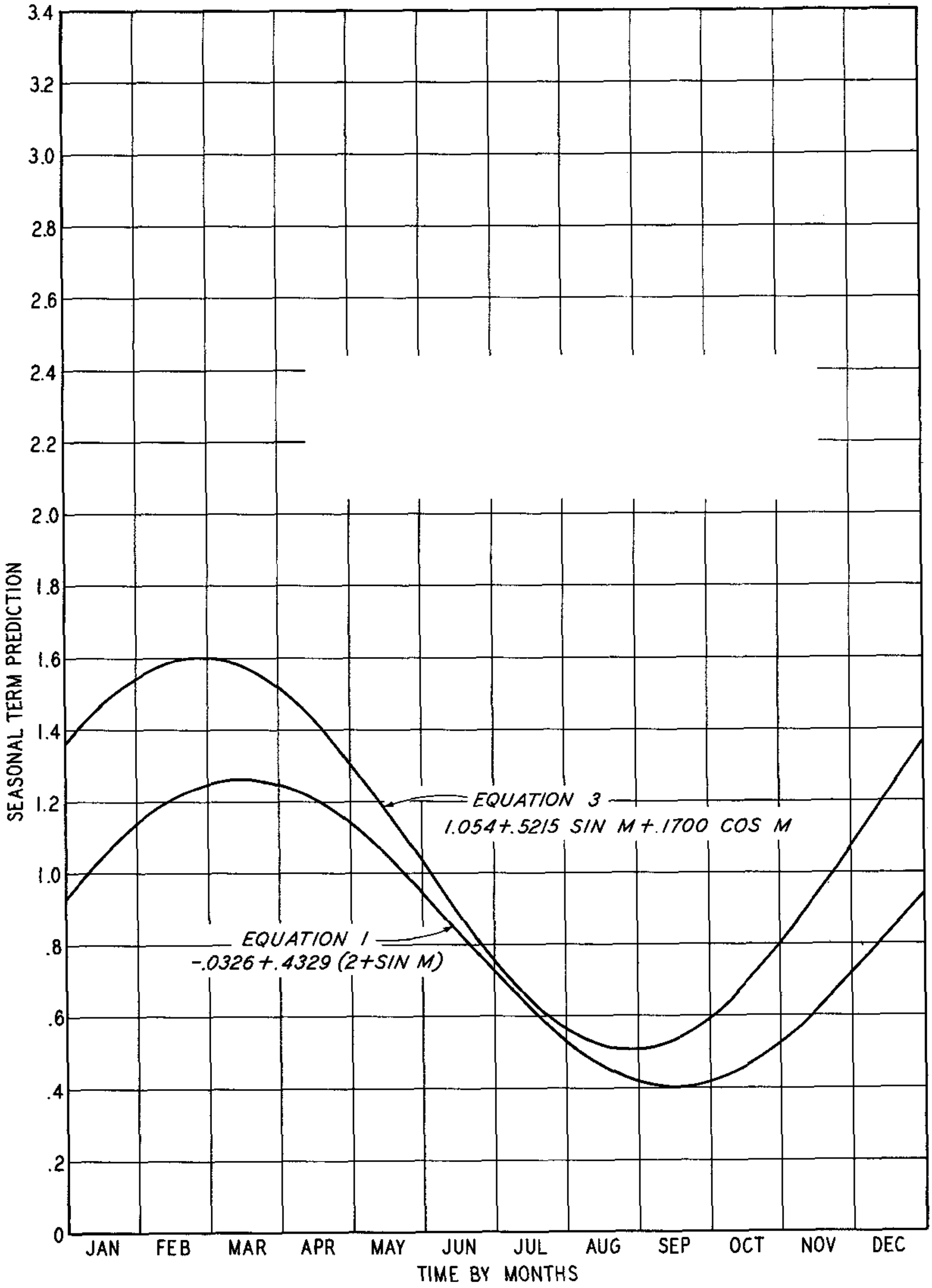

FIGURE 3.— Chestuee Creek Watershed: Comparison of season-regression terms (equation 1 vs. equation 3).

PLATE 4

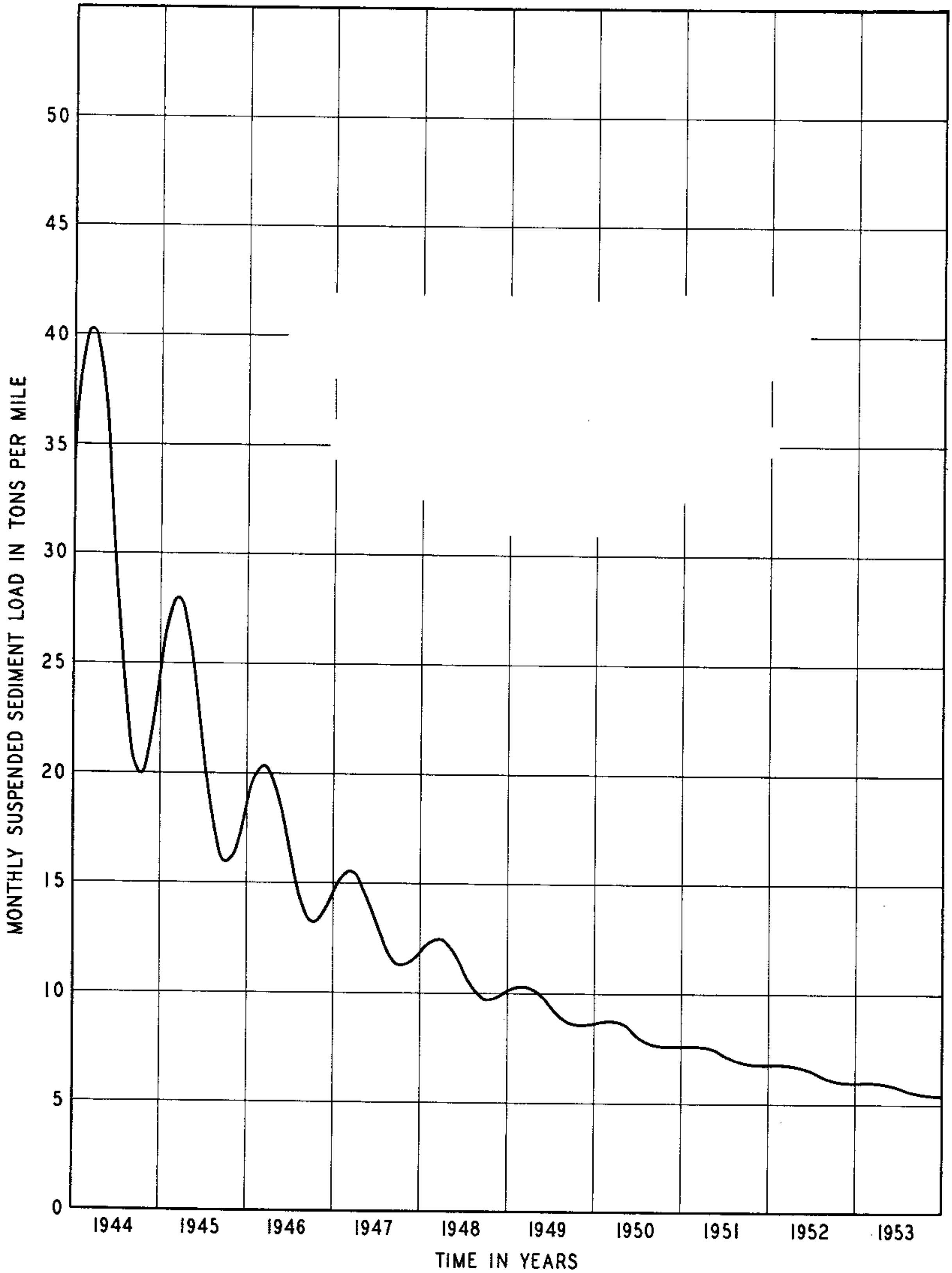

FIGURE 4. — Chestuee Creek Watershed: Suspended sediment prediction by time regression function modified by season (equation 4).

$$Y = -12.19 - 0.0956\, P_1^2 P_2^{1/3} + 0.4613\, P_1^2 P_2^{1/3} (2 + \sin M) + 14.55 e^{-0.8319T} + 9.853 e^{-4.581T} (2 + \sin M) \qquad (4)$$

The coefficients of the rainfall terms are not much different from those in equation 1. However, the arrangement of coefficients in the two time-regression functions indicates that this relationship has undergone considerable change. Figure 4 is a plotting of the composite time-regression function of equation 4. It is evident that there is a considerable seasonal difference in the amount that the sediment load was reduced.

To estimate the magnitude of reduction in sediment loads by seasons, equation 4 can be used as a prediction device. If appropriate mean monthly rainfall values are used for the precipitation variables and time is allowed to vary from a specific month in 1944 to the same month in 1953, estimates can be made of the magnitude of the change in sediment transport by seasons. The equation indicates that average rainfall would have resulted in a total of 106 tons of sediment per square mile in March 1944 as compared to 72 tons in March 1953 for a reduction of 34 tons, or 32 percent. Similarly, for September the equation indicates that average rainfall would result in a total load of 16.9 tons per square mile in 1944, but only 2.4 tons in 1953 for a reduction of 14.5 tons, or 86 percent.

Thus, a slight modification in the equation, made because the original was not sufficiently versatile to describe desirable relationships, has resulted in a far better understanding of the sediment transport characteristics of the watershed. The monthly sediment reduction indicated by the original equation was 29 tons per month on the average, whereas that indicated by the modified equation varied from a high of 34 tons in March to a low of about 14.5 tons in September. This latter result not only gives more insight to the changing sediment transport relations; it is also more realistic.

Although statistical interpretation of the results obtained from fitting the four equations to the Chestuee Creek data is beyond the scope of this paper, certain interesting implications can be drawn. In all three of the equations fitted by the computer, very little improvement over the fit of the original equation was accomplished. The multiple-correlation coefficient for all equations was 0.9 and the standard error about 25 tons per square mile. The fact that significant improvements in the fit were not realized, despite the fact that the number of restraints on the equation were varied and improvements made in the model, indicates that this is about the limit of the adjustment of these data that can be made with these variables. If we consider that the variables used in the equation are monthly totals, although sediment transport is primarily a function of individual storm characteristics, a substantial standard error is not unexpected. Further improvements in the fit of the model could probably be made only if additional information were introduced.

Conclusion

The electronic computer has provided the hydrologist with the analytic means of solving equations of an extremely complex nature. No longer need he be limited by linear equations or transforms to linear equations. Mathematical models can be developed that utilize to a much greater degree the complex functional relationships that exist in nature. On the other hand, the efficiency and speed of the computers allow a direct approach to empirical model building. The data can be used to aid the hydrologist in building a model. The results of one fitting of an equation to the data can be used as a guide to improving the basic model. Model building in this manner can lead the hydrologist to a much better understanding of the relationships involved. It enables the hydrologist to construct his model in such a manner that the final equation, even though entirely empirical, can yield physically interpretable results, because the model can be based on logical and rational considerations. The development need not be biased by a foreknowledge of requirements of simplicity and linearity.

An example of model manipulation, utilizing monthly suspended sediment data, is shown in the paper. The use of a month as a time base for suspended sediment measurements not only precludes any attempt to find physical causal relationships; it severely limits the number of meaningful parameters available. Despite these limitations, results are obtained from these data that lead to a good understanding of the sediment transport characteristics of a watershed.

Land Use and Ecological Factors in Relation to Sediment Yields

[Paper No. 11]

By Otis L. Copeland, Jr., *chief, Division of Watershed Management Research, Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture*

America's development for more than three centuries has been advanced largely by the prodigious utilization of her natural resources, especially soil, water, timber, forage, oil, and minerals. But this progress created attendant problems of depletion or deterioration of these basic resources. Important resource problems that concern this audience are the impoverishment of productivity, impairment of hydrologic processes, aggravation of flood peaks, and the increasing menace of sedimentation as a result of land use.

This discussion deals with ecological factors and land uses that influence sediment yields, and although the terms "soil erosion" and "sediment yield" are not synonymous, they are closely related and may occasionally be used interchangeably. "Sediment yield," as used in this paper, is the quantity of transported soil material resulting from land use and channeling of valley fill, the value of which varies with the size and condition of any given drainage area under consideration. "Soil erosion" refers to the detachment and movement of soil particles on-site, but does not necessarily imply movement into channels. Quantitatively, the amount of erosion may greatly exceed sediment yields measured in channels or at off-site locations.

Erosion and sediment production are not strangers to agricultural scientists and land managers, and their relation to land use is nothing new in this country and elsewhere. To discuss them is like "an old refrain" played again. The antiquity of the concept of land use and soil erosion and thus sediment yield is aptly illustrated by the Union of South Africa's appointment in 1920 of a commission to inquire into ways of improving water resources of the farms. Among the commission's findings were these: "Soil erosion is caused by reduction of the Country's mantle of vegetation." And further, "The soil belongs to the nation, not to the individual, and its dissipation through erosion is a national calamity that demands the aid of everyone to combat it" (*5*).

Recognition of sediment yield problems and the need for corrective action has progressed steadily in this country. Congressional action creating the national forests, establishing the Soil Conservation Service and later the organization of soil conservation districts, passing the Taylor Grazing Act, the C.C.C. program, and the various flood control and watershed protection programs are ample evidence of public concern and a desire to provide for remedial action. And, while no one would question the direction toward which the programs were oriented, there is serious concern about the slow rate of progress being made in applying knowledge now available to assure a coordinated and integrated approach to problems of land use to control sediment production at its point of origin. Phenomenal population pressures give an added sense of urgency to the need for accelerated progress in remedial programs.

Sediment production as a result of erosion on damaged watersheds indicates the loss of control over water in its contact with the soil. It results in such visible kinds of damage as silted reservoirs, clogged transmission structures, damaged hydroelectric facilities, buried valley lands, destroyed fish habitat, and scoured channels. Accompanying these visible damages, but far more insidious, is the gradual loss of the soil resource and consequent lowering of productivity.

In this paper, such land uses as logging and road construction, grazing, and recreation are considered. Ecological factors to be considered include vegetation, geological parent material and soils, slope, precipitation, and fire. Man may logically be regarded as an ecological factor because he may profoundly influence the environment through his various uses of the land. Ample evidence supports the contention that man has been a potent force in accelerating sediment yields because of his activities. Too often he has failed to reckon with the powerful forces of nature. This is not to say that man has extended his horizons of land use wrongfully — rather, let us say, too often unwisely. The crux of the situation is that public pressures will not long tolerate the continued failure to apply the protection necessary to maintain stability on our watersheds and thereby keep sediment production in check.

To achieve rapport in this discussion, a differentiation should be made between normal and accelerated sediment yields, because it is the latter with which we are concerned. This differentiation has been stated succinctly by Bailey (*2*):

> Every watershed is the product of many natural processes, including rock weathering, soil formation, erosion, and biotic succession, all of which have been operating under the impact of climate over the ages. Because of local differences in the climate, the resistance of rock to weathering, and such other features as the aspect, and length and steepness of slopes, differences have developed in the character of the plant cover and soil mantle, and in runoff and erosion. In some drainage basins, streams fluctuate but little either seasonally or annually, and carry negligible quantities of sediment. Others are frequently in violent flood stage and are generally muddy. Still others exhibit runoff and siltation characteristics between these extremes. Where such variations are but manifestations of different degrees of control established by nature, there is little that watershed management can do toward their control.
>
> It has been definitely established, however, that many of the floods and much of the sediment load carried by streams are not of normal proportions, but have been magnified by impairment of the plant cover and soil mantle on the watershed slopes and in valley bottoms. Watershed management can reduce such discharges and siltation rates, but only to the extent that they have been increased by watershed deterioration above the normal.

Notable progress has been made in curbing and controlling sediment yields through land management augmented by engineering structures. Watershed management and rehabilitation practices, now being applied more widely than ever before, are designed to control sediment at its source. These practices are being improved as research continues to reveal more definitely the interrelations among climatic, edaphic, and vegetation factors that control the swing of the pendulum of soil stability. Let us now examine the influence of ecological factors and land uses on sediment yields.

Precipitation

The magnitude of kinetic energy generated in 30 minutes by different rainfall intensities is shown in figure 1, constructed from basic energy data by Wischmeier and Smith (*19*). This graph shows that a rain falling at an intensity of 0.1 inch per hour produces in 30 minutes kinetic energy equaling 58,500 foot-pounds. A rain with an intensity of 2 inches per hour generates, in 30 minutes, kinetic energy of slightly more than 2 million foot-pounds. This would be sufficient to raise an acre furrow-slice 1 foot high. A rain of 8 inches per hour intensity would produce, in 30 minutes, enough energy to raise an acre-foot of soil almost 3 feet. While it is obvious that this is cumulative energy generated over the stated period, these values emphasize the tremendous force unleashed by torrential rainfall. It is dissipation of this energy toward which land use must be oriented.

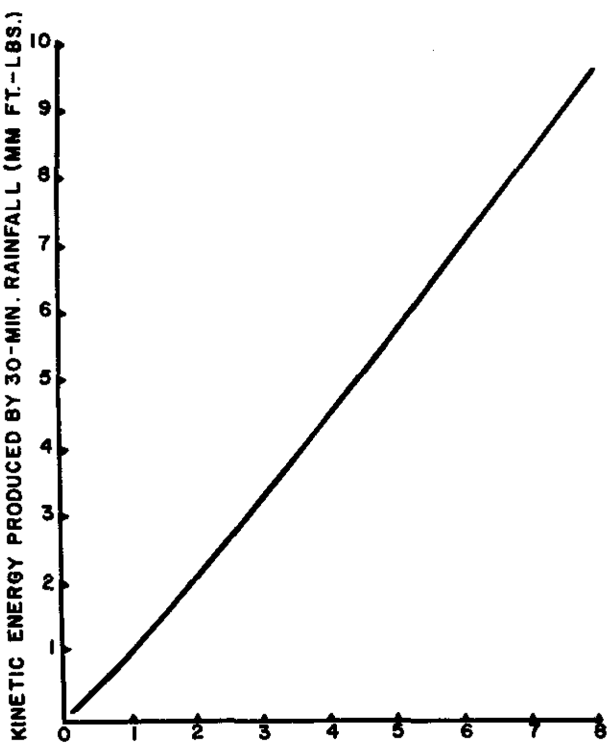

FIGURE 1.—Kinetic energy produced by 30-minute rainfalls of different intensities.

Although the last rainfall intensity mentioned above may be considered extreme, high-intensity storms are common over much of the United States and particularly in the Intermountain States. These storms, usually of short duration and limited extent, produce rain that is a powerful eroding agent. Examples of high-intensity storms are shown in figure 2; here it may be observed that the maximum intensity occurred at different time periods in each storm. Seldom do these storms occur when the soil mantle is saturated; rather they occur when the mantle has the capacity to store several inches of water. The critical characteristic is that the *rainfall intensities of these cloudbursts frequently* exceed the infiltration rate of the soil, especially when plant cover is depleted and overland flow is then inevitable.

Soils

A consideration of soils in relation to sediment yield introduces an almost infinite number of conditions that affect the infiltration of water very much and, conversely, the amount of overland flow and sediment yielded. Among these are texture of surface soil, inherent structure and consistence, depth of soil (especially to restrictive layers), porosity, and the percolation rate of subsurface horizons. Collectively, these factors determine the receptivity of water into that topmost thin skin of the soil mantle.

Soils derived from different geologic parent materials often exhibit varied capacities to infiltrate precipitation. These differences may be inherent or induced, and are illustrated by the data below obtained on the Boise River watershed (*15*).

Infiltration rate (inches per hour):	*Granite*	*Basalt*	*Sedimentary rocks*
Soil in normal condition..	6.9	7.1	5.6
Soil in eroded condition..	2.8	1.5	2.0
Watershed in each type (percent)	75.4	9.4	15.2

Erosion by water of the more receptive surface horizon has reduced infiltration 60, 80, and 64 percent, respectively, on soils derived from granite, basalt, and sedimentary rocks. Further reductions are possible as erosion exposes less permeable horizons and as the total infiltration capacity is diminished by creating shallower profiles. The greatest reductions in infiltration rates after erosion occurred in the finer tex-

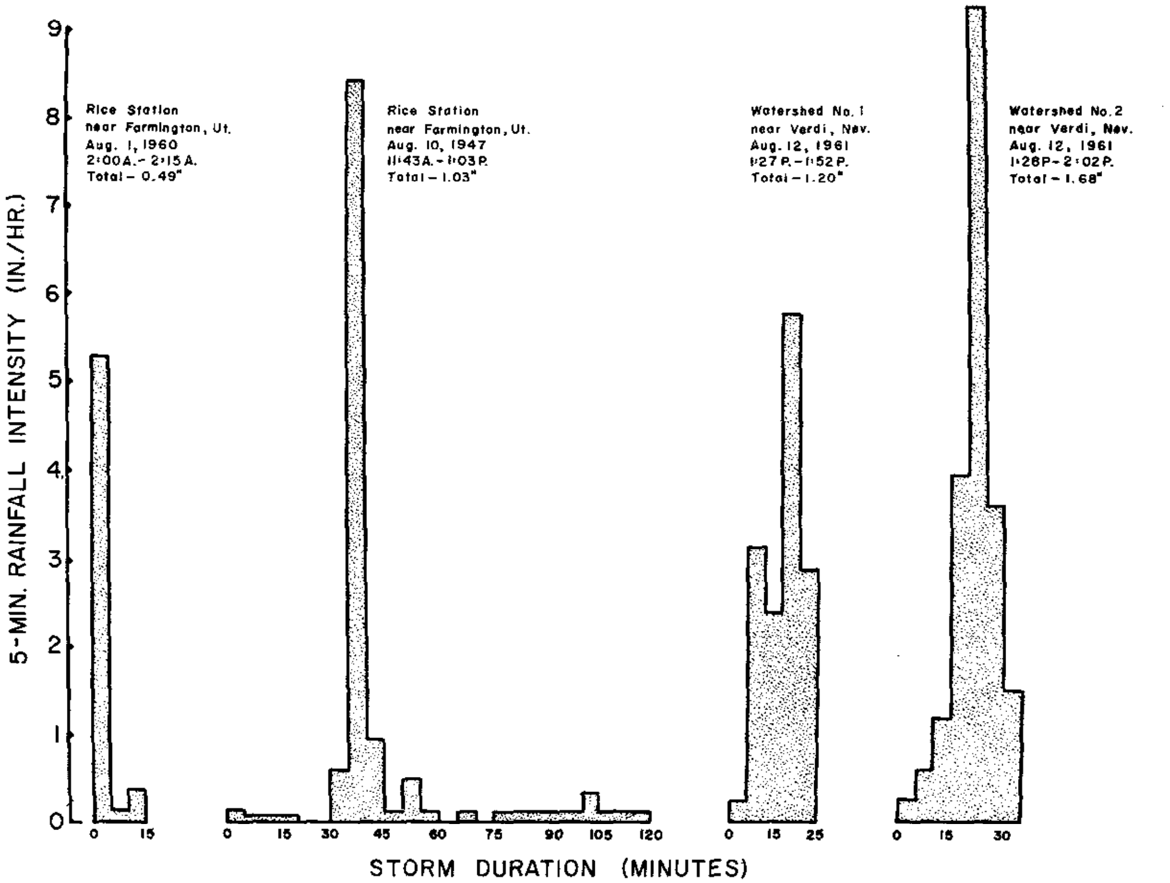

FIGURE 2.—Rainfall intensities of three storms (one measured at two locations) by 5-minute periods.

tured soils derived from basalt and sedimentary rocks.

Packer[1] investigated six major soil groups in the northern Rocky Mountain region to determine the levels of resistance to erosive cutting by overland flow on logging roads. He found that the order of increasing erodibility of the soils was hard sediments, basalt, granite, glacial silt, andesite, and loess. The general prevailing characteristic of the more erodible soils is their tendency toward single-grained structure and uniform texture.

Sediment yields are also influenced by other soil characteristics. Swelling of soils upon being wetted, compaction by trampling of animals, by machinery, or the impact of falling rain increase sediment production by reducing infiltration.

As soil bulk density increases, there is a corresponding decrease in porosity, a reduction in infiltration, and an increase of overland flow.

[1] Personal communication, P. E. Packer, September 1962.

[2] Personal communication, R. O. Meeuwig, September 1962.

Where ground cover is depleted to less than the minimum density required to protect the soil, sediment yields from relatively small areas may increase fantastically. Curves in figure 3,*A* show how sediment yields vary in relation to bulk density. These curves are based upon results from 160 plot tests of infiltration carried out by Meeuwig[2] in which 2.5 inches of simulated rainfall were applied in 30 minutes. Under low densities of ground cover, typical of deteriorated sites, there may be as much as a fourfold increase in sediment yields as soil bulk density increases from 0.8 to 1.4. The inset correction factor curve shows that sediment production increases sharply on sites with depleted cover as slope gradients exceed about 25 percent. Where ground cover is complete, changes in sediment yields with increasing slope gradients are minor. This point is discussed more fully later in this paper.

On soils derived from sedimentary material in Montana, similar pronounced increases in eroded sediment in relation to bulk density are shown in figure 3,*D*. Although the amounts are

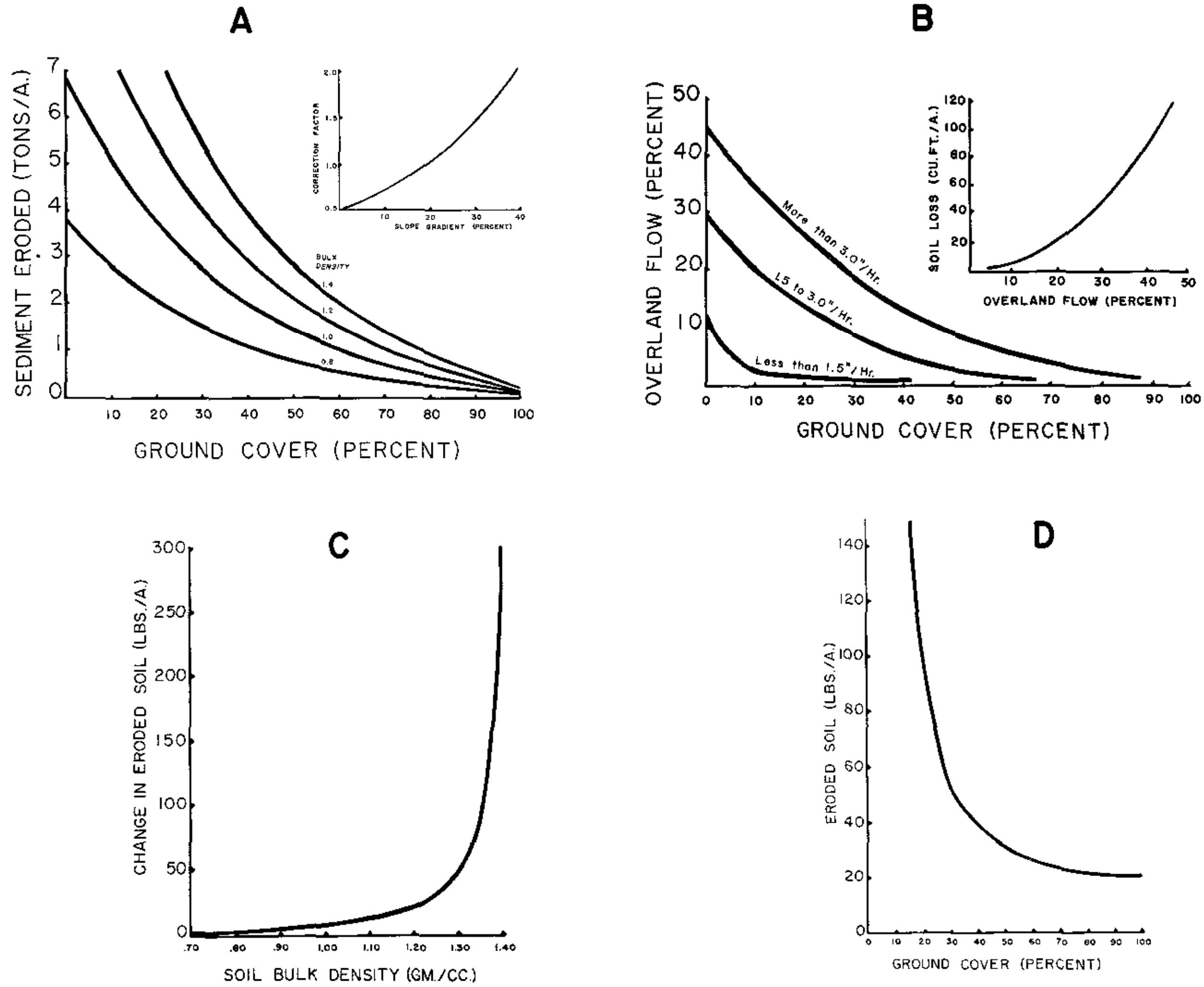

FIGURE 3.—*A*, Sediment eroded from central Utah rangelands in relation to ground cover and soil bulk density. The inset curve is a correction factor for sediment yield as affected by slope gradient. *B*, Overland flow by different storm intensity classes as a function of ground cover. The inset curve relates sediment to overland flow (Davis County Experimental Watershed, Utah). *C*, Changes in the amount of sediment produced in relation to soil bulk density on elk winter range in Montana. *D*, Sediment production as a function of ground cover at a mean bulk density of 1.14 on elk winter range in Montana.

considerably less than those in figure 3,*A*, the trend is the same (*12*). Packer concluded that one prerequisite to maintaining soil stability on this elk winter rangeland is a soil bulk density of 1.10 or less.

Vegetation

Residual soils result from the weathering of parent material as influenced by time, climate, relief, and vegetation. The retention of the weathered material in place and its maturation as soil in the face of vagaries of weather and other natural phenomena depend upon simultaneous vegetation development, especially on steep mountainous areas.

Bailey (*1*) measured numerous slopes in Idaho and Utah to determine the maximum angles of repose of those vegetated and barren. He found that barren talus-covered slopes stood at gradients between 68 and 80 percent, or at an angle of about 36°. In contrast, densely vegetated slopes underlain by fine-textured soils derived from material similar to the talus did occur on slopes with gradients up to 173 percent, or 60° (fig. 4). Without the stability afforded by vegetation, these soils could not have accumulated. They would have been displaced by gravity or would have been blown or washed away, and the resulting slope gradient would not have exceeded that of the talus.

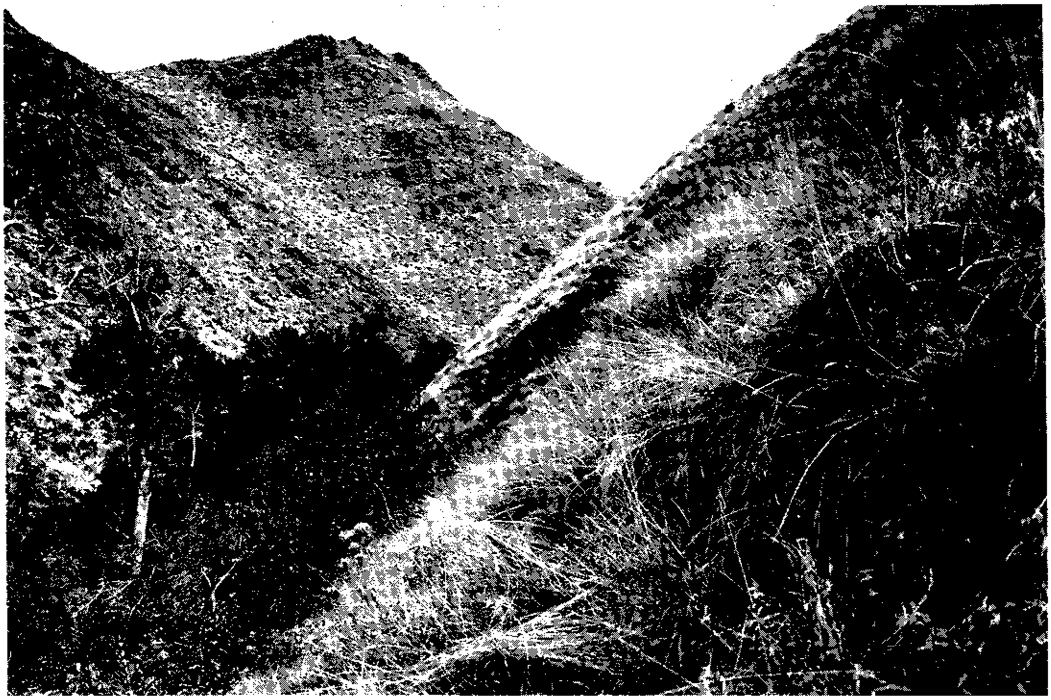

FIGURE 4. — Vegetated slopes underlain by fine-textured soils with a well-developed profile are stabilized at angles far steeper than the angle of repose for similar nonvegetated material. These slopes in south-central Idaho have gradients that exceed 100 percent.

Despite many variations in types of vegetation, its role in promoting soil stability is multifarious. It binds the soil, promotes infiltration, dissipates raindrop energy, develops greater porosity, and enriches the surface soil. Thus, the maintenance of an adequate cover of vegetation is the key to stability of soils on sloping lands. The presence or absence of vegetation determines whether the soil stability balance is maintained or whether degradation sets in.

Watershed rehabilitation treatments were developed and applied to damaged headwater areas of numerous drainages in Davis County, Utah, beginning in 1933. These damaged areas comprised less than 10 percent of the total area but were sources of unprecedented mud-rock floods. Plots were established in 1936 on the cover-depleted and eroding flood-source areas and on nearby well-covered noneroding lands that were considered to be nonflood-source areas. Overland flow and sediment yield data in table 1 gathered from these plots substantiate the role that vegetation plays in protecting the soil.

TABLE 1.—*Summer storm rainfall and resultant overland flow and soil losses from Parrish plots, Davis County Experimental Watershed, Utah*

Storm dates	Total rainfall	Non-flood-source area		Flood-source area		Artificially denuded	
		Overland flow	Soil eroded	Overland flow	Soil eroded	Overland flow	Soil eroded
	In.	*Pct.*	*Cu.ft./acre*	*Pct.*	*Cu.ft./acre*	*Pct.*	*Cu.ft./acre*
July 10, 1936	1.14	0.7	0	42.8	181.5	...	...
July 16, 1936	.89	.4	0	43.4	153.6	...	...
July 28, 1936	1.21	.2	0	33.0	83.2	...	...
Aug. 18–20, 1945	3.09	.5	0	24.3	92.8	...	...
July 10, 1950	.70	.9	0	12.6	(1)	61.3	215.3
Aug. 19, 1951	1.15	.6	0	8.4	(1)	46.6	186.2
Aug. 4, 1954	1.17	.4	0	3.8	(1)	31.3	91.3
Aug. 19–20, 1959	.98	.6	0	2.3	(1)	43.7	98.4
Sept. 3, 1960	.63	...	...	...	...	31.0	110.0
Aug. 25, 1961	.64	...	...	...	...	28.6	89.2
July 13–14, 1962	2.59	...	...	...	...	39.0	401.3

[1] Trace.

Nonflood-source plots on the Davis County Experimental Watershed supported vegetation of a density capable of limiting overland flow to an average of about 0.5 percent of 10.33 inches of summer rainfall from eight major erosion-producing storms from 1936 to 1959, most of which fell at high intensity. For 25 years, no measurable sediment has been yielded from any of these plots. Nearby flood-source plots yielded 511 cubic feet of sediment per acre during the first four storms; 36 percent of the total rainfall was lost as overland flow. Improvement in plant cover on these former flood-source plots during the last 15 years has reduced overland flow to 6.8 percent, and sediment yields have been nil. Contrasted to this situation is that of other plots denuded artificially. Overland flow from these plots averaged 40.2 percent of the rainfall from seven major storms from 1950 to 1962, with an average sediment yield of 170 cubic feet per acre per storm.

Relation of Vegetation to Overland Flow and Erosion

There is little question of the beneficial effect of ground cover in controlling erosion. Numerous studies have demonstrated repeatedly that major reductions in vegetation and the frequent accompanying compaction of soils impair desirable hydrologic processes, especially those involving safe disposal of precipitation. Despite knowledge of these consequences, only limited research has been directed towards establishing watershed protection requirements for the numerous soil and vegetation complexes that characterize forest and range lands. Much of this effort has been centered in the Intermountain States.

Studies on five major range vegetation-soil complexes to determine requirements for controlling overland flow are summarized briefly below.

Wheatgrass-Cheatgrass Range

Studies have shown that, for effective control of overland flow and erosion on coarse-textured, single-grain-structured soils derived from granite, no less than 70-percent ground cover is required, and that bare openings between plants or patches of litter should not exceed 4 inches on wheatgrass sites and 2 inches on cheatgrass sites (*11*). These conditions have provided effective control of overland flow under a 30-minute simulated rainfall of 3.7 inches per hour. Observations on extensive similar sites subjected to natural high-intensity rainfall substantiate the validity of these minimum protection requirements.

Because of a contention that high-intensity rainfall bursts seldom exceed 5 to 10 minutes, further study was made to determine whether less stringent ground cover requirements would suffice. Figure 5 relates cumulative overland flow and cumulative sediment yields to ground cover by 5-minute periods (*17*). These curves show unmistakably that, irrespective of which 5-minute period is considered, both overland flow and sediment increased only slightly as

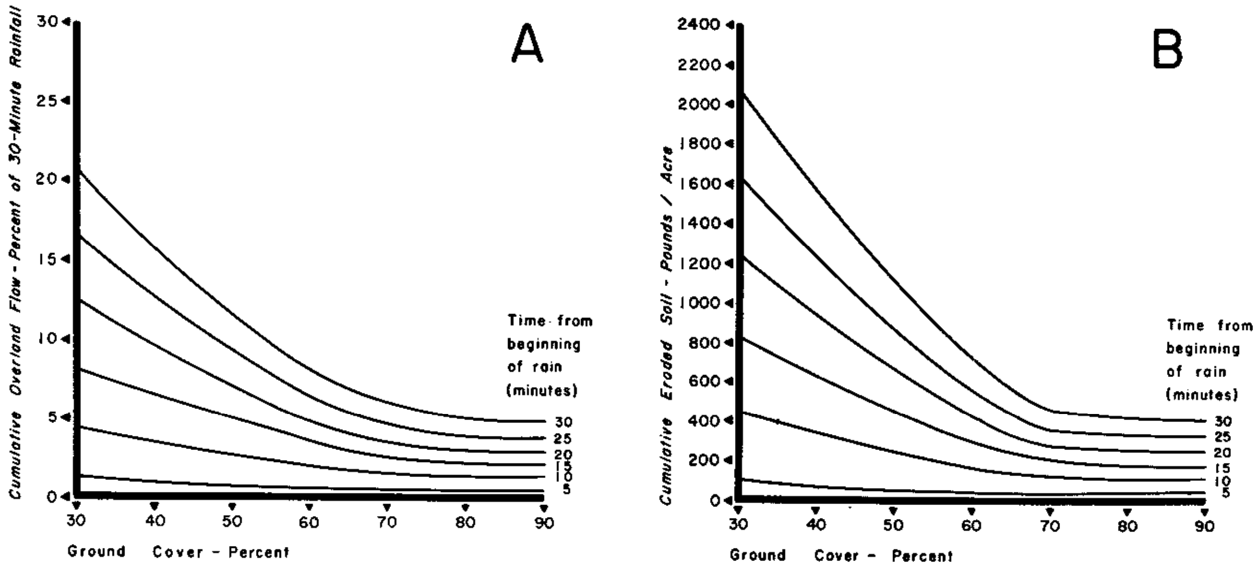

FIGURE 5.—*A*, Cumulative overland flow; and *B*, cumulative soil eroded by a simulated rainfall of 1.87 inches for 30 minutes by 5-minute periods in relation to ground-cover density. This study was conducted on wheatgrass range sites on soils derived from granite (*17*).

ground cover was reduced from 90 to 70 percent; but both increased tremendously with further reductions in ground cover below 70 percent.

Subalpine-Herbaceous Range

Subalpine-herbaceous range in Utah is commonly underlain by fine-textured clayey soils derived from limestone and carbonaceous shales. Since 1915, studies of the effects of ground cover changes, through land use, on sediment yields have been underway on the A and B watersheds (*10*). Overland flow and sediment production from these watersheds is summarized in table 2 by time periods.

Upon establishment, these two watersheds were protected from grazing; later, it was imposed as a treatment on watershed B. To facilitate the comparison of the effects of treatments, the history of these two watersheds was divided into six periods. In the first period, watershed A, in an extremely depleted condition (16-percent plant cover) produced 6 times more runoff and more than 5 times as much sediment as did watershed B (40-percent plant cover).

TABLE 2.—*Average plant cover density and average annual summer storm runoff and sediment yield on watersheds A and B by periods, 1915-58 (10)*

Period	Years	Average plant cover		Average annual summer storm runoff			Average annual summer storm sediment		
		A	B	A	B	Ratio A:B	A	B	Ratio A:B
		Pct.	*Pct.*	*Cu.ft./acre*	*Cu.ft./acre*		*Cu.ft./acre*	*Cu.ft./acre*	
1	1915–20	16	40	913	153	6.0:1	134	25	5.4:1
2	1921–23	30	40	922	260	3.5:1	105	37	2.8:1
3	1924–30	40	40	362	171	2.1:1	24	10	2.4:1
4	1931–45	40	30	445	556	1.0:1.2	21	29	1.0:1.4
5	1946–52	40	16	64	288	1.0:4.5	3	36	1.0:12.0
6	1953–58	40	50	292	92	3.2:1	10	1	10.0:1

During the second and third periods, vegetation on watershed A improved, resulting in less runoff and sediment. In the fourth period, watershed B was grazed lightly to reduce the plant cover to 30 percent. Immediately, the magnitude of overland flow and sediment production reversed, and B produced more of each than did A. In the fifth period, B was overgrazed to render it comparable to the condition of A in the first period (16-percent plant cover). Overland flow and sediment yields increased markedly. Sediment yield on B surpassed the yield from A at the beginning of measurements. After this period, B was contour-furrowed and reseeded. Again, the sixth period brought a profound reversal of overland flow and sediment yields — an improvement that far exceeds the original condition.

This oldest continuous pair of range watersheds in the United States has demonstrated remarkably well that ground cover and land use are inextricably linked to proper functioning of hydrologic processes.

Aspen-Herbaceous Range

The aspen-herbaceous range has been the locus of severe mud-rock floods in northern Utah. On the Davis County Experimental Watershed, where the fairly deep, intermediate-textured soils have been derived chiefly from gneisses and schists, records obtained continuously since 1936 from 16 plots ranging from $\frac{1}{40}$- to $\frac{1}{10}$- acre in size and supporting varying amounts of ground cover, provide information upon which watershed protection requirements can be based (*9*). When only those summer storms that produced sediment from the plots are considered, it is evident that by limiting overland flow to no more than 5 percent of rainfall depth, a reasonable degree of stability can be maintained on this type of range. These long-term records provided a basis to develop ground cover requirements to provide protection under different intensities of rainfall. Relations of overland flow to ground cover by storm intensities are shown in figure 3,*B*. For 5-minute intensities of less than 1.5 inches per hour, a ground cover density of at least 5 percent was required to restrict overland flow to 5 percent or less. Five-minute intensities of 1.5 to 3.0 inches per hour required 45-percent ground cover, and those in excess of 3 inches per hour required at least 65-percent ground cover to achieve desired minimum overland flow.

Grass-Forb Winter Range

Study sites were located in Montana on intermediate-textured soils derived from mixed sandstone and shale. These grass-forb vegetated slopes are the winter range for large numbers of elk. Over a 2-year period, plots with a ground cover of 70 percent yielded almost as little sediment as those with 100 percent (*12*). But as ground cover was reduced below 70 percent, sediment eroded from plots increased markedly (fig. 3,*D*).

Results from these four widely separated areas representing diverse vegetation, soil, elevation, and precipitation characteristics, suggest strongly that a minimum ground cover density is required to control overland flow and erosion from these ranges. They also emphasize the relation of bulk density and slope gradient to sediment production under conditions of depleted plant cover. Where complete cover exists, these two factors are of much less significance.

Effects of Land Uses on Sediment Yields

Logging

Albeit numerous studies have determined the amount of soil disturbance created by logging and fewer studies have sought to measure actual sediment yields, we still lack thoroughly comprehensive programs of research to determine quantitatively the integrated effects of various methods of logging upon watersheds. This situation may aptly be attributed to the almost overwhelming complexity of the problem, and perhaps, for this reason, the effects of logging have been studied piecemeal, or by facets.

Soil disturbance in itself is not inimical to watershed stability. It becomes so when erosion produces sediment that is transported by runoff to lower lying channels. Some disturbance bares the soil only temporarily and is silviculturally desirable for the natural regeneration of forest species. Often, however, extreme disturbance also results in destruction of undue amounts of young or lesser vegetation, thus prolonging the time of natural recovery or increasing the effort required to stabilize the disturbed areas artificially. Frequently, on-site disturbance is a forerunner of sedimentation. This then leads to off-site disturbance, and a great need exists for recognizing the potential for this situation to develop. When it does develop, then there is synonymy between soil disturbance and sediment yields.

The magnitude of soil disturbance, its potential seriousness, and the conditions under which it occurs warrant brief review. Results of a study in Oregon and Washington by Garrison and Rummell (*6*) showed that 15 percent of logged areas suffered deep disturbance created by tractor logging, whereas cable logging produced equal disturbance on only 1.9 percent of the area. Deep soil disturbance on slopes exceeding 40 percent was 2.8 times greater than on gentler slopes.

Another study in the Pacific Northwest (*14*) revealed that clear cutting 12 units on the H. J. Andrews Experimental Forest disturbed 8.8 percent of the total area by road building and another 3.6 percent by the construction of landings, for a total of 12.4 percent.

On the Fernow Experimental Forest in West Virginia, average turbidity of streamflow during logging operations was 490 p.p.m.; 1 year after logging, it was 38 p.p.m.; and 2 years after logging, 1 p.p.m. On one drainage where little planning of the logging was done, maximum turbidity reached 56,000 p.p.m. On a comparable drainage where a well-planned logging system was applied, maximum turbidity was only 25 p.p.m. (*18*).

Haupt (*7*) reported that the area of soil bared by harvesting ponderosa pine on 16 compartments, ranging from 30 to 78 acres, on the Boise Basin Experimental Forest, in south-central Idaho, was closely related to the number of trees and volume of timber removed. Stem selection was used in eight compartments; group selection in the others. Under the two harvesting systems, an increase from 1,500 to 6,500 trees cut per square mile resulted in increased soil baring from 29 to 114 acres for single tree selection, and from 29 to 84 acres for group selection. On these moderate slopes of fairly deep soil, single tree selection and harvest produced the greater soil disturbance. Total area of soil disturbance for all compartments under both systems averaged 8.1 percent.

Facilities for making postlogging sediment yields have been in operation in all compartments since 1954. Because of the carefully designed logging plan and generally good application on the ground, measurable quantities of sediment have been recorded in only two compartments. In both, this sediment resulted from the encroachment of a logging road on a channel.

In marked contrast to some of the above examples, on the Stamp Creek timber sale covering 800 acres on the Chattahoochee National Forest in Georgia, logging was required in every month of the year under a carefully developed plan. Logging resulted in an average sediment content of the streamflow of 5 as compared with a sediment content of 4 p.p.m. on a stream from an unlogged watershed (*4*). This sediment content is only one-half that permitted by the standards for drinking water published by the U.S. Public Health Service.

Road Construction

Of man's activities on forested lands, disturbance caused by road construction is the greatest precursor of sediment yields. A few examples aptly illustrate the seriousness of this problem, which is most acute during and for the first few years after road construction.

On the H. J. Andrews Experimental Forest (*16*), 1.7 miles of logging roads were constructed in a 250-acre watershed, exposing mineral soil over 6.2 percent of the area. For 6 years preceding road construction, sediment content of the streamflow never exceeded 200 p.p.m. even after high-intensity storms. Rains commenced shortly after road construction, and suspended sediment of the streamflow exceeded

1,700 p.p.m. An adjacent control watershed without roads produced a sediment content of only 22 p.p.m. after the same rainstorm. Thus, the first storm on this watershed after road construction produced a streamflow sediment content 81 times greater than the undisturbed watershed. About 2½ years later, the logged watershed produced sediment at the rate of 4.7 times as much.

One other example of the deleterious effects of roads on sediment production is provided in south-central Idaho by experimental drainages situated on highly erodible coarse-textured soils derived from granite.[3] Although no sediment was yielded from areas without roads, three adjacent watersheds, in which jammer logging roads were constructed without any extra precautionary stabilizing or protective treatments, produced yields of 12,400, 8,900, and 89 tons per square mile in one season. These sediment yields are attributed to the lack of adequate cross drains coupled with uncommonly heavy precipitation.

Fire

When an area is subjected to wildfire or prescribed burning, vegetation is lost. But because prescribed burning is designed as a controlled operation, attention in this discussion is centered on wildfires, over which no planned control is exerted.

Sartz (*13*) measured soil losses that occurred after wildfire in the Douglas-fir region of the Northwest. Erosion of burned-over transects caused 0.07- to 0.18-foot reductions in the surface soil levels. These reductions varied directly with changes in slope gradient.

The cutting and burning of slash of young pine in Colorado increased sediment production 4½ times or from 640 pounds to 3,000 pounds per acre over the average for a 10-year period (*8*).

In the summer of 1959, 9,517 acres of foothill rangeland situated above the city of Boise, Idaho, was burned by a wildfire. Little vegetative cover was left. A few weeks after the burn, an extremely high-intensity rainstorm struck the area. Within hours, lower lying farmland and residential areas were inundated by sediment, bouldery debris, and floodwaters (fig. 6). The city of Boise suffered flood damages estimated at one-half million dollars. Storm-cut rills and gullies, ranging from ½ inch to 8 inches deep and from 1 inch to 18 inches in width, averaged 83 per 100 feet along the contour on some of the denuded watersheds. These burned watersheds produced two other floods during the next month that added to the initial flood damages.

[3] Personal communication, H. F. Haupt, September 1962.

FIGURE 6. — Pastures and farmland near Boise, Idaho, covered 1 foot to 3 feet deep with debris from the August 20, 1959, flood.

In August 1961, a sediment-laden flood originated on the burned slopes of two experimental watersheds in Dog Valley, near Verdi, Nev. The year before, an intensely hot wildfire swept over all of one and a part of the other watershed, obliterating practically all of the ground cover and killing most of the overstory timber (fig. 7). The maximum 5-minute intensity of the storm was 9.24 inches per hour (fig. 2).

Sediment filled the stilling basins back of two weirs, and spilled into channels below for a distance of 1 mile or more. Watershed No. 1, completely burned, produced about 16,100 cubic feet of sediment from its 242 acres for a rate of 0.97 acre-foot per square mile. Watershed No. 2 (300 acres), of which only a portion was burned, produced 10,125 cubic feet or 0.49 acre-foot per square mile. The unburned portion produced scarcely a trace of sediment. The sediment production rates for a single rainstorm of 30 minutes' duration reflect the enormous erosion potential unleashed by the destruction of vegetation.

Excessive Grazing

Unregulated and excessive grazing proves destructive and has been shown unmistakably to be the cause of sediment yields far in excess of the normal. This is especially true for steep rangelands of the Western States. A marked increase in flooding, channel cutting, and sediment production after the introduction of herds onto these lands is a matter of historical record. Excessive grazing by livestock herds in the Santa Clara, Kanab, Long Valley, Paria, Escalante, Kitchen Valley, Ford, Parrish, Farmington, Pleasant Creek, and countless other drainage basins in Utah alone, induced rapid deterioration of vegetation. Floods, heavily laden with sediment, issued from these overgrazed

FIGURE 7. — A densely vegetated forest cover obliterated by fire. The stable slopes and channels were transformed by a high-intensity storm into raw, eroding areas that continue to yield large quantities of sediment.

lands within varying periods of time — some as short as 7 years (*3*).

In many areas this severe use, coupled with relatively short growing seasons often punctuated by droughts, soon resulted in diminution or destruction of plant cover. Under these conditions, "the rains came," and localized storms of short duration produced rainfall intensities frequently in excess of the infiltration capacities of the soil. Overland flow developed, erosion followed, and the concentration of water and sediment resulted in flood discharges of great violence.

One example will suffice to illustrate the disastrous effects that may ensue. In the Parrish watershed in Davis County, Utah, overgrazing and some man-set fires depleted drastically the natural vegetation over the 1,378-acre drainage basin, especially in the headwaters area. Virtually all vegetation was destroyed on areas aggregating only 12 percent of the watershed (fig. 8). Four mud-rock floods issued from this watershed in 1930, causing more than one-third of a million dollars' damage to property and developments below the mouth of the canyon. In that one summer, the short-time sediment yield derived from both damaged slopes and channel fill, when calculated on a square-mile basis, equaled 153 acre-feet. In sharp contrast, the nearby undamaged Morris Creek watershed has produced sediment at the rate of only 0.0025 acre-foot per square mile per year. The literature abounds with references to other floods after overgrazing.

Recreation

Along with old, extensive, and well-established land uses, we are now confronted with another rapidly expanding land use that bodes a serious erosion and sediment yield problem. Although not as widespread geographically as other uses, the sediment production problem

FIGURE 8. — An excessively grazed area at the head of Parrish Creek. After the destruction of plant cover, these low-gradient slopes contributed heavily to the 1930 floods.

caused by the increasing impact of recreation is growing in importance. Overgrazing along trails and near campgrounds, concentrated pawing, trampling, and walking destroys vegetation, compacts the soil, reduces infiltration, and sets in motion both wind and water erosion. Promiscuous use of cross-country vehicles, especially "jeeps" and "scooters" or similar self-propelled wheeled vehicles, is creating erosion and sediment problems at an alarming rate.

Concerted effort is needed to quantify the damages and develop ameliorative measures for this problem that is rapidly being aggravated by increasing recreational pursuits.

Discussion

This synoptic consideration of selected data on sediment yields has highlighted a number of basic tenets, which, if ignored, can only lead to a continuance or acceleration in sedimentation; or which, given proper regard and application, can substantially reduce sediment yields resulting from the impact of land uses.

Soil is a product of climate and vegetation acting on geological parent material over a long period of time. Vegetation diminishes soil erosion and enhances soil stability. Vegetation may be destroyed purposely, wantonly, or accidentally. But irrespective of the manner in which vegetation is destroyed, the ultimate effects are identical. This conclusion is based on mounting volumes of evidence that vegetation is essential to the development, productivity, and stability of all soils.

Soils vary in their inherent resistance to erosion and their behavior or reaction to different uses. Some are more easily disturbed than others; some are more easily compacted than others; and some regain stability more readily than others. Therefore, protection must be shaped, designed, and applied in accord with the characteristics of the soil in question.

All land uses are potential precursors of sediment production. Abusive or excessive uses inevitably increase sediment yields. These must be guarded against because, ordinarily, natural recovery of stability by damaged watersheds often proceeds so slowly as to be unacceptable to proper land management.

Examples of sediment yields presented herein are necessarily limited. Yet, it is believed that they suffice to illustrate the delicate balance that exists between formative and disruptive forces. Little new information has been presented herein, but implications of the relations of various soil characteristics to sediment yields are sufficient to whet a more inquisitive pursuit of more specific and quantifiable relations. Although more is known of the effects of land use on sediment yields than is generally practiced, much yet remains to be learned to fill existing voids. Logging methods need discovery or improving so that timber may be extracted from erodible areas without creating intolerable watershed damage. Roads must be better fitted to the topography to reduce the excessive cutting and filling now so characteristic of many logging roads. Disposal facilities need to be improved to reduce damages from water that concentrates on logging roads.

A little arithmetic illustrates the magnitude of the water disposal problem from roads. From a storm producing 1 inch of rain, a 12-foot road 1 mile long would intercept 39.5 thousand gallons of water. If the annual precipitation were 30 inches, the 1 mile of 12-foot width road would receive 21.5 thousand, 55-gallon barrels of water. Assuming a forest area with 10 miles of road per section, then 215,400 barrels of water would be intercepted. Because infiltration rates on road surfaces are low, most of this water soon becomes runoff — erosion occurs, sedimentation increases, and flood threats are heightened.

No one questions the need for continuing concerted effort to reduce destruction caused by wildfires. But with increasing use of prescribed fires, their effects on sediment production need to be determined for different soil-vegetation complexes.

Lastly, acceptable grazing intensities must be determined and rigorously applied to maintain soil stability on undamaged or rehabilitated rangelands and to promote stability on those now damaged.

We have progressed in understanding relations and associated problems between ecological factors, land uses, and sediment yields; yet, further refinements are needed. These will be forthcoming, but in the meantime a proper synthesis and application of knowledge now at hand would do much to reduce further the loss of soil and the production of sediment.

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SEASONAL DEBRIS MOVEMENT FROM STEEP MOUNTAINSIDE SLOPES IN SOUTHERN CALIFORNIA

[Paper No. 12]

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Most people become concerned about flood-borne debris only when it causes property damage or is deposited in reservoirs. Much of the debris is scoured from stream channels, where it accumulates as the product of side-slope erosion. The interest in debris movement down mountain slopes, then, stems from flood and debris control problems downstream. Though debris produced during storm runoff is often the most spectacular, dry-season debris movement is an important part of the erosion in the San Gabriel Mountains. This paper reports a comparative study of dry- and wet-season debris movement in these steep, unstable watersheds.

A study in the Los Angeles River Watershed by Retzer and others [1] showed the sources and processes of debris movement. They mapped the sources of debris and determined the important source areas, in approximate descending order, to be "(1) streambanks and slopes rejuvenated by undercutting; (2) slopes with south exposures; (3) very steep slopes; (4) fault zones and steep fault faces; and (5) deep colluvial-alluvial deposits on slopes where undercut by roads or streams."

The active agents of erosion were observed to be gravity, water, wind, and the daily freeze-thaw cycle, the latter occurring primarily at high elevations. These agents can act alone, but they commonly work together, especially water and gravity.

Erosion took place mainly as granular movement on the surface rather than as deep-seated movements of soil masses. Granular debris moved as dry creep and as slope wash. Both of these processes were active over the entire study area. About 90 percent of the area mapped was affected by dry creep movement to some degree.

Dry creep movement is not found in most regions. It requires steep slopes with dry, loose material on the surface. The dry slide material ranges in size from larger rocks to fine soil particles. When the slopes are vegetated, some of the dry creep material is detained behind rocks, stumps, and brush. Other material not detained continues to move downslope and collect as cones in channels.

The slopes of the San Gabriel Mountains maintain a precarious equilibrium. The average slope of the land is more than 65 percent, or above the angle of repose for unconsolidated soil materials. Downslope movement may be triggered by slight disturbances: movement of animals, the wind, or earth tremors.

Surface Debris Movement Study

A study was started in 1953 to determine the cause (gravity or water), rates, and amounts of debris moving downslope and into channels.[2]

Study Sites

Nine study sites were located in the Los Angeles River Watershed. Five of these sites are on rejuvenated slopes.[3] The other four sites are on slopes not affected by rejuvenation (table 1).

TABLE 1.—*Characteristics of debris movement study sites*

Location (name and No.)	Slope condition	Aspect	Area	Cover density	Average slope
			Acres	*Percent*	*Percent*
Lower Brown —site 1	Rejuvenated	NE	3.45	95	70
Lower Brown —site 2	do	NE	3.36	95	70
Lower Brown —site 3	do	SE	.72	65	90
Lower Brown —site 4	do	SE	1.45	65	90
Lower Brown —site 5	do	SE	.34	65	90
Upper Brown —site 6	Non-rejuvenated	SW	.68	95	55
Falls Canyon —site 7	do	NE	1.53	95	60
Singing Springs —site 8	do	SW	1.30	65	60
Singing Springs —site 9	do	NE	1.64	85	55

Study sites were located on generally north- or south-facing slopes that were undisturbed by fire or road building. The experimental sites were chosen in a single rock type — the Wilson Diorite, which underlies about one-third of the San Gabriel Mountains. The soils are character-

[1] RETZER, J. L., and others. PRELIMINARY REPORT, ORIGIN AND MOVEMENT OF SEDIMENTS IN THE LOS ANGELES RIVER WATERSHED, CALIFORNIA. U.S. Forest Service. 103 pp., 1952. [Typed.]

[2] ANDERSON, H. W., COLEMAN, G. B., and ZINKE, P. J. SUMMER SLIDES AND WINTER SCOUR . . . DRY-WET EROSION IN SOUTHERN CALIFORNIA MOUNTAINS. U.S. Forest Serv. Pacific Southwest Forest and Range Expt. Sta. Tech. Paper 36, 12 pp., illus. 1959.

[3] Rejuvenated slopes are the steep slopes flanking stream channels in which renewed channel downcutting has removed the toe of the slope, creating an unstable condition where active erosion is taking place.

istically shallow, coarse-textured, noncohesive, and very erodible.

Measurement of Debris

Debris moving downslope is caught in troughs that are connected to the original soil surface by a concrete apron. The troughs are built on the contour from a point of a ridge across a segment of the slope and end near a drainage channel. Troughs are placed across erosion chutes [4] at the rejuvenated slope study sites. Catchment troughs range in length from 10 to 431 feet. Four-foot high barriers are installed at several of the sites to catch bouncing rocks and excessive debris yields.

The material caught in each trough is removed and weighed, corrected for moisture, and sampled for organic matter and rock content.

Results

Debris Production From Unburned Slopes

Anderson, Coleman, and Zinke [5] reported the first 5 years' debris production from these sites under long unburned conditions. They found that the greatest source of debris was from the south-facing rejuvenated slopes. These sites yielded an average of 3.56 tons per acre per year — 5 to 10 times the average on other sites. Debris movement during the dry season exceed wet-season movement at most of the study sites. Even under unburned conditions, at least 0.2 ton per acre per year was measured at all study sites.

Rainfall during the first 4 years of the study was 77 percent of normal. The fifth year's precipitation was 143 percent of normal, but there were no high intensity storm periods. The first gentle rains increased the cohesion of the soil and tended to reduce wet-season debris movement.

Krammes [6] reported a sixth year's (1958–59) debris production under unburned conditions. The south-facing rejuvenated slopes were again the greatest producers. Precipitation during the season was 70 percent of normal. One storm caused the wet-season movement to exceed dry-season movement at the south-facing rejuvenated sites and the north nonrejuvenated site 9. Six years of debris production under unburned conditions appears in tables 2, 3, and 4.

Debris Production From Burned Slopes

In October 1959 a wildfire swept through seven of the nine study sites (sites 1 through 7). Debris movement began almost immediately after the fire passed.[6] The fire destroyed the low-growing brush that formerly detained de-

[4] Erosion chutes are caused by the concentrated movement of soil and rock down segments of steep slopes during both wet and dry periods. Reference: BLACKWELDER, ELIOT. THE PROCESS OF MOUNTAIN SCULPTURE BY ROLLING DEBRIS. Jour. Geomorphology 5(4): 324-328. 1942.

[5] See footnote 2.

[6] KRAMMES, JAY S. EROSION FROM MOUNTAIN SIDE SLOPES AFTER FIRE IN SOUTHERN CALIFORNIA. U.S. Forest Serv. Pacific Southwest Forest and Range Expt. Sta. Res. Note 171, 8 pp., illus. 1960.

TABLE 2.—*Debris production by seasons, south-facing rejuvenated slopes (Lower Brown Canyon)*

Period	Site 3			Site 4			Site 5			Average sites 3, 4, and 5		
	Season			Season			Season			Season		
	Dry	Wet	Yearly	Dry	Wet	Yearly	Dry	Wet	Yearly	Dry	Wet	Yearly
	Tons per acre			Tons per acre			Tons per acre			Tons per acre		
Prefire (1953–59)	0.84	1.86	2.70	0.82	0.83	1.65	1.99	0.89	2.88	1.27	1.42	2.69
Postfire												
1st year (1959–60)	7.62	2.58	10.20	28.69	3.26	28.95	23.38	.81	24.19	21.93	2.74	24.76
2d year (1960–61)	1.43	34.97	36.40	5.05	21.53	26.58	1.24	10.30	11.54	3.51	23.87	27.38
3d year (1960–62)	2.94	29.83	32.77	6.97	9.55	16.62	......	......	(1)	5.62	16.57	[2]22.19

[1] Trough destroyed by large boulder.
[2] On the basis of sites 3 and 4 only.

TABLE 3.—*Debris production by seasons, north-facing rejuvenated slopes, colluvial soils (Lower Brown Canyon)*

Period	Site 1			Site 2			Average sites 1 and 2		
	Season			Season			Season		
	Dry	Wet	Yearly	Dry	Wet	Yearly	Dry	Wet	Yearly
	Tons per acre			Tons per acre			Tons per acre		
Prefire (1953–59)	0.14	0.15	0.26	0.13	0.13	0.26	0.13	0.14	0.27
Postfire:									
1st year (1959–60)	4.35	.49	4.84	3.55	.23	3.78	3.95	.36	4.31
2d year (1960–61)	.23	1.40	1.63	.25	1.57	1.82	.24	1.48	1.72
3d year (1961–62)	.45	.82	1.27	.11	1.68	1.79	.28	1.25	1.53

TABLE 4.—*Debris production by season, south- and north-facing nonrejuvenated slopes (Upper Brown, Falls Canyon, and Singing Springs)*

Period	Site 6 south			Site 7 north			Site 8 south [1]			Site 9 north [1]		
	Season			Season			Season			Season		
	Dry	Wet	Yearly	Dry	Wet	Yearly	Dry	Wet	Yearly	Dry	Wet	Yearly
	Tons per acre			*Tons per acre*			*Tons per acre*			*Tons per acre*		
Prefire (1953–59) . . .	0.32	0.23	0.55	0.16	0.10	0.26	0.13	0.22	0.35	0.08	0.12	0.20
Postfire:												
1st year (1959–60).	.64	1.53	2.17	2.05	2.03	4.08	.03	.02	.05	.03	.01	.04
2d year (1960–61).	.11	4.48	4.59	.08	2.47	2.55	.04	.96	1.00	.04	.28	.32
3d year (1961–62).	.02	2.13	2.15	.01	1.28	1.29	.03	.46	.49	.03	.18	.21

[1] Vegetation unburned.

bris on the side slopes. Great quantities of debris moved downslope and into stream channels.

First Postfire Year

Dry-season debris movement in the first year after the fire ranged from 0.6 to 21.9 tons per acre (tables 2, 3, and 4). South-facing slopes flanking rejuvenated stream channels again had the highest annual production, more than 10 times the already high prefire rate (fig. 1). Nearly 90 percent of the debris came during the dry season.

North-facing rejuvenated slopes showed a postburn rate of 4.3 tons per acre per year, or an increase of about 16 times the unburned average (table 3). Debris production from the north nonrejuvenated site increased 16 times. The smallest increase (4-fold) occurred at the south nonrejuvenated site (table 4). Rock outcrops may have served to stabilize this site somewhat.

Precipitation during the first postfire year was 59 percent of normal and no high intensity storms were recorded.

The burned area, including the study sites, was seeded with annual ryegrass (*Lolium multiflorum*) and black mustard (*Brassica nigra*) after the fire. Because of the below-normal rainfall and extended dry periods during the wet season, the seeding was not successful. On the rejuvenated sites the seed moved downslope with the debris and was buried in the stream channel.

Second Postfire Year

Rainfall in the 1960–61 year, although only 35 percent of normal, contained four storms, totaling 7.35 inches of rainfall that produced debris movement. The south-facing rejuvenated sites, which were the most unstable, produced almost 27 tons per acre (table 2).

Most of the debris was moved in the second storm of the year. The highest 5-minute intensity recorded during that storm was 1.68 inches per hour. More wet-season debris was produced during this storm from all sites than had occurred during any of the previous 8 years of measurement. Wet-season debris production appears to be related more closely to intensity than total amount of storm rainfall.

Dry-season debris production in the second postfire year was considerably less than in the first postfire dry-season.

Third Postfire Year

Precipitation during the 1961–62 year was 96 percent of normal. The first three storms of the year, with a total of 5.62 inches of rainfall, produced more than 10 tons per acre at the south-facing rejuvenated sites. Another 5 tons per acre were measured in the rest of the wet season (almost 19 inches of rainfall). Wet-season debris movement exceeded dry-season movement. Dry-season debris movement was still considerably higher than the prefire rate on the south-facing rejuvenated sites but much less than the rate during the short period just after the fire (table 2).

Discussion

Debris that is eroded from the side slopes arrives in the channels through the action of wind, water, and gravity. However, these forces do not act equally or independently. There is always a gradual downslope movement of debris in the San Gabriel Mountains. The gradual soil movement during dry seasons is the "base flow" and the wet-season movement is analogous to "storm flow." Debris movement was separated into dry-season and wet-season movements to determine variations in rate between seasons. The first light rains of the wet season quite often have little or no effect on dry movement. As soil moisture increases, cohesiveness is given to the soil and dry movement slows down. This lasts as long as soil moisture is maintained. With additional rainfall, wet movement predominates. If prolonged dry periods between storms cause a reduction in surface moisture, dry creep begins again.

Over the years, many tons of debris are deposited in stream channels during both wet and dry seasons. This material remains poised in the channels and will be moved only when winter runoff has sufficient carrying power. Such flows occur on the average of once in every 5 to 6 years. Thus, side slope erosion provides much of the flood debris that is thought of as bank or channel scour. Stabilizing these steep mountain slopes remains as a challenge to future erosion-control efforts in the San Gabriel Mountains of southern California.

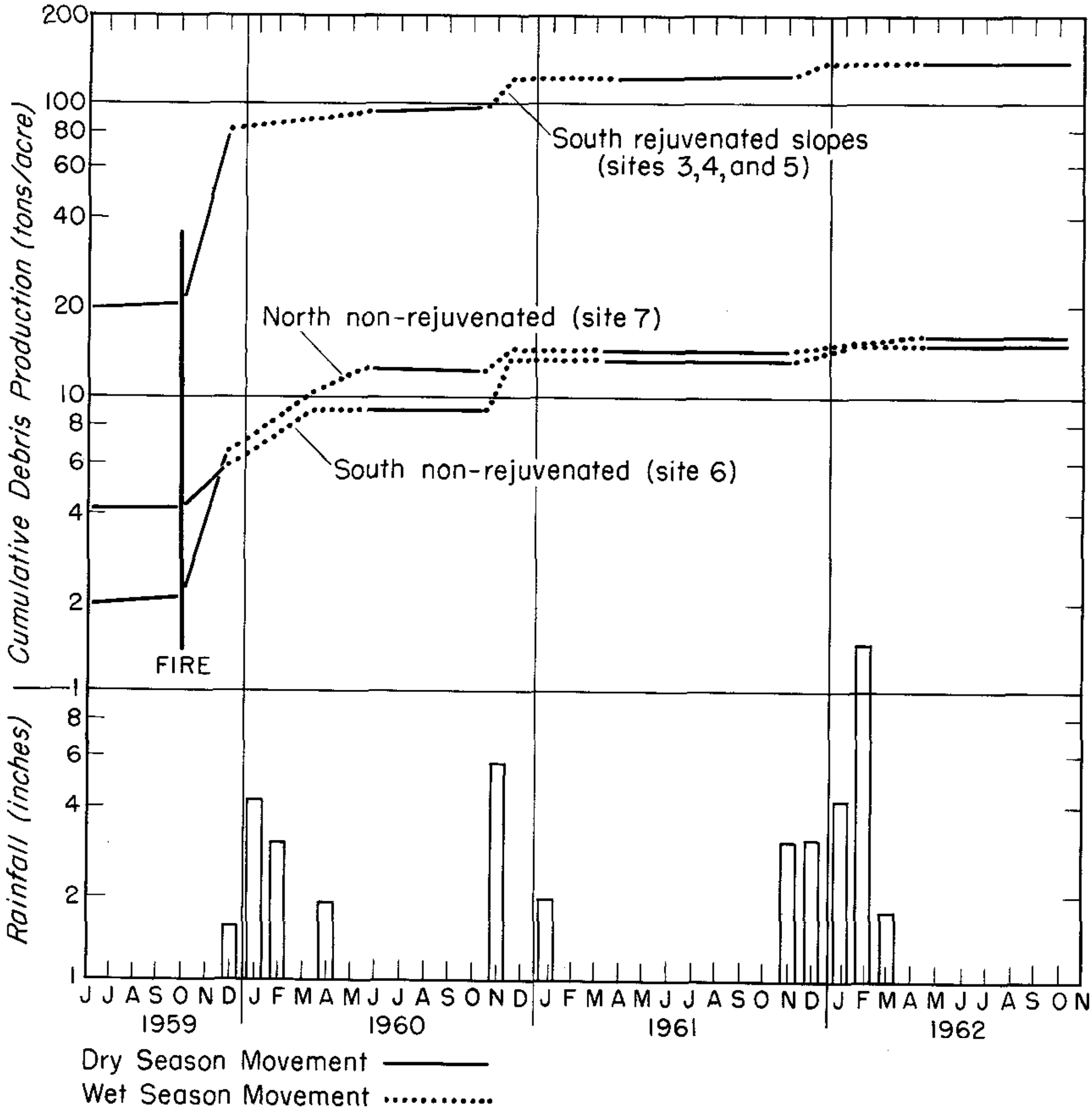

Figure 1. — Seasonal debris movement before and after fire in the Los Angeles watershed.

FUNCTION AND SIGNIFICANCE OF WIND IN SEDIMENTOLOGY

[Paper No. 13]

By W. S. CHEPIL,[1] *research investigations leader, Southern Plains Branch, Soil and Water Conservation Research Division, Agricultural Research Service* [2]

Abstract

The actions of wind on soil may be classed roughly into three categories: (1) Soil removal, (2) deposition, and (3) mixing. The wind's activity on soil is mostly in arid regions, but deposition extends even onto the humid regions.

Erosion of soil by wind includes three types of soil movement — saltation, surface creep, and suspension. Impacts of grains in saltation cause movements by surface creep and suspension. Dust carried in suspension is lifted by upward currents of turbulent wind. Once lifted off the ground, it is carried high in the air and is deposited in uniform layers far from its source. Fine dust may circle the earth many times. The composition of freshly deposited dust is like the composition of loess of the Pleistocene age. Estimates show that during the last 40 years an equivalent depth of 1.2 inches of soil material, on the average, has been removed from about 750,000 square miles of the Great Plains. In one semiarid portion of the Great Plains, an average of 9 inches of topsoil was removed from fields that were cultivated for about 20 years.

Removal of dust from one source is compensated by deposition elsewhere. Estimates have shown that during the last 20 years about one-half inch of atmospheric dust has been deposited in grassland near the wind-eroded region. Research is being undertaken to determine rates of deposition in humid regions of the United States.

Introduction

Unlike water, which tends to carry the soil from higher to lower elevations onto alluvial plains and into the sea, the wind scatters the fine soil constituents and deposits them in a uniform mantle over extensive areas near and far from their source. Removal of these fine soil materials from one area is therefore somewhat compensated by deposition at another. Movement also occurs in reverse so that considerable mixing of soils great distances apart occurs.

Removal is mostly from arid regions, but deposition and mixing extend imperceptibly, even to a casual observer, onto the humid regions.

Nature of Wind Erosion

Wind erosion is characterized by three types of soil movement — jumping (saltation), rolling and sliding (surface creep), and floating in the air (suspension). Impacts of grains in saltation cause movements by surface creep and suspension (*6*).

Saltation is caused by lift and drag forces against the surface. The saltating particles are the most erodible. They range from about 0.1 to 0.5 mm. in equivalent diameter (based on 2.65 density).

Particles too large to be moved by wind alone creep readily under impacts of saltation. They range from about 0.5 to 2 mm. in equivalent diameter, depending on wind velocity.

Contrary to general opinion, dust is highly resistant to erosion by direct pressure of the wind but is readily moved by impacts of larger particles moved in saltation. Once kicked up by saltation, it is carried by the upward currents of turbulent flow. Dust carried in suspension is generally less than 0.1 mm. in equivalent diameter. Dust clouds often rise 3,000 to 4,000 meters and are the most visible and therefore the most dramatic aspects of dust storms (fig. 1).

Abrasion

The impacts of saltation also cause clods and surface crust to disintegrate to small fragments, which in turn are moved by wind. The longer erosion continues and the more the wind shifts from different directions, the greater is the quantity of erodible material formed by abrasion and the higher the rate of erosion. The materials detached from clods and surface crust tend to accumulate in dunes or drifts toward the leeward side of fields and, if they are fine, to be carried far through the atmosphere. The smaller the detached dust particles, the farther they are transported by the wind (*6*).

Avalanching

The tendency for saltating grains to accumulate toward the lee of fields causes an increase of erosion (avalanching) for a distance of 500 yards or more before the maximum soil flow that a wind of a given velocity can sustain is reached. Often the maximum flow is not reached because the distance across the eroding field is limited. The rate of soil avalanching varies directly with soil erodibility; that is, the more erodible the soil, the greater is the rate of avalanching and the shorter the distance at which maximum rate of erosion (soil flow) is reached. By the same token, the more erodible the soil, the narrower the erodible field has to be to keep the rate of soil flow down to a tolerable limit. This limit is generally taken as 0.2-ton-per-rod-

[1] Died Sept. 6, 1963.

[2] In cooperation with the Kansas Agricultural Experiment Station, Kansas Department of Agronomy Contribution No. 809.

FIGURE 1. — Great quantities of dust are moved long distances during periods of wind erosion. Black blizzards such as this are the most dramatic aspects of duststorms.

width-per-hour under a 40-mile-per-hour wind velocity for bare soil before cultivation in spring. This is one-tenth of the possible maximum intensity that would occur under the same conditions without restricted distance across an erodible field (*3*).

Sorting

The wind acts on many soils like a fanning mill on grain — removing the finer fractions and leaving the coarser ones behind (*2, 7*). Silt and clay are thus removed and lag sands and gravels are left behind. Over the years, this sorting action makes the soils progressively coarser in texture. Finally, nothing is left but the infertile, skeletal material forming shifting sand dunes and gravelly pavements. History of many old civilizations is a record of struggles against such deterioration of the land (*1, 11*).

Sorting occurs on soils developed from glacial till, residual material, mountain outwash, and sandy materials of various origins. The wind separates such materials into several distinct grades:

Residual soil materials. — Nonerodible clods and rocks that remain in place.

Lag sands, lag gravels, and lag soil aggregates. — Semierodible grains that are moved slowly by wind and deposited here and there on the surface of eroded areas. They are moved primarily by surface creep.

Sand and clay dunes. — Highly erodible grains that usually are not very far removed from an eroded area. Their movement is primarily in saltation.

Loess. — Dust, which once lifted off the ground by impacts of saltating grains, is carried high in the air and is deposited in uniform layers near and far beyond the dunes. Dust is carried in true suspension. The composition of freshly deposited dust is like the composition of the loess deposited in the Pleistocene age (*2, 13, 14, 16*). Huge deposits of loess in many parts of the world show the great importance of wind as a geologic mover of dust.

In some cases, wind erosion almost completely removes the surface soil. This nonselective removal by wind is associated with loess that was already sorted and deposited from the atmosphere during past geologic eras.

Soil Removal

In the southern High Plains of the United States, Daniel (*7*) studied the physical changes in soils under cultivation and accelerated wind erosion. His studies were based on a comparative difference in mechanical composition of virgin soils and drifted material from cultivated land. He found that soil materials carried by wind from coarse- and medium-textured soils and subsequently deposited in drifts (dunes) contained on the average 38 percent less silt and clay and 29 percent more sand than the adjacent virgin soil. No direct comparison was made of the composition of virgin and adjacent cultivated soil.

In Canada, Doughty and coworkers (*8*) studied the physical and chemical changes in soils brought about by cultivation and erosion in the Brown, Chestnut, and Black soil zones on the Prairie region. Their study was based on direct comparison in physical and chemical composition between cultivated and adjacent virgin soils. They found that:

(1) The greatest loss of silt, clay, and organic matter due to cultivation occurred on extremely sandy soils and the least on clay soils.

(2) Many loamy sands lost virtually all silt and clay that they contained under virgin conditions less than 60 years previously. During dry periods, some of these soils changed to shifting dune sand and were abandoned. During wet periods, vegetation encroached and stabilized some of the active dunes.

(3) Sandy loams lost about 15 percent of their original silt and clay content in the top 4 inches of soil and gained a corresponding proportion of sand. Provided the same rate of selective removal continues in the future, these soils will turn to virtual sand dunes within 150 or fewer years of cultivation.

(4) The medium-textured glacial till loams and silt loams lost on the average 6.5 percent of their original silt and clay in the 4 inches of topsoil. At this rate of loss, about 500 to 1,000 years would be required for the surface soil material to change to dune sand.

Further studies of mechanical sorting of soil by wind in Kansas and Colorado (*2*) showed that on loess soils, i.e., soils derived from material originally deposited by wind during the Pleistocene period, wind erosion did not affect the texture of the drifts or the residual soil. But on soils derived from Permian sandstone, the drifts contained 65 percent more sand and 65 percent less silt and clay than the residual soil. The wind-eroded fields contained 17 percent more sand than the adjacent noneroded fields. Depth of sampling in all cases was 1 inch. This change in condition of the soil was a result of only two or three windstorms that occurred in 1 week when 0.85-inch depth of soil was removed from the eroded fields.

Daniel (*7*) and Chepil (*2*) found that removal of soil by wind, with or without any sorting, caused the general depletion of organic matter by virtue of some or all of the topsoil, in which organic matter is generally concentrated, being removed. Where sorting of soil material occurred, the damage to surface soil (to depth of cultivation) was two-fold: (1) Depletion of organic matter, and (2) removal of silt and clay. The drift soil (soil that has been moved about by the wind and deposited in drifts on or near eroded fields) contained 71 percent sand as compared with 38 percent in the top 4 inches of noneroded fields. This depletion of silt and clay added further to the hazard of wind erosion and to the problem of how to hold the remaining soil.

Another study on the effects of wind erosion was conducted in western Kansas in 1949 and 1950 on soils developed from loess (*4*). These soils belong to the Ulysses and Baca series. Some parts of this region had approximately 60 percent of the land in native sod before World War II. Progressive breaking of the sod for cultivated crops started in 1942 and was virtually completed in 1950. A unique opportunity, therefore, existed to determine possible changes in soils associated with time-after-breaking. Physical and chemical analyses were conducted on (1) 31 newly broken fields (broken between 1936 and 1948), (2) 31 intermediate (broken between 1939 and 1944), and (3) 30 old cultivated (broken before 1936). The study showed that:

(1) The old cultivated fields had little or no topsoil (A horizon) left. The average distance to the lime layer was 10 inches, whereas on newly broken land it was 19 inches. This means that 9 inches of soil were gone within an agricultural history of about 2 decades.

(2) There was no appreciable accumulation of drifted material. Much of it was apparently fine enough to be carried into the atmosphere the same way it arrived. Only slight quantities of sandy material were observed near an occasional temporary watercourse.

(3) On the old cultivated fields the B horizon constituted the surface soil. This soil contained more clay and less silt and sand than did the surface soil of the newly broken land (table 1).

(4) There was substantially less organic residue (stubble and straw) in old than in newly broken fields. Apparently, the productivity of the old cultivated fields had dropped considerably during the short period under cultivation. This resulted in greater exposure of the soil to wind and water erosion. However, the soil of the old cultivated fields was cloddier and contained more coarse (> 0.5 mm.) water-stable aggregates than did the newly broken fields.

(5) Soil losses, as measured by wind tunnel tests (table 1), were smaller from old cultivated fields than from newly broken fields, despite the newly broken fields having more crop residues. It is evident that the greatest rate of removal of soil by wind would occur within a few dry years after breaking. The native grasses were

TABLE 1.—*Physical and chemical properties of surface soils at various periods after breaking of virgin sod in western Kansas*

Fields (number)	Years after breaking	Clay <0.002 mm.	Total organic matter	Nitrogen	Organic residue >1.19 mm.	Clods >0.84 mm.	Water-stable aggregates >0.5 mm.	Amount eroded in wind tunnel	Computed erodibility [1]
		Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Tons/acre*	*Tons/acre*
30......	19	21.0	2.13	0.120	0.67	58.1	12.9	0.40	0.49
31......	6	18.0	2.49	.129	.89	54.4	11.6	.46	.60
31......	2½	17.0	2.53	.129	1.13	50.2	10.3	.64	.80
Level of significance		Differences necessary for significance at indicated levels							
1 percent...........		2.3	0.37	0.013	0.24	4.5	2.4	0.25	0.25
5 percent...........		1.7	.28	.010	.21	3.3	1.8	.19	.18

[1] Based on dry soil fractions > 0.84 mm. Data from Chepil, Englehorn, and Zingg (*4*).

effective in creating a loose, finely granulated soil structure — a structure highly susceptible to erosion by wind. However, the grasses were able to protect the soil from erosion. Accelerated erosion occurred only after the land had been denuded of vegetation by overburning, overpasturing, and overcultivation (*12*).

To trace the removal of soil beyond the eroded fields, Chepil and Woodruff (*5*) measured dust concentration in the air during duststorms. They found that the average rate of dust movement in western Kansas and eastern Colorado during the 1954 and 1955 duststorms was about 10,000 tons per hour per vertical square mile against the earth's surface.

Further analyses of the Chepil and Woodruff (*5*) data indicated that the total duration of the 1954 and 1955 duststorms at Dodge City, Kans., (which lies on the eastern outskirts of the severely wind-eroded area) was about 435 hours. This means that 4.35 million tons of dust per square mile perpendicular to wind direction moved past that location and presumably from the wind-eroded area during 1954 and 1955. If it is assumed that this region is 400 miles wide along the direction of wind and that an acre-foot of soil weighs 2,000 tons, 0.1-inch depth of soil emigrated during 1954 and 1955. From the 1922-61 weather records at Dodge City, the total duration of duststorms was estimated to be 5,200 hours. If the intensity of duststorms was assumed to be the same throughout the whole period, the net removal during the 40 years was 1.2 inches (3 cm.) of soil. This estimate would be greater or smaller if we assumed the region to be narrower or wider than 400 miles along the direction of wind and greater if the dust transported above 1 mile were considered. On this basis, it is estimated that 48 million acre-feet of soil were removed from the United States part of the Great Plains of about 750,000 square miles during the 40 years. Some dust might have been brought into the wind-eroded region, but because the region is practically surrounded by mountains and humid regions, the immigrated quantity was probably relatively small.

Deposition and Mixing

The Great Plains region's loss must have been compensated by some other regions' gain. It is reasonable to expect that considerable dust deposition must have occurred in the more humid areas, especially east of the wind-eroded region. Preliminary measurements indicated that between 5 and 10 tons of dust per acre per annum were deposited at Manhattan, Kans. (in the wet subhumid region) during 1954 and 1955 as compared to an average of about 8 tons per acre per annum removed from the Great Plains during the same years. Smaller deposition probably occurred east of Manhattan. No information is available on what these quantities might have been for areas farther east or west of the Great Plains. Such information would be exceedingly valuable in helping to determine rates of soil renewal in different regions.

Considerable information is available on the depth, composition, and distance from source of loess deposited in past geologic eras (*10, 15*). Some information on the composition and source of dust presently deposited from the atmosphere in different regions is also available (*2, 8, 14, 16*). Furthermore, Free (*9*) estimated from meager data that the mean annual deposit east of the Mississippi River at that time was not less than 0.01 inch (1.67 tons per acre).

Authentic records of distance that dust can travel are rare. Free (*9*) cited records that indicated that dust can travel thousands of miles from its source. One notable example is that of Australian duststorms reaching New Zealand, 1,500 miles distant. Another is that of dust originating in the Sahara and traveling over southern and central Europe to Germany and England, about 2,000 miles. During the 1930's, dust deposits presumed to have originated in the Great Plains were observed on the Atlantic seaboard, 1,500 miles away. No information appears to be available in the literature on probable quantities of dust that could be trapped and retained with suitable land management. Therefore, in 1954, Chepil[3] undertook to find

[3] Unpublished data.

out rates of accumulation of aeolian material on sand and loamy sand in southwestern Kansas as influenced by land management. On land that had been returned to grass in 1946, a distinct layer of dust was present. The average depth of the dust layer was 0.4 inch (table 2) and its composition was a loam containing 64 percent silt and clay. Some of the dust evidently worked its way down about 1 inch deep, probably from insect and rodent activity and trampling by livestock. It is evident that the grass trapped at least one-half inch of aeolian material in approximately 10 years. The nearest cultivated field was about a mile away. On this field there was no evidence of dust accumulation (table 2). Here, the sandiest soil was the surface one-half inch. The surface soil evidently had been losing the finer mechanical constituents as fast or faster than it had been gaining them.

TABLE 2.—*Average composition and depth of atmospheric dust deposited in grass in western Kansas during 1946–56*

Site description	Depth	Mechanical composition in 1956		
		Sand >0.05 mm.	Silt 0.05–0.002 mm.	Clay <0.002 mm.
	Inches	*Percent*	*Percent*	*Percent*
Good grass cover established on abandoned cultivated land in 1946	0–0.4	35.6	40.3	24.1
	0.4–0.9	70.0	22.2	7.8
	0.9–1.9	89.7	7.1	3.2
	1.9–3.9	82.8	11.7	5.5
	3.9–5.9	82.0	10.8	7.2
Land cultivated primarily to grain sorghum since 1935	0–0.5	85.1	10.6	4.4
	0.5–1.0	86.4	9.4	4.5
	1.0–2.0	82.4	11.2	6.4
	2.0–4.0	77.3	15.7	7.4
	4.0–6.0	77.8	14.8	7.4

It is evident from this study that a fine soil texture, comparable to that of loess, can be regained slowly under grass on sandy soils in dry regions such as western Kansas if wind erosion on surrounding cultivated lands continues at the rate it has in the recent past.

Conclusions

The greatest damage from wind erosion has been the removal of fine constituents from soils containing a certain proportion of sand. This sorting action is apparently responsible for the formation of sandy wastes in dry regions.

On loess soils there is no such sorting action; the whole soil is removed bodily by the wind. The degree of damage to soil here is governed primarily by the depth of soil material.

The rate of soil removal since the breaking of virgin sod in dry regions has been enormous when considered in terms of the probable time required for soil material to be formed or laid down. Some of the stable grassland has been changed to shifting dunes within a generation.

Available data indicate that some of the dust removed from the Great Plains has been deposited in a thin mantle all the way east to the Atlantic Ocean and beyond. The deposited dust was probably the first to be removed by sheet erosion into streams, alluvial plains, and into the sea. Accumulations of loess east of the Great Plains apparently occurred only where the rate of deposition resulting from wind erosion exceeded the rate of removal, mostly by water erosion.

The extensive damage from erosion in dryland regions has been due to lack of adjustment between methods of land use and environment. Extensive grain growing has been one of the primary factors contributing to erosion. Why? Because greater income can be derived from grain than from utilizing native grass. Agricultural use of the land, therefore, has been developed largely on the basis of immediate rather than permanent returns from the land. This has resulted in considerable soil dissipation. Future population (if and when it expands beyond what the land will easily support) will pay for this dissipation.

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CAUSES OF VARIATIONS IN RUNOFF AND SEDIMENT YIELD FROM SMALL DRAINAGE BASINS IN WESTERN COLORADO

[Paper No. 14]

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Abstract

During a study of the effects of grazing on runoff, sediment yield, vegetation, and infiltration rates in paired, grazed and ungrazed, drainage basins in the Badger Wash area, it was determined that runoff and sediment yield were considerably less in the ungrazed basin of each pair, although no large changes in composition or density of plant cover were recorded.

A study of erosion on the hillslopes at Badger Wash revealed a seasonal cycle of loosening and compaction of the soil. The soil is loosened by frost action and then is compacted by rainbeat during the spring and summer. In grazed basins trampling by livestock causes an earlier and more pronounced compaction of the loosened soil, but in ungrazed basins the soil remains loose for a longer period of time and greater infiltration occurs. Therefore, the grazed basins yield higher rates of runoff and sediment yield, despite negligible changes in vegetational cover, because of the longer period of compaction resulting from livestock trampling.

Tentative conclusions on the basis of the first 5 years of record indicate that grazing exclusion, although not responsible for immediate major changes in plant density, does affect the rate of runoff and sediment yield.

Introduction

Much of the Western United States is arid to semiarid, and very little is known about factors governing erosion and runoff. With the abundance of more productive land in humid areas, the need for information on the semiarid and arid lands was not particularly urgent on a national scale. As a fuller understanding of utilization of the national resources was gained, it became apparent that large areas, which were sometimes thought of as "not worth spending money on," might eventually have to be utilized to the fullest extent possible. In order to formulate plans for proper utilization of semiarid rangeland, something must be known of the processes involved in the hydrology of these lands.

Much of the Colorado Plateau is semiarid-to-arid rangeland. Extensive areas underlain by shale are characterized by scant vegetation and high rates of runoff and sediment yield. Much discussion has taken place regarding the former condition of the forage on this range, and the statement is frequently heard that the land once supported considerably more vegetation than it does at the present time.

In 1953 several Federal agencies selected the Badger Wash drainage basin in western Colorado as the site of an intensive investigation of effects of grazing on runoff, sediment yield, vegetation, and infiltration rates. These data are collected as an aid in establishing criteria for land treatment practices. The Badger Wash basin, the location of which is shown in figure 1, is typical of a large part of the Colorado Plateau underlain by Mancos shale, which comprises a major outcrop area extending westward from Grand Junction, Colo., at the base of the Book Cliffs. Federal agencies originally involved in the study were Geological Survey, Forest Service, Bureau of Land Management, and Bureau

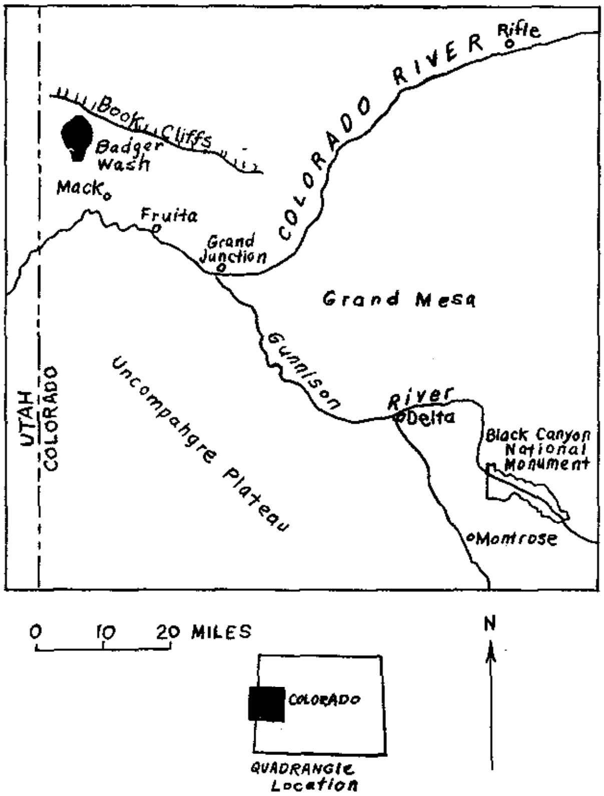

FIGURE 1.— Index map showing location of Badger Wash.

of Reclamation. In 1955 the Fish and Wildlife Service began the investigation of small mammal populations. A detailed description of the complete Badger Wash study may be obtained from the project report.[1]

The Geological Survey is concerned primarily with the measurement of precipitation, runoff, and sediment yield. In 1958 a study of hillslope morphology and erosion was begun by S. A. Schumm of the Geological Survey, and this study provided data that helped explain some characteristics of the runoff data. This paper combines some aspects of the original Badger Wash study and the hillslope study.[2] [3]

[1] LUSBY, G. C., TURNER, G. T., THOMPSON, J. R., and REID, V. H. HYDROLOGIC AND BIOTIC CHARACTERISTICS OF GRAZED AND UNGRAZED WATERSHEDS OF THE BADGER WASH BASIN IN WESTERN COLORADO. U.S. Geological Survey Water-Supply Paper 1532-B, 73 pp. 1963.

[2] SCHUMM, S. A. SEASONAL VARIATIONS OF EROSION RATES AND PROCESSES ON HILLSLOPES IN WESTERN COLORADO. Zeit. Geomorphologie, 23 pp. 1964.

[3] SCHUMM, S. A., and LUSBY, G. C. SEASONAL VARIATIONS OF INFILTRATION AND RUNOFF ON MANCOS SHALE HILLSLOPES IN WESTERN COLORADO. Jour. Geophysic. Res. 68: 3655-3666. 1963.

[4] THORNTHWAITE, C. W. ATLAS OF CLIMATIC TYPES IN THE UNITED STATES 1900-1939. U.S. Dept. Agr. Misc. Pub. 421, 7 pp., 96 plates. 1941.

Geology and Topography

The Badger Wash area is underlain by Mancos shale of late Cretaceous age. The shale is of marine origin and is highly saline. Thin sandstone beds are present at scattered locations and the weathering of these sandstone beds produces areas of sandy soils. The shale weathers to form a thin mantle of soil material overlying a zone of shale fragments on top of the bedrock. The weathered mantle is generally not more than 1 foot thick. Alluvial material is quite limited in areal extent, being restricted mainly to small areas along the larger stream channels.

Climate

The Badger Wash area is generally classified as arid, although according to Thornthwaite[4] the climate is semiarid about 50 percent of the time. Average annual rainfall at Fruita, Colo., located 16 miles southeast of the study area, is 8.3 inches, but yearly amounts range widely about this average. Temperatures range from below 0° F. to above 100° F. during most years. Potential evaporation rates in the area are high. Evaporation from a U.S. Weather Bureau Class A pan at Grand Junction averages about 90 inches for the months April to October.

Methods of Investigation

Runoff and sediment yield at Badger Wash are measured in reservoirs at the lower end of 8 paired drainage basins ranging in size from 12 to 101 acres. Drainage basins were chosen in matched pairs so that each pair was as nearly similar as possible with respect to size, soil, vegetation, topography, and aspect. One basin of each pair was fenced to exclude grazing. Reservoirs are equipped with water-stage recorders for measurement of inflow. Sediment yield is computed from periodic topographic surveys of the reservoir.

Precipitation is measured in nine recording rain gages located in the eight drainage basins, and rainfall amounts are computed for each basin by the Thiessen polygon method.

Runoff and Sediment Yields

During the period 1954–61 runoff from ungrazed basins averaged about 80 percent of that from the grazed basins (fig. 2) and ranged from 69 to 89 percent in the four pairs. A difference in sediment yield was measured that was even more pronounced than the change in runoff, with amounts ranging from 18 to 54 percent less in the ungrazed areas. The reduction of sediment yield did not appear to be directly correlated with reduction of runoff. In fact, the pair of basins that showed the greatest difference in runoff showed the least difference in

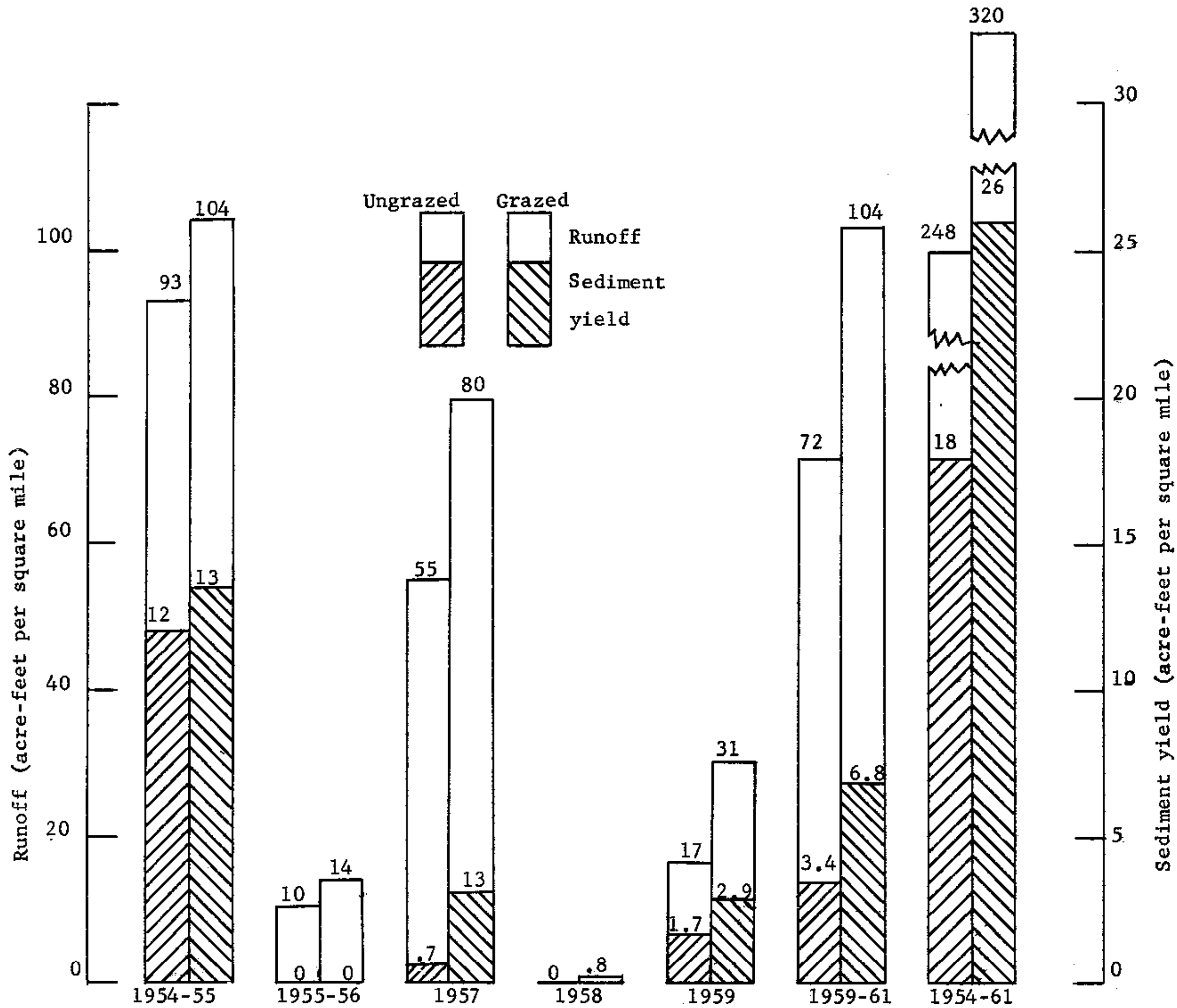

FIGURE 2. — Runoff and sediment yield — grazed and ungrazed areas.

sediment yield. According to Turner,[5] at the end of the first 5 years of the period, vegetation had not increased appreciably over that at the beginning of the study. If this is the case, some other factor besides vegetation density must be responsible for the change in runoff amounts.

In the study of hillslope erosion Schumm[6] described a cycle of heaving and compaction of the soil surface on Mancos shale hillslopes. This cycle is summarized briefly as follows. After a summer storm the soil surface is sealed and wet. As the soil is dried, a network of fine dessication fractures, which close when wetted, are formed. In this condition the hillslopes are relatively impermeable, and slopewash and rilling occur. During cycles of freeze and thaw during the winter, heaving takes place that destroys the rill patterns, loosens the soil, increases permeability and causes downslope creep of the Lithosol. When rain occurs during the next spring and early summer the soil is highly permeable and is able to absorb more rainfall than later in the year. As more rain falls during the summer, the soil again becomes compacted and infiltration rates are lowered. This cycle is illustrated in figure 3.

The occurrence of this cycle is borne out by analysis of precipitation and runoff records in Badger Wash. All storms greater than 0.10 inch during the period 1954–61 were arranged by

[5] See footnote 1.

[6] See footnote 2.

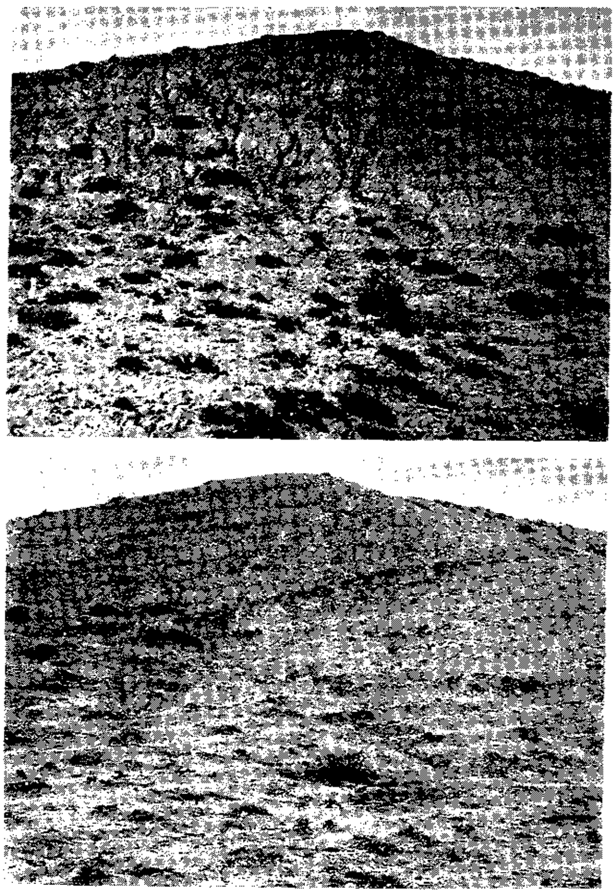

FIGURE 3.—Hillslope at Badger Wash, showing rilled surface in August 1959 (top) and same slope showing unrilled surface with some tracking in March 1961 (bottom).

0.10-inch increments and compared with runoff during two periods, April–June and August–October. As shown in table 1, runoff was greater during the fall period for all classes of storm.

Although the cycle of freeze and thaw apparently takes place in all drainage basins at Badger Wash, the effect on runoff appears to be greater in certain areas than in others. One of the pairs of drainage basins is located in an area of considerably rougher topography than the other basins. This area is composed of extremely steep slopes, a low density of vegetative cover, generally shaly soil mantle, and high drainage density. As generally considered, this area would appear likely to produce more runoff than other basins being studied, but such is not the case. Actually runoff amounts from this area have been about the same or slightly less than from the other basins, although sediment yield is considerably more. This anomaly is explained by differences in the cycle of soil

[7] See footnote 1.

TABLE 1.—*Spring and late-summer precipitation and runoff at Badger Wash*[1]

Range of storm precipitation (inches)	Period	Storms	Average precipitation	Average runoff	Runoff-precipitation
		Number	*Inches*	*Inch*	*Ratio*
0.10–0.20...	Apr.–June..	13	0.15	0.001	0.007
	Aug.–Oct...	23	.15	.008	.050
0.21–0.30...	Apr.–June..	4	.26	0	0
	Aug.–Oct...	11	.27	.039	.145
0.31–0.40...	Apr.–June..	3	.32	.007	.022
	Aug.–Oct...	11	.34	.063	.185
0.41–0.50...	Apr.–June..	3	.47	.020	.043
	Aug.–Oct...	7	.47	.093	.198
0.51–0.60...	Apr.–June..	1	.58	.120	.207
	Aug.–Oct...	2	.56	.180	.322
0.61–0.70...	Apr.–June..	1	.69	.004	.006
	Aug.–Oct...	4	.66	.290	.440
0.91–1.0....	Apr.–June..	0	......	......	......
	Aug.–Oct...	1	.94	.380	.400
1.31–1.40...	Apr.–June..	0	......	......	......
	Aug.–Oct...	1	1.34	.470	.350
All storms, 0.10–1.40...	Apr.–June..	25	.26	.004	.015
	Aug.–Oct...	61	.34	.079	.232

[1] From reference given in footnote 3.

expansion and compaction among basins. This swelling does not take place to as great an extent in the sandier soils as it does on the shaly soils. Although runoff may not be any greater from these steep shaly slopes than from other basins in the area, the sediment yield has been more because of the large supply of material made available for transport by frost action during the winter.

As shown previously, runoff and sediment yield have been considerably less from ungrazed areas than from grazed areas even though vegetation has not changed appreciably from area to area. Normally both cattle and sheep are grazed at Badger Wash from about November 16 until May 15. The trampling effect of grazing animals is quite apparent in the area as shown in figure 4. Undoubtedly the period from March 1 to May 15 is the period during the year when the top few inches of soil would be most adversely affected by trampling. Early in the spring the soil surface is in a loosened condition, and for a short period it contains enough moisture to provide maximum compactability.

Thompson[7] obtained penetrometer readings of the top 5 inches of soil in connection with the 1958 infiltrometer runs at Badger Wash. These tests were made in the infiltrometer plots after the wet run at each site and were completed during August and September. Unfortunately, penetrometer readings were not obtained during the 1953–54 seasons, but results of the 1958 tests show that significantly more force was required to penetrate the top inch of soil in the grazed basins than in the ungrazed basins. Also the difference in readings between paired basins was greatest in the basins underlain by sand-

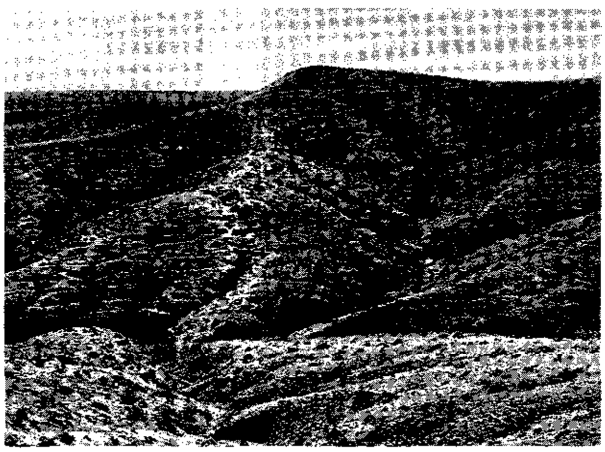

FIGURE 4. — Hillslope at Badger Wash, showing effect of trailing by livestock.

stone and this difference appeared to persist into the second and third inch of soil. This difference may have been caused by one or a combination of factors about which at this time we may only speculate. The sandstone soils are apparently less subject to loosening by freeze and thaw than shale soils and could therefore have more carryover effect of compaction by trampling from year to year. Also, because of the nature of the topography and better inherent vegetation on the sandstone soils, these areas may have received more prolonged use than shaly areas. In any case, consideration of the penetrometer data would indicate that the upper part of the soil mantle is affected by grazing animals. The results are a higher runoff and sediment yield from the grazed areas, in spite of no large vegetational change.

Conclusions

Runoff from steep, highly dissected areas at Badger wash has been about the same as that from other less dissected areas of gentler slope. This is probably caused by loosening of the soil by frost action, which is dominant in steep shaly areas, thus making the soil more permeable. Although runoff has been about the same for the steep shaly areas and gentler sandy areas, sediment yield has been considerably more from the shale area. This indicates that sediment concentrations in runoff are much greater in these rough areas, which is a result of frost action making slopes unstable.

Runoff and sediment yields from paired drainage basins during the 8-year period 1954–61 were also determined to be materially affected by grazing animals. Although the loosening action of frost takes place in both grazed and ungrazed basins, the presence of livestock in grazed basins during the early spring period tends to cause compaction of the soil by trampling, thereby causing more runoff even though density and character of vegetation had not changed significantly during the first 5 years of the period.

THE ROLE OF THE LARGE STORM AS A SEDIMENT CONTRIBUTOR[1]

[Paper No. 15]

By ROBERT F. PIEST, *hydraulic engineer, USDA Sedimentation Laboratory, Soil and Water Conservation Research Division, Agricultural Research Service*

Introduction

A knowledge of the sediment contribution of large rainstorms, relative to the total quantity of sediment removed from a watershed over a long period of time, is a prerequisite to the planning of an efficient soil conservation program. Because the large storm has especially high flow rates and other erosive features that are apparent to even the casual observer and that are of great concern to technicians engaged in the design of soil conservation structures, its role as a sediment contributor is not always seen in proper perspective.

Wischmeier,[2] in an extensive study of soil losses from small, cultivated, single-cover plots at seven locations throughout the country, found that three-fourths of the soil losses were caused by an average of about four storms per year. Also, in a study of storm classes, he indicated that about one-third of the total soil losses was due to extreme storms having return periods greater than 2 years; one-third was due to moderate storms with return periods between 1 and 2 years; and another third was due to smaller storms with return periods shorter than 1 year. The bulk of soil loss on small cultivated plots, therefore, can be attributed to the more numerous storms that have at least a 50-percent probability of occurrence in any given year.

The purpose of this study is to evaluate the role of large storms in causing soil losses from small mixed-cover watersheds that range in size from 100 to about 100,000 acres.

Study Procedures

To attain the study objectives, it was necessary to estimate runoff and sediment yields for

[1] Cooperative research with Mississippi State University and University of Mississippi.

[2] WISCHMEIER, W. H. STORMS AND SOIL CONSERVATION. Jour. Soil and Water Conserv. 17 (3). 1962.

all storms, their frequency of occurrence, and the average annual runoff and sediment yields from each of the 72 watersheds studied. Suspended-sediment records seemed to offer the best approach to this study for watersheds in the size range under consideration.

A review of suspended-sediment bibliographies revealed that relatively little field data had been collected, until recently, from small watersheds. Records were most often available in daily summary form, although the tabulations of runoff and sediment yield by storm were available in a few cases. For the best sampled watersheds, the record lengths did not exceed 5 to 8 years; this was not enough to serve as the sole basis for predicting long-term sediment yield trends or for accurate determination of storm magnitude-frequency relation.

The average annual (long-term) yields upon which these storm studies were based were derived from the above-mentioned fragmental daily-runoff and suspended-sediment records and from long-term runoff records of watersheds in the vicinity. These yields are the subject of a paper.[3] The calculations of runoff and sediment quantities for large storms for the most part are based upon the premise that these storm quantities and durations are closely represented by daily quantities. Some of the assumptions inherent in the use of daily records to arrive at storm yields — the definition of a storm and some of the problems involved in assigning a return period to a storm of a specific size — are now discussed.

The Storm

A storm, unless specifically qualified, is generally understood to be a disturbance of the ordinary average conditions of the atmosphere, which may include any or all meteorological disturbances, such as wind, rain, snow, hail, etc. In this study we are concerned with the runoff-sediment producing aspects of the storm; most major runoff-producing events are rainstorms.

The duration of a storm has been variously defined. For studies on fractional-acre plots, it is considered by the ARS National Runoff and Soil Loss Data Laboratory to be ended when less than 0.05 inch of precipitation occurs during a period of 6 consecutive hours. To be consistent, for watersheds in the size range we are considering, the minimum duration of a storm should be approximately that time which will allow for practical hydrograph separation of discrete storms on the larger watersheds. This is usually less than 24 hours. Also, on the larger watersheds, 6 hours is about the minimum time between storms that will allow, with fair accuracy, hydrograph separation of successive storms.

Considering the nature of the data we are analyzing, which is usually published in daily summary form, and the runoff characteristics of watersheds in the 100- to 100,000-acre size range, the most consistent definition of a storm would be that it is a precipitation event, usually rainfall, that has a practical runoff duration of less than 24 hours.

This definition fits nearly all conditions that can be anticipated. For example, a sharp thunderstorm which produces a single runoff event on 100- and 100,000-acre watersheds will typically have practical runoff durations of less than 3 hours and 15 hours, respectively. (That is, more than 95 percent of the runoff and sediment load will pass from basin in that time, although the remainder may require several days.)

Due to these considerations, runoff volumes for watersheds in the size range herein considered are approximately the same whether reported on a daily or a storm basis.

The Flow Duration Curve

Experience with flow duration data indicates that, unless extremely unusual meteorological conditions prevail, a stream-gaging record of relatively short duration will closely approximate long-term conditions for low and moderate discharges. Only the high discharge portion of the short-term flow duration curve is subject to any great change.

Also, a daily flow duration curve is very similar to a duration curve that is based upon storm volumes if the duration of each storm is considered to be a day. Figure 1 shows typical variation between "storm" and daily flow duration curves for a 1.76- and a 117-square-mile watershed in northern Mississippi. The duration curves for a given watershed are very similar, but for very high discharges the "storm" duration curve values are slightly higher. (The divergence of the low-discharge parts of the curves is accented here by the fact that these streams are not ephemeral, but this divergence is irrelevant to a report concerned with sediment yields.)

From these and other data, the author has concluded that the high discharge part of the "storm" flow duration curve has somewhat greater values for a given duration than the daily flow duration curve. This finding is logical, in view of the fact that a few storms have durations greater than 24 hours, whereas others occur before and after midnight and partial storm volumes are therefore reported over several days.

A corrective procedure has been used that will allow the daily flow duration curve to

[3] PIEST, R. F. LONG-TERM SEDIMENT YIELDS FROM SMALL WATERSHEDS. For presentation at meeting of Internatl. Union of Geodesy and Geophysics, Berkeley, Calif. August 19-31. 1963.

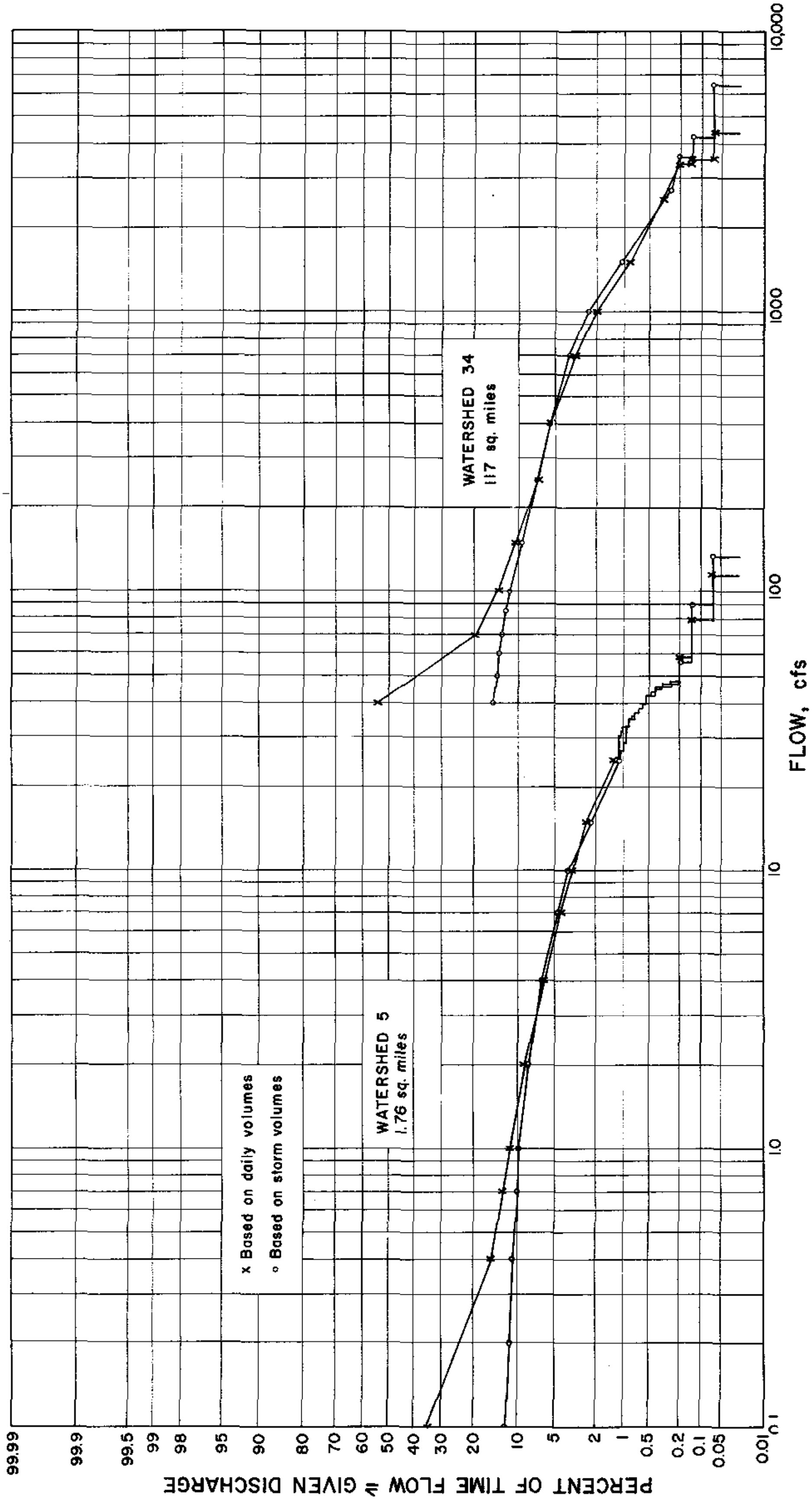

FIGURE 1.—Daily versus storm flow-duration curves for Pigeon Roost Creek watersheds, January 1957–December 1960.

approximate the "storm" flow duration more accurately. If a known relation between rainfall parameters and runoff volumes exists (such as a rainfall-runoff regression) or if data are available that allow graphical rainfall-runoff relations for short periods of record to be extrapolated on the basis of Weather Bureau data on extreme rainstorms, then computed estimates of runoff volumes for large storms with known return periods will verify a daily flow duration curve for use in storm analyses or will indicate needed adjustment.

A partial duration series of storm volumes is also a helpful check on the daily flow duration curve, although records are usually so short that limited confidence can be placed in this procedure.

The Water-Sediment Relation

The average daily water-sediment relation, as defined by short-term records for each of the watersheds, was extrapolated to represent long-term conditions by several procedures. The principal extrapolation assumption was that, at some high runoff volume, the concentration would reach a maximum and subsequent higher storm runoff volumes would contain sediment concentrations, on the average, that did not vary appreciably from this maximum. (Experience indicated, however, that this assumption did not apply for a few watersheds that were light sediment contributors.) The representative long-term water-sediment curve was then utilized with the long-term flow duration curve to construct a sediment duration curve.

As with daily flow duration curves, we have assumed that there is little practical difference between the water-sediment relation, whether on a storm or daily basis. Figures 2 through 5 compare daily and storm water-sediment relations for a large and a small watershed in Pigeon Roost Creek Basin. The middle and upper discharge segments of the curve are nearly identical, although there is evidence that a storm curve has slightly lower sediment discharges, at comparable runoff rates, than the daily curve.

Computations

The 4-year daily record of runoff for watershed 32, Pigeon Roost Creek Basin, Mississippi, was extrapolated on the basis of index-station[4] comparisons. By this procedure, runoff records were generally compared with a minimum of two long-term records for streams in the vicinity. The extrapolated daily flow duration curve $[q_w = f(t)]$, with time as independent variable, is plotted against the daily mean discharge rate (q_w), in cubic feet per second, as the dependent variable (fig. 6). If the dimensionless time scale is assumed representative of a given long-term period (Y), in years, this variate can be converted into (t) days, from 0 to 365.25 Y, and the area under the curve, in cubic feet per second-days, is then the total runoff volume (Q_w) for the long term period.

$$Q_w = \int_0^{365.25\,Y} f(t)\,dt$$

The percentage (P) of the total runoff volume that can be attributed to the highest m days (or storms) of record is then

$$P = \frac{\int_0^{m} f(t)\,dt}{\int_0^{365.25\,Y} f(t)\,dt} \times 100$$

In figure 6 the large crosshatched area represents the 50 highest ranked events in 100 years.

In practice, the runoff volumes are best computed by use of Simpson's rule or by graphic approximation.

A sediment duration curve can be constructed similarly from the flow duration information of figure 6 and knowledge of the average long-term water-sediment relation (sediment rating curve). The high sediment discharge part of a sediment duration curve is reproduced in figure 7, where the abscissa values are in terms of ranked events, each having a duration of 1 day rather than percentage of time.

Summary and Conclusions

Table 1 summarizes the relative sediment contributions of storms of various sizes from 72 small watersheds in 17 States. The watershed sediment yield caused by large storms (with a return period greater than 2 years) varied from 3 to 46 percent of total suspended-sediment yield; the yield from moderate storms with a 1- to 2-year return period ranged from 3 to 22 percent of the total; storms with a return period of less than 1 year were the cause of 34 to 92 percent of total suspended-sediment yield.

For most watersheds more than one-half of the soil losses are attributable to the smaller storms that occur more often than once a year, on the average. We can therefore expect that recommended land use and land treatment practices in upland areas, i. e., those elementary conservation measures that do not cost much and can be readily renewed after damage from major storms, would result in significant reduction in downstream sedimentation. In some problem areas, they would be sufficient to sustain the design life of a reservoir without the aid of expensive auxiliary structures.

The accuracy of computations is not sufficient to discern many trends, but it is clear that

[4] SEARCY, J. K. WATER SUPPLY PAPER 1542A. U.S. Geological Survey. 1959.

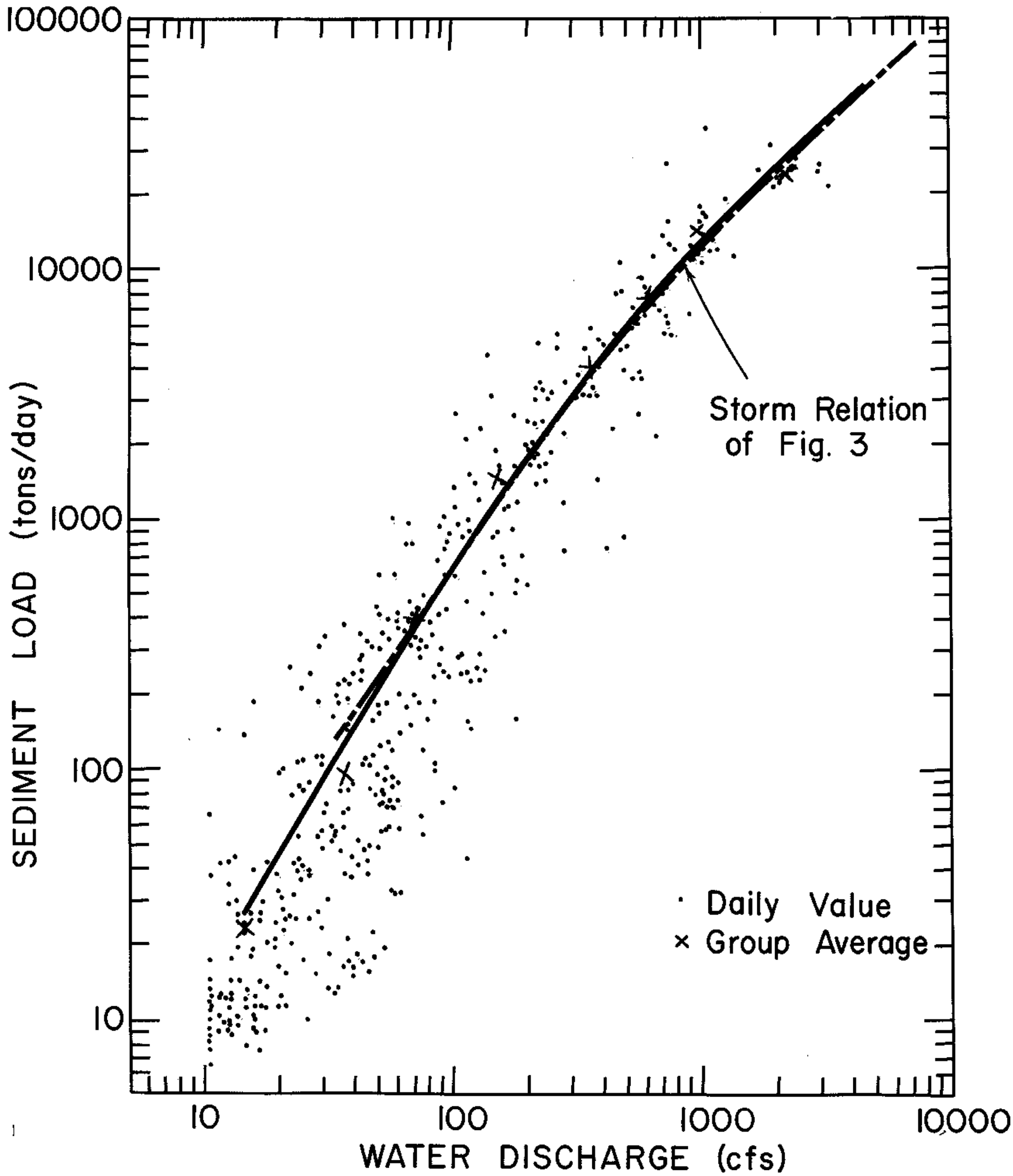

FIGURE 2.—Direct runoff versus sediment discharge, by day, Pigeon Roost Creek Watershed 34, January 1957–December 1960.

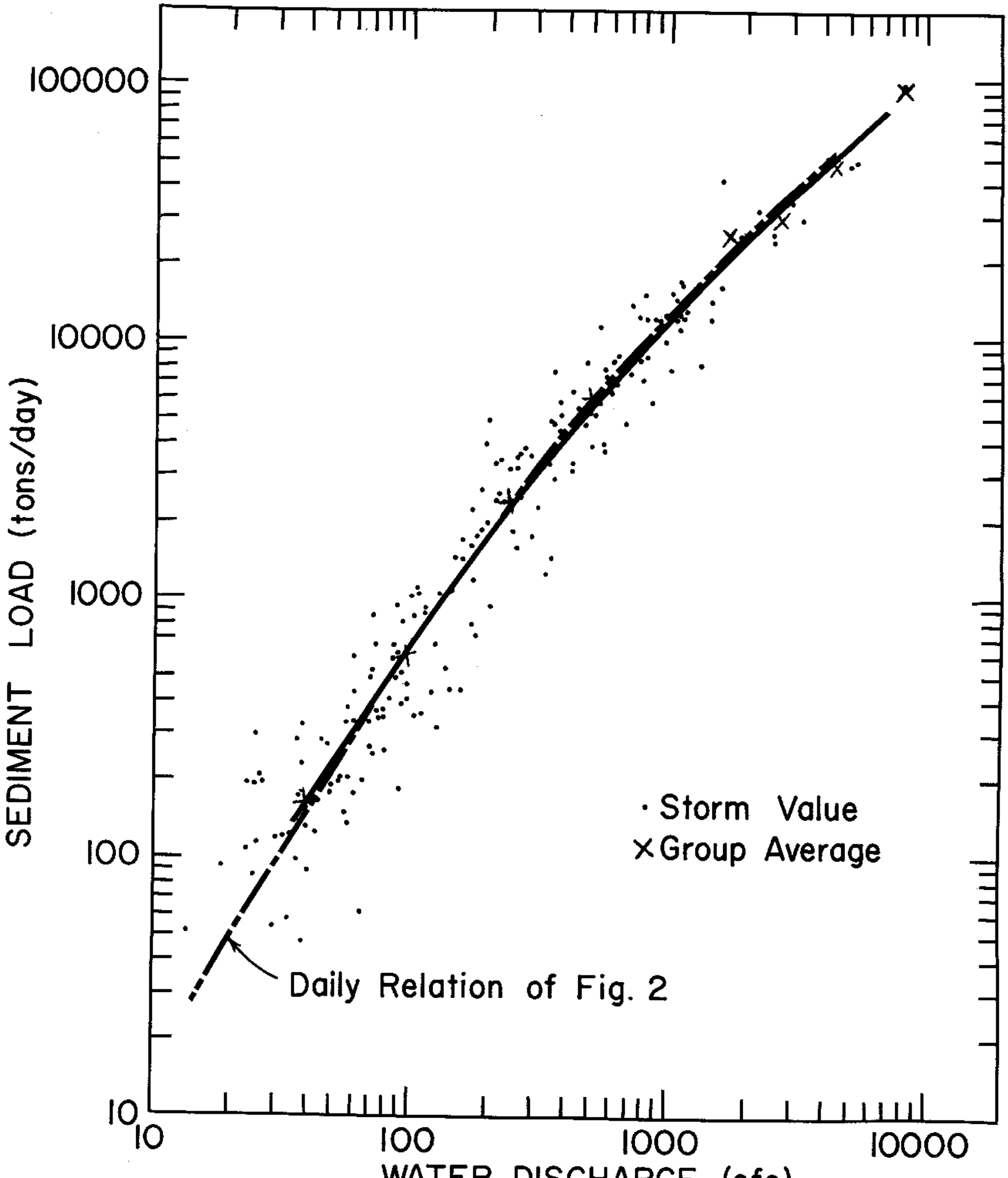

FIGURE 3. — Direct runoff versus sediment discharge, by storm, Pigeon Roost Creek Watershed 34, January 1957–December 1960.

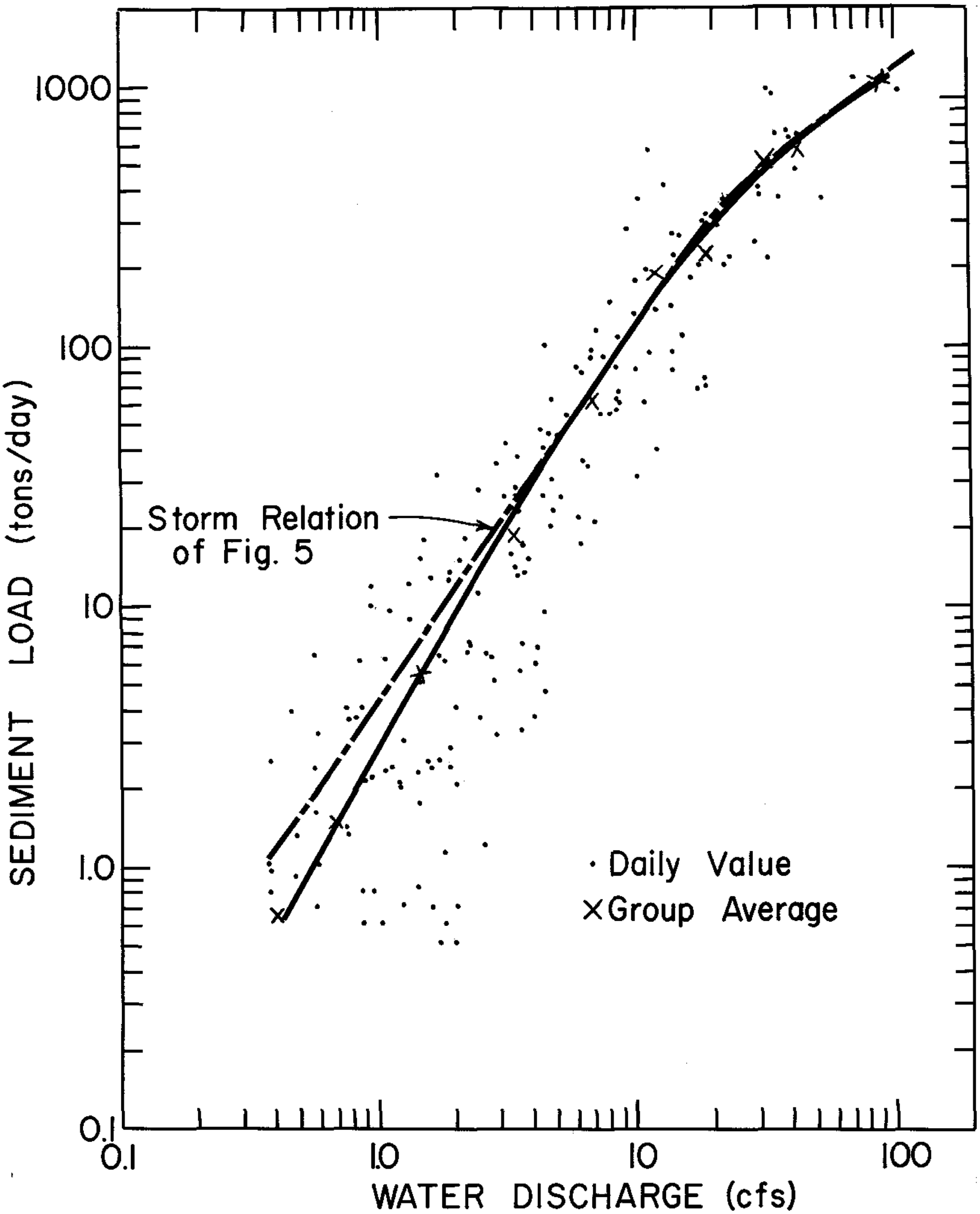

FIGURE 4. — Direct runoff versus sediment discharge, by day, Pigeon Roost Creek Watershed 5, January 1957-December 1960.

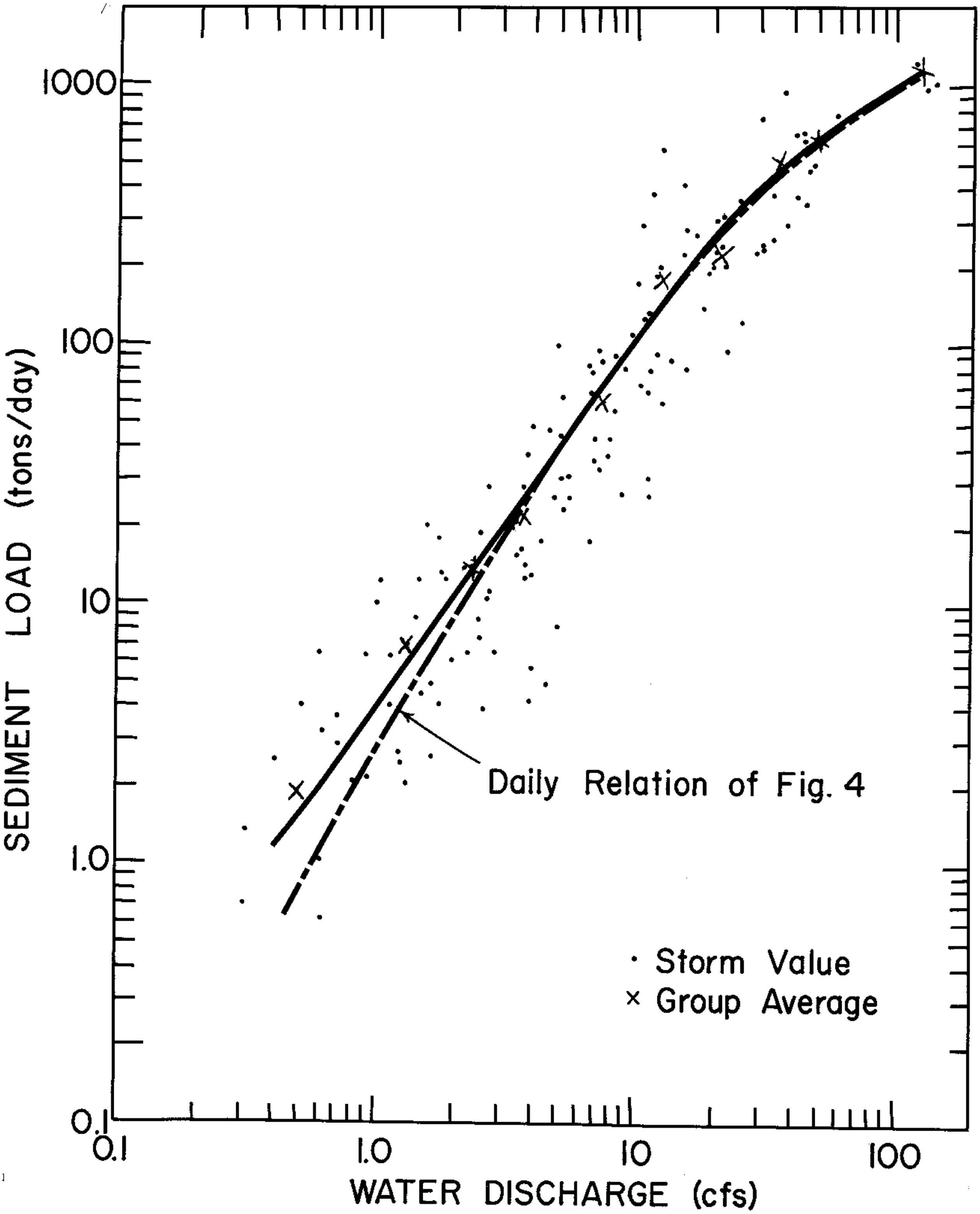

FIGURE 5. — Direct runoff versus sediment discharge, by storm, Pigeon Roost Creek Watershed 5, January 1957–December 1960.

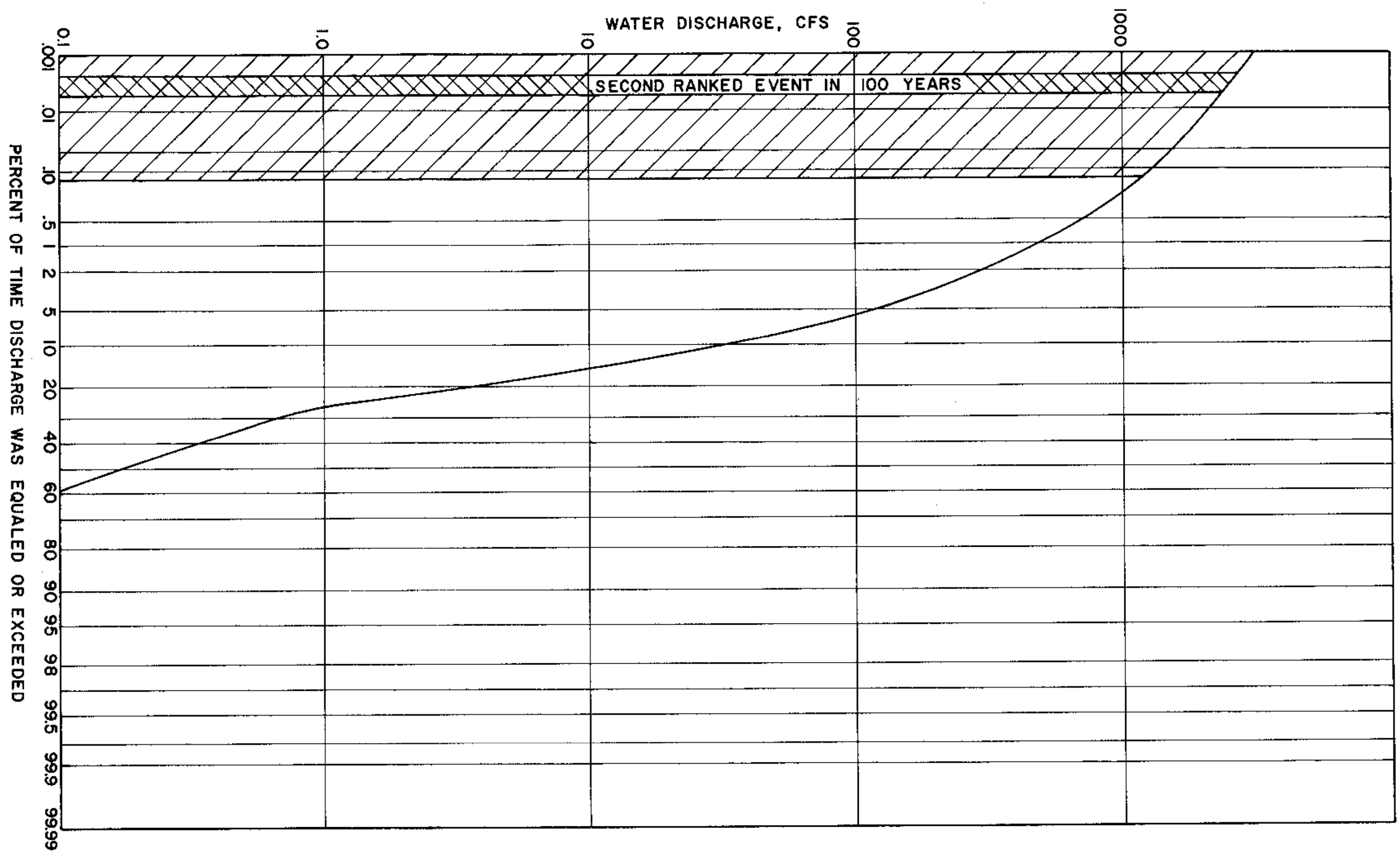

FIGURE 6. — Long term discharge-duration curve representing top-ranked runoff events, Watershed 32, Pigeon Roost Creek Basin, Miss.

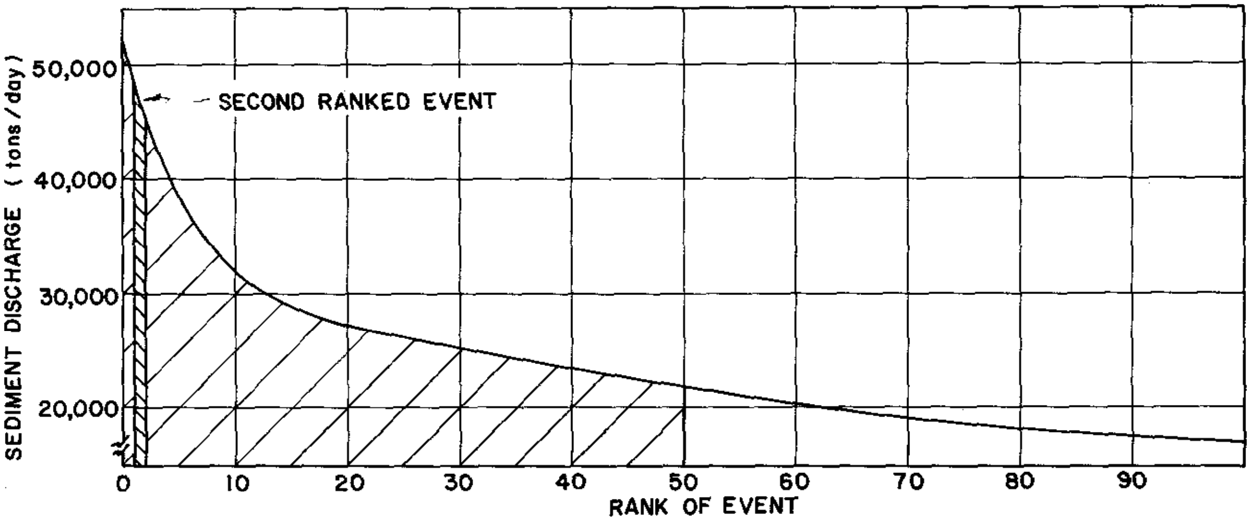

FIGURE 7.—Long term sediment discharge-duration curve representing top-ranked events, watershed 32, Pigeon Roost Creek Basin, Miss.

watershed soil losses resulting from very large storms are proportionally greater in the semiarid Great Plains than in the humid Southeast. Also, the relative sediment contribution of any given large storm tends to decrease with increasing watershed size. These factors are logical, since the average number of runoff events per year are known to vary geographically and with watershed size.

The relative quantities of direct runoff attributable to large storms are substantially less than the relative sediment quantities.

TABLE 1.—*Portion of average annual sediment yield contributed by large, moderate, and small storms*[1]

Watershed	Drainage area	Period of sediment record	Relative contribution by storm type		
			Large	Moderate	Small
	Sq. miles	*Month and year*	*Pct.*	*Pct.*	*Pct.*
Kiowa Creek at Kiowa, Colo.	111	4/56– 9/60	36	16	48
North Clear Creek at Blackhawk, Colo.	55.8	4/52– 6/55	3	5	92
Scantic River at Broad Brook, Conn.	98.4	11/52– 9/56	17	3	80
Davids Creek near Hamlin, Iowa	26	7/52– 9/59	30	11	59
East Fork Hardin Creek near Churdan, Iowa	24	7/52– 9/57	18	10	72
Honey Creek near Russell, Iowa	13.2	7/52– 9/59	17	11	72
Mule Creek near Malvern, Iowa	10.6	7/54– 9/59	39	16	45
Paint Creek at Waterville, Iowa	42.8	11/52– 9/57	18	10	72
Ralston Creek at Iowa City, Iowa	3.01	4/52– 9/59	15	8	77
Tarkio River at Blanchard, Iowa	200	6/34– 6/40	12	7	81
East Limestone Creek near Ionia, Kans.	27.3	4/35– 6/38	32	18	50
Elm Creek near Ionia, Kans.	22.7	4/35– 6/38	44	22	34
West Buffalo Creek near Jewell, Kans.	15.2	4/35– 6/38	33	17	50
Cane Branch near Parkers Lake, Ky.	.67	2/56– 9/58	25	14	61
Helton Branch at Greenwood, Ky.	.85	10/57– 9/58	18	12	70
Plum Creek at Waterford, Ky.	31.9	10/54– 9/58	10	7	83
Watershed 4, Pigeon Roost Creek Basin, Miss.	3.13	1/57–12/60	19	11	70
Watershed 5, Pigeon Roost Creek Basin, Miss.	1.76	1/57–12/60	12	8	80
Watershed 10, Pigeon Roost Creek Basin, Miss.	8.64	1/57–12/60	13	8	79
Watershed 12, Pigeon Roost Creek Basin, Miss.	35.6	1/57–12/60	13	8	79
Watershed 17, Pigeon Roost Creek Basin, Miss.	50.2	1/57–12/60	14	9	77
Watershed 19, Pigeon Roost Creek Basin, Miss.	.38	1/57–12/60	15	9	76
Watershed 24, Pigeon Roost Creek Basin, Miss.	0.80	1/57–12/60	15	9	76
Watershed 30, Pigeon Roost Creek Basin, Miss.	0.18	1/57–12/60	21	12	67
Watershed 32, Pigeon Roost Creek Basin, Miss.	31.13	1/57–12/60	11	7	82
Watershed 34, Pigeon Roost Creek Basin, Miss.	117	1/57–12/60	10	7	83
Watershed 35, Pigeon Roost Creek Basin, Miss.	11.8	1/57–12/60	12	8	80
East Fork Big Creek near Bethany, Mo.	95	4/49– 9/54	24	13	63
West Tarkio Creek near Westboro, Mo.	105	6/34– 6/40	11	7	82
Watershed 3, Hastings, Nebr.	.75	1/57–12/61	29	13	58

TABLE 1.—*Portion of average annual sediment yield contributed by large, moderate, and small storms*[1]

Watershed	Drainage area	Period of sediment record	Relative contribution by storm type		
			Large	Moderate	Small
	Sq. miles	*Month and Year*	*Pct.*	*Pct.*	*Pct.*
Watershed 5, Hastings, Nebr.	.64	1/57–12/61	37	19	44
Brushy Creek near Maywood, Nebr.	130	4/51– 9/58	32	15	53
Dry Creek near Curtis, Nebr.	20	4/51– 9/58	46	15	39
Fox Creek at Curtis, Nebr.	77	4/51– 9/58	42	16	42
Medicine Creek above Harry Strunk Lake, Nebr.	542	4/51– 9/58	37	14	49
Mitchell Creek above Harry Strunk Lake, Nebr.	53	10/51– 9/57	34	15	51
Stoney Brook at Princeton, N.J.	44.5	1/56– 9/58	24	13	63
Kayaderosseros Creek at West Milton, N.Y.	90	2/53– 6/65	13	9	78
East Fork Deep River near High Point, N.C.	13.9	4/34– 6/38	18	10	72
Horse Pen Creek at Battleground, N.C.	15.9	5/34– 6/38	11	7	82
Muddy Creek near Archdale, N.C.	14.2	5/34– 9/40	12	7	81
Uharie River near Trinity, N.C.	11.3	5/34– 8/40	14	9	77
West Fork Deep River at High Point, N.C.	33.0	2/34– 9/40	13	8	79
Little Miami River near Oldtown, Ohio	129	8/52– 9/57	14	8	78
Little Miami River near Selma, Ohio	50.6	9/52– 9/57	11	7	82
Massie Creek at Wilberforce, Ohio	64.3	9/52– 9/58	14	7	79
North Fork Little Miami River near Pitchin, Ohio	29.1	8/52– 8/58	11	7	82
North Fork Massie Creek at Cedarville, Ohio	25.6	7/54– 9/58	13	7	80
South Fork Massie Creek near Cedarville, Ohio	20.2	7/54– 9/58	14	8	78
Todd Fork near Roachester, Ohio	234	9/52– 9/56	16	9	75
Council Creek near Stillwater, Okla.	30.2	10/35– 6/37	14	7	79
Stillwater Creek at Stillwater, Okla.	165	10/35– 6/37	20	12	68
West Fork Brush Creek near Stillwater, Okla.	13.1	10/35– 6/37	23	13	64
Bixler Run near Loysville, Pa.	15	2/54– 9/58	15	9	76
Corey Creek near Mainesburg, Pa.	12.2	5/54– 9/58	24	14	62
Elk Run near Mainesburg, Pa.	10.2	5/54– 9/58	24	12	64
South Tyger River near Reidville, S.C.	106	5/34– 6/38	8	5	87
South Tyger River near Woodruff, S.C.	174	4/34– 6/38	6	4	90
North Tyger River near Moore, S.C.	162	4/34– 6/38	8	5	87
Watershed 1, Riesel, Tex.	.28	1/39–12/47; 1/61–12/61	29	16	55
Watershed Y-2, Riesel, Tex.	.21	1/44–12/47; 1/61–12/61	28	15	57
Big Elm Creek near Buckholts, Tex.	166	3/34– 9/36	24	12	64
Big Elm Creek near Temple, Tex.	68.6	3/34– 6/36	28	14	58
Deer Creek at Chilton, Tex.	81.8	3/34– 9/36	29	13	58
Elm Fork Trinity River near Muenster, Tex.	46	10/56– 9/58	35	13	52
North Elm Creek near Ben Arnold, Tex.	30.3	10/34– 9/36	25	14	61
Pin Oak Creek near Hubbard, Tex.	17.6	10/56– 9/58	35	14	51
Black Earth Creek near Black Earth, Wis.	45.9	10/54– 9/59	20	10	70
Coon Creek at Coon Valley, Wis.	77.2	4/34– 9/40	25	13	62
Little LaCrosse River near Leon, Wis.	77.1	4/34– 9/40	9	6	85
Mt. Vernon Creek near Mt. Vernon, Wis.	16.1	1/54– 9/59	13	8	79
Yellowstone River near Blanchardsville, Wis.	29.1	8/54– 9/59	16	10	74

[1] With return periods greater than 2 years, less than 2 and greater than 1 year, and less than 1 year, respectively.

GEOLOGY IN SEDIMENT DELIVERY RATIOS

[Paper No. 16]

By SAM B. MANER, *soil conservationist, Engineering and Watershed Planning Unit, Soil Conservation Service*

Introduction

The delivery of erosional material from place of origin to any downstream point is a complex process conditioned by variations in several characteristics of watersheds. These variations are morphometric in origin, primarily topographic in nature, with the principal surficial action agents being hydrologic, hydraulic, and gravitational in character. The complexity of sediment delivery is governed largely by the intensity of the interaction between the variables that shape and control the topographic features of erosional land forms.

In this paper the hydrologic characteristics of drainage basins are considered to be climatic in nature to the extent that rainfall in terms of intensity, frequency, duration, and seasonal distribution and runoff are hydrologically descriptive of an area. Sampling of climatically homogeneous areas eliminates many variations in sediment delivery ratios that could otherwise be attributed to drainage basin variations in hydrologic characteristics.

The hydraulic characteristics of drainage basins, such as channel width, depth, shape, slope, and bed material types, are basically geomorphic properties.

Sediment delivery ratio [1] studies in four physiographic areas indicate characteristics of drainage basins such as channel density, relief–length ratio, and drainage basin size to be significantly related to average annual sediment delivery ratio.

Since the above descriptive terms also are indicative of the topographic features of watersheds, sediment delivery ratio is apparently the function of a group of variables that shape and control the relief features of erosional land forms. The shape and distribution of features of landscapes are conditioned by geologic type and structure, nature and depth of eroding materials, erosion process, and the sequence of topographic development or the stage of the geomorphic cycle.

The relation of sediment delivery ratio variables to the morphological aspects of drainage basin development are discussed in the following pages.

Drainage Basin Size

Drainage basin size is basically a surface reflection of geologic structure and lithology. It has been found to be a significant indicator of sediment delivery ratio in the Blackland Prairies,[2] the Southeastern Piedmont area, (*3*) and the Springfield plain area of Illinois.[3]

In the Blackland Prairies, Maner [2] found drainage basin size to be closely associated with channel density (mi./sq. mi.), watershed relief (ft.), main stem channel length (ft.) and relief–length ratio as well as sediment delivery ratio. These findings indicate basin size to be a "composite–parameter" made up of at least four variables. Thus, in this area, the apparent geomorphic link between drainage basin size and sediment delivery ratio are the morphometric characteristics of drainage basins that control channel density and relief–length ratio (discussed in other sections of this paper) and perhaps other, as yet, unevaluated variables.

One unevaluated aspect of the sediment delivery–drainage basin size relation is the hydrologic-hydraulic influences. In the field of hydrology and stream hydraulics it is generally known that drainage basin size is related to discharge volume per unit area, time of concentration, etc. However, little is known in regard to how these factors may influence the sediment delivery ratios of drainage basins. Wolman and Miller (*7*) have pointed out the probable nature of some of these relations in their study of magnitude and frequency of forces in geomorphic processes. They show drainage basin size to have a somewhat unique relation to the frequency characteristics of sediment transport. For example, for drainage basins larger than 8,000 to 9,000 square miles, less than 50 percent of the average annual runoff is produced by storms having a frequency of once each year. In contrast, storms of similar frequency account for more than 70 percent of the average annual runoff from drainage basins ranging in size from 0.1 to 3.0 square miles. This characteristic discharge, frequency, annual runoff relationship, coupled with the fact of higher discharge per unit area produced by smaller areas, would indicate higher sediment delivery ratios to be associated with smaller drainage basins.

Perhaps another significant aspect of the drainage basin size–sediment delivery ratio could be explained within the framework of the concept that geomorphic cycle stage changes not only with time but with distance from the drainage basin mouth. On this basis the intensity of topographic development in terms of relief, channel density, valley side slopes, stream gradients, etc. moves upstream, with the youthful and early maturity part of the geomorphic cycle followed by late maturity and old age. As one moves upstream, the drainage basin area decreases and the topographic factors that promote sediment delivery become more intensified, resulting in higher sediment delivery ratios. Strahler (*6*), in an analysis of drainage basin topography, developed the hypsometric integral as a measure of geomorphic cycle stage, and this integral may be of value in relating drainage basin size to sediment delivery ratio.

Channel Density

The apparent link between channel density and sediment delivery ratios, especially where the major source of sediment is from sheet erosion, is the distance over which sediment laden, relatively shallow, low velocity runoff must travel before concentrating in permanent drainage channels. Any increase in channel density reduces the possibilities of deposition of erosional material between the place of entrainment and the downslope point where channelized flow begins. Channel density is, therefore, an index of the efficiency of a drainage network in collecting runoff delivering erosional material to any downstream point.

The degree of channelization for a given size drainage basin on structurally similar geologic areas, in a given climatic zone, is primarily dependent upon drainage basin lithology. Lithology, in turn, is a major factor in

[1] The ratio of sediment yield to gross erosion.

[2] MANER, S. B. FACTORS INFLUENCING SEDIMENT DELIVERY RATIOS IN THE BLACKLAND PRAIRIES LAND RESOURCE AREA. U.S. Dept. Agr. Soil Conserv. Serv. [Filed at SCS Fort Worth, Tex., office.]

[3] MANER, S. B., and GEIGER, A. F. [Unpublished study from files of U.S. Department of Agriculture, Soil Conservation Service, at Forth Worth, Tex.]

determining the resistance of surficial materials to erosion, due to its relationship to surface and subsurface permeability. In general, resistance to erosion is less in rocks of low permeability. Hence, drainage basins on shales and similar fine-grained sedimentary rocks commonly have high channel density values and consequently higher sediment delivery ratio values. Drainage basins on coarse-grained clastic rocks, in contrast, tend to have fewer miles of channels per square mile of drainage area and a corresponding lower sediment delivery ratio.

In the Blackland Prairies, a relatively homogeneous area lithologically, Maner [4] found channel density to be closely associated with drainage basin size. The results of this study indicate the lithology or textural characteristics of the surface mantle to be a prime factor in intensity of channel development if basin area remains approximately constant. Any increase or decrease in basin area results in a decrease or an increase in channel density, respectively. This association of drainage basin size with channel density is believed to be due to the increase in relief per unit of area associated with reduction in drainage basin area and the runoff intensity-frequency character of decreasing drainage basin area.

Some other geomorphic characteristics of drainage basins that have been found to be associated with channel density or drainage density include relief ratio (*6*), relief-length ratio,[4] stream gradients (*5*),[4] and valley side slopes (*2, 6*).

Relief-Length Ratio[5]

Drainage basin relief and length expressed as relief-length ratio have been found to be significantly related to sediment delivery ratio in four widely separated, morphologically different physiographic areas (*1, 3*).[6] Schumm (*4*) found a close association between soil loss and relief ratio in a study of several "stockpond"-type reservoirs in Utah, Arizona, and New Mexico.

Quantitatively, relief-length ratio is an index of drainage basin concavity as well as of the cross sectional slope characteristics of a drainage basin. Morphologically, it is an excellent indicator of several topographic characteristics of drainage basins. For example, Schumm (*4*) found relief ratio (essentially the same as relief-length ratio) to be closely correlated with stream gradients, valley side slopes, drainage density, and basin shape in a study of drainage system evolution and slope development in a badlands area near Perth Amboy, N.J. Maner [7] found relief-length ratio to be significantly related to drainage basin size, channel slope, and channel density in the Blackland Prairies of Texas.

Results obtained in the Red Hills physiographic area indicate relief-length ratio may be an excellent parameter for estimating sediment delivery ratio for a group of drainage basins that differ considerably in structure, lithology, size, and other geomorphic characteristics.

Conclusions

The link between drainage basin geology and sediment delivery ratio is the drainage-network elements. The initial scale, shape, and distribution of these elements are a function of geologic structure and lithology. The current shape, scale, and distribution of these elements are conditioned by the kinds of geomorphic processes active in a given area and the length of time the processes have been active. The fact that interrelation between geomorphic characteristics of drainage basins does exist indicates the current stage of the geomorphic cycle to be a prime factor in determining which of the drainage basin characteristics are best related, quantitatively, to sediment delivery ratio.

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[4] See footnote 2.

[5] Watershed relief, in feet (defined as difference in elevation between average elevation of the watershed divide at headwaters of main stem drainage and elevation of streambed at damsite), divided by maximum watershed length, in feet, measured approximately parallel to the main stem drainage from damsite to watershed divide.

[6] See footnotes 2 and 3.

[7] See footnote 2.

GULLY CONTROL METHODS IN IOWA

[Paper No. 17]

By PAUL JACOBSON, *state conservation engineer, U.S. Soil Conservation Service*

Gully problems in Iowa vary significantly as one goes from the deep loess area in western Iowa to the area of shallow loess over till in eastern Iowa.

In the Ida-Monona-Hamburg area of western Iowa gullies are characterized by deep entrenchment with nearly vertical banks. Gully depths in this area will range to 100 feet, with a great number in the range of 30- to 40-foot depths. In the Marshall area gullies are similar to the Ida-Monona area to which it is adjacent, but they are not as deep. Generally they are about 15 to 25 feet deep, with a few ranging to as much as 30 feet in depth.

In the shallow loess over heavy till area of southeastern Iowa, gullies take on different characteristics. They are of much less depth and the shape changes from vertical banks to sloping banks. The slope of the banks generally is about 2 to 1, and they tend to become vegetated over a period of years. This type of gully exists all through southern and eastern Iowa with the exception of the Fayette area. In the Fayette area, gullies are similar to the deep loess area of western Iowa, except that depth is limited by interception with limestone in the bottom of the gully.

Gully problems in the level soils of north-central Iowa are very limited, with only an occasional gully along the major streams requiring treatment.

Development of Gullies

The rate of gully advancement, as indicated by Thompson,[1] varies more, owing to the size of drainage area than to most other factors. Rates of gully advance within soils areas in Iowa probably have not varied significantly. However, the character of the gully to some extent determines the degree to which people are willing to live with gullies. In the loess area deep gullies are associated with a corresponding greater width as time progresses. This greater width causes much higher land destruction by a gully of comparable drainage area. Also, the great depth of the gullies and the vertical banks in this area have made it difficult to provide access to cropland areas already dissected by deep gullies.

The corresponding demand for gully control by local people has been much greater in deep loess areas.

Present Gully Control Methods for Deep Loess Areas

Present gully control methods for deep loess areas are similar to methods used in eastern Iowa in that the main emphasis is to provide for water disposal. Generally, structures have been located so they would submerge overfalls, or they have been located so a grassed waterway could be built to provide protection for the overfall. Due to the depth of gullies, the height of head necessary for control has been rather large. The type of structure used has consisted mainly of pipe drop inlets that store part of the runoff and provide a slow release rate through the conduit. In order to be assured that the temporary storage pool is available during the life of the structure, sediment storage capacity must be provided. Estimated sediment deposits expected during the future 50-year period are based upon the land use and treatment of the drainage area. Another structure used to a lesser extent in this area is the concrete chute. It also is adapted to control the high heads required by these deep gullies; however, the cost of this type of structure often exceeds that of a drop inlet.

Are Present Gully Control Methods Doing the Job?

When consideration is given to the major problems of western Iowa, it might be well to analyze present goals and objectives of the gully control program. One of the major problems in obtaining maximum yields in this area is the shortage of moisture. Thus, one goal should be to store water on the land where it falls so it can be used for crop production. The soils of this area are well suited to making this goal possible. They have high infiltration rates and large water-holding capacity.[2]

Possible Improvement of Western Iowa Gully Control Methods

All gully control methods, as has been done in the past, should be coordinated with the necessary land treatment needed. In the deep loess area, sheet erosion has been extremely high under the cropping system and the land treatment practices being followed. Over a 50-year period soil losses of as much as 5 or 6[3] inches occur in the watershed.

[1] THOMPSON, J. R. QUANTITATIVE EFFECT OF WATERSHED VARIABLES ON THE RATE OF HEAD ADVANCEMENT. Amer. Soc. Agr. Engin. Meeting, Paper 62-713. Chicago. 1962.

[2] BROWNING, G. M. EFFECTIVE UTILIZATION OF WATER IN HUMID AND SUBHUMID AGRICULTURAL AREAS. Natl. Water Res. Symposium Proc. March 28 to 30, 1961. Washington, D.C.

[3] Unpublished material from studies on Mule Creek, Nepper, and Theobold Watersheds, Iowa.

This suggests that any gully control method now being practiced will bench the valley areas. It also suggests that if gully control is to be feasible, sheet erosion on the hillside will need to be controlled. This control probably can be achieved by two methods: (1) Retiring most of the hill ground to permanent grass; (2) bench terracing the hillsides.[4]

In all probability, based on the present relatively intense use of this land and the high productivity possible on these deep loess soils, the first alternative will not be accepted by farmers.

Level terraces, however, have been fairly well accepted in western Iowa. They provide a means whereby much of the runoff can be held until it soaks into the soil.[5] In dry years the yields of corn in the terraced channel have been recorded at 105 bushels to the acre vs. 41 in the sloping area between terraces. This suggests that terraces should received increased acceptance.

Since gully development is dependent on drainage area and the accompanying runoff, it follows that if drainage area at the overfall is eliminated by level terraces, gully advancement for the main part can be controlled by completely terracing the area. This leaves three major purposes for gully control structures.

(1) To furnish crossings on a farm to get to fields that have been isolated by the deep vertical-sided gullies.

(2) To bench valleys, making level areas above the structure suitable for farming and incidentally reclaiming large areas of land that are presently voided by the large gullies.[6]

(3) To furnish water areas suitable for recreation and wildlife.

On item 2 there could be considerable development in western Iowa. If structures are used primarily to bench land and to develop suitable conditions for maximized farming of valley areas, structure locations will change from those presently being used and recommended. The structures probably will be moved downstream to a point where the maximum area of farmland would be provided in the valley after the benching process has been completed.

Jones Creek Is Example of Valley Benching

About 20 years ago the Jones Creek Watershed was planned and installed in Monona County in western Iowa. The watershed is in the Hamburg area where upland slopes, which are mainly over 20 percent, have remained in permanent native vegetation. The valleys were dissected by deep gullies that had voided large parts of the farmland area. Structures were located at the lower end of gully junctions, so they would develop benches in the valley with sufficient area so they would be suitable for farming. The structures were designed as full-flow concrete chutes. Provisions were made initially so these structures could be raised when sediment had deposited to the lip of the structure. Benches have developed above these structures to or above the original lip of the chute. The structures have not been raised, but nevertheless they have demonstrated that valley benching is desirable and feasible. It can be observed that after structures are filled with sediment and filling has progressed above the structure lip, new gullies at a higher level will develop in the sediment plain above the structure. This will be true, unless structure heights are raised at a rate about equal to the deposition of sediment above the inlet of the structure. This process will go on until benches are at such a grade that no further soil movement will occur.

The Future of Gully Control

This discussion indicates that gully control methods presently being used in western Iowa need some reorientation of objectives and goals. As more and more level terraces are installed on hillsides, drainage areas of overfalls and the corresponding runoff will be reduced.

As terraces are installed, the level area in the valley remaining below the terraced area becomes more like the Jones Creek Valley and valley benching on many areas becomes possible. This is probably looking at the ultimate plan for the development of the deep loess area of western Iowa, but it does follow the pattern of proposed development of similar deep loess areas throughout the world. As more and more water is stored on the hillsides and in the valleys and as more and more areas approach being level, surface runoff will be reduced. This will probably be accompanied by rising underground water tables and it is probably that tile drainage will be required in the valleys. Flood control provided by this type of program would be by storing water in the soil itself, which was suggested by Hendricks.[7] The feasibility of this is also pointed out by 10 years of runoff studies on Jones Creek by Iowa State University during the cropping season where the maximum annual

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[4] JACOBSON, PAUL. A NEW METHOD FOR BENCH TERRACING STEEP SLOPES. Amer. Soc. Agr. Engin. Paper 62-716A. Chicago. 1962.

[5] Annual Reports, Bluffs Fruit Farm, Iowa State University.

[6] MESSINES, JEAN. FOREST REHABILITATION AND SOIL CONSERVATION IN CHINA, 1962. Translation to English, Unasylva 2 (No. 6), p. 103.

[7] HENDRICKS, E. L. PHILOSOPHY OF WATER DEVELOPMENT. Natl. Water Res. Symposium Proc., Mar. 28 to 30, 1961. Washington, D.C.

runoff has been 0.8 inch.[8] Thus, it would seem that gully control in this deep loess area should be to provide one of the three objectives listed previously.

New Studies

New studies are being initiated in western Iowa to verify the practicability of controlling gullies by complete terracing of the hillside. Runoff studies are being made in the Macedonia watershed on which a large part of the 400 acres of upland watershed has been terraced. Also, land has been purchased for 4 small watersheds of 90 to 160 acres to study runoff and gully head advance where the area is in grass, completely terraced, or in a row crop, without terracing.

Gully Control in Shallow Loess Over Till Areas

As we move into the shallow loess over till area in Iowa, our gully treatment program should have a different objective. In this area we do not have deep soils that are capable of storing large quantities of water temporarily which can later be removed by crops or tile. Here it will be necessary for the gully control structure to be one of the steps to provide a stable channel for removal of excess water. The land treatment program will consist of a cropping system and the necessary terraces to control erosion and reduce sediment to tolerable limits. Depending upon the intensity of cropping, the usual treatment may consist of a terrace or two at the top of the hill in the shallow loess soil. The terraces as used will lead the water to a hillside channel or waterway that can be stabilized. The remaining water disposal system will depend for the most part on developing a grassed waterway to remove runoff water at a velocity that will be safe for grass. A structure in this case will be needed to furnish transition from the broad waterway to the narrower downstream channel. The downstream channel is normally stable, because of its reduced grade. In this area, the gully control structure will have two of the reasons listed for western Iowa and a third objective as follows: (1) Water storage for recreation; (2) a structure to furnish a crossing to areas that have been made inaccessible by gully dissection; and (3) a transition from a broad waterway cross section to the narrower stream channel cross section.

If recreation is desirable and large areas of highly productive land will not be covered by water, the gully control can be accomplished by a pipe drop-inlet type of structure. Sediment storage will be provided for the estimated life of the structure, with enough additional volume provided for gully control and recreational purposes. This type of structure furnishes an ideal transition from the broad upstream waterway to a narrower downstream, entrenched watercourse. In addition to furnishing a transition, this type of structure provides for reduced downstream flow. To some minor extent, this will reduce downstream floods and to a greater extent it will provide for more downstream stabilization than where normal quantities of runoff must be provided.

In other cases where it is merely necessary to provide a transition from a broad waterway to a narrower downstream channel, a toe wall, a drop spillway, or a drop structure on a road culvert will provide the necessary transition. The depth of gully at the transition will generally determine whether a toe wall or a drop spillway is used. Where the channel at the transition is less than 4 feet deep, a toe wall is used. For greater depths a drop spillway is used.

Economics of Control Measures

Where gully control measures are proposed, the benefits derived should exceed the cost of the control measures. In watershed work a study is made of the reduction of damage by gully encroachment to upland areas by the installation of the control. Also reduction of downstream damage due to flooding, or covering of cropland by infertile overwash, or filling of drainage channels is enumerated, and the damage computed.

Similar studies are sometimes conducted where gully control measures are installed on a cost-sharing basis. Or, if the farmer is willing to invest money, this indicates the enomomic feasibility of the control measures.

Summary

1. The necessary land treatment program always should be applied to the land as part of the gully control program.

2. It is probable that as means are found for storing more water in the soil for use by crops that the number of structures needed for gully control can be reduced.

3. Gully control structures should be planned for multiple use, such as benching the land, furnishing recreation, providing part of a water disposal system, and furnishing road crossings across the gullies.

4. Many of the ideas presented in this paper are based on observations or limited research material. More research is needed.

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[8] GRAY, D. M., and JOHNSON, H. P. RAINFALL AND RUNOFF RELATIONSHIP FOR LOESS OF WESTERN IOWA. Agr. Engin. [In press.]

SEDIMENT REDUCTION THROUGH WATERSHED REHABILITATION

[Paper No. 18]

By EDWARD L. NOBLE, *forester, Intermountain Region, Forest Service, Ogden, Utah*

History is replete with stories recounting the failures of man to recognize, control, and conquer the devastating effects of sediments from steep mountainous lands. Learned men have documented the reasons for the tragic downfall of highly developed civilizations in Mesopotamia, Israel, Egypt, and elsewhere. Most agree that it was not conquest of the land by an invader nor the loss of fertile fields that depopulated the land, but the relentless encroachment of silt into the canals and rivers that forced the people to move elsewhere or starve.

We may now say 7,000 years later that such an occurrence could not happen again; that our engineering skills and general knowledge preclude such disasters that befell the ancient civilizations (*8*). In part, such an assumption is true, for we have expended billions of dollars to construct dams, levees, canals, and intricate irrigation systems. With such developments, we have assured ourselves of a continuing expansion of irrigated agriculture, industry, and attendant municipalities.

There is no question of our awareness of the critical water shortage problem that faces America today. Such awareness was well documented by the voluminous testimony before the Senate Select Committee on National Water Resources. Nor is there a question of the need for continued development of entire river basins to obtain water for the growing industrial and population expansion which is so imminent. Such recognition is well reflected by the huge annual appropriation of funds for water development and flood control purposes by both Federal and State governments.

With such concrete recognition of the water problems and the vast programs now underway and planned, you may reflect that we have or will have the situation under control and that the continued construction of dams and other structural projects will provide the utopia which we are presumably seeking.

No argument prevails that such programs are vital and essential to insure an expanding economy and continuing prosperity. However, there is a question of their continued success if we ignore the need for onsite uses of water and fail to recognize the hydrologic conditions on the watersheds themselves.

The principle of regulatory stream behavior and maintaining soil stability through land management is not new. It was advanced as a guiding principle over 50 years ago by the late geologist, Thomas C. Chamberlin, who stated, "The key lies in due control of the water which falls on each acre . . . The highest crop value will usually be secured where the soil is made to absorb as much rainfall and snowfall as practical . . . This gives a minimum of wash to foul the streams, to spread over the bottom-lands, to clog the reservoirs, to waste the water power, and to bar up the navigable rivers."

Since the time of Dr. Chamberlin's keen observation, we have learned much regarding the hydrology of watershed lands. The depths of the soil have been probed, and the interrelation between soil cover, precipitation patterns, and water disposal have been critically examined. By so doing, the research workers have established the fact that a very fundamental relation exists between land condition and hydrologic behavior. We have also learned through experience and the practical application of research results that upstream engineering and improvement of watershed conditions can greatly reduce land erosion and the resultant damages of sedimentation.

Recognizing, then, the fundamental relation between land condition and watershed behavior, we are able to set as our objective the maintenance of both the productive and the hydrologic or water-regulating functions of the land. By achieving this objective, we are able to obtain the greatest quantity of forage and fiber from the land and simultaneously make certain that water is yielded with the greatest possible regularity and with the least possible load of sediment.

In developing a program of sediment reduction through watershed rehabilitation it is necessary to ascertain fundamental facts such as (1) the geologic norm, (2) type of flooding, (3) watershed protection requirements, and (4) adaptability of the site for treatment.

Geologic Norm

Essential to the formulation of any flood and erosion control program through watershed rehabilitation is an understanding of the relation between current flooding and erosion to the geologic norm (*1*, *3*). This is necessary as watershed rehabilitation measures are primarily aimed at controlling water runoff and erosion from those areas on which accelerated erosion is occurring.

Watersheds with their soil and plant mantle, topography, and streamflow character have been inherited from the geologic past. Their

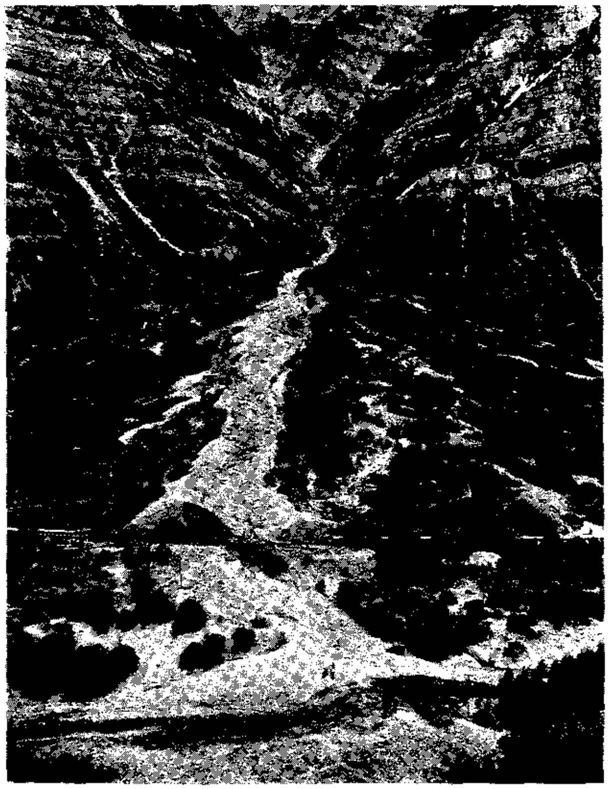

FIGURE 1. — Left, Morris Creek Watershed, Utah, north-facing basin whose average slope is 48 percent with extreme gradients of more than 80 percent. Precipitation averages 30 inches annually, which is completely infiltrated. Dense vegetation provides protection against erosion. Sediment production from this watershed is only 0.0025 acre-foot per square mile per year and represents a low geologic norm (*6*). Right, Lost Creek Watershed, Utah; 85 percent of area comprised of steep barren slopes. Active erosion and periodic flooding are characteristic of this basin, giving it a high geologic norm. Small islands of soil protected by vegetation show no evidence of overland flow and erosion. Erosion removes soil material as rapidly as it forms from unvegetated slopes (*6*).

streams exhibit great natural variation in erosion and flood behavior. Some streams are usually clear and flow with a relatively constant volume, but the regimen of other streams is marked by great variance in volume and time of flow and vast differences in sediment content. Each stream is the resultant of such normal factors and forces as climate, topography, geology, and the plant and soil mantle. We know, for example, that erosion is proceeding so slowly in some areas that soil is being formed and accumulated more rapidly than it is being removed. Streams from such areas carry only negligible loads of sediment. We know, too, that in other areas climatic and geologic conditions limit soil formation, plant growth, and fixing of the land surface. From these drainages runoff has always been rapid and erosion pronounced, giving rise to muddy and highly fluctuating streams. Moreover, we know that between these extremes are all gradations of watershed and sedimentation rates (*6*). Variation in sediment production in relation to watershed conditions are shown in figure 1.

From some knowledge of the geologic norm, a study of the condition of the watershed, and a determination of the history of runoff from a flooding stream, we can determine whether erosion is accelerated or normal. If accelerated, an opportunity for rehabilitation exists.

Type of Flooding

Flooding from high mountain watersheds usually occurs as wet-mantle floods, due to rapid snowmelt runoff, or as dry-mantle floods resulting from high intensity summer rainstorms.

Although watershed rehabilitation measures have proved valuable in preventing serious damage from both types, they are primarily used to control surface runoff of water and erosion from floods classed as dry mantle. Accordingly, a knowledge of the characteristics of dry- and wet-mantle floods is necessary in order to design appropriate treatment measures.

Some characteristics of dry-mantle and wet-mantle floods (7)

Factor	*Dry-mantle flood*	*Wet-mantle flood*
Soil mantle-condition.	Dry—high water storage capacity.	Wet—storage capacity exhausted.
Precipitation	Short, intense rainfall.	Prolonged rainfall or snowmelt, or both.
Storm area	Usually small—may be only 5 to 10 percent of flooding drainage.	Relatively large—usually all of flooding drainage.
Volume of water	Relatively small—may be only a few acre-feet.	Relatively large—thousands of acre-feet.
Manner of flow to stream channels.	Over surface	Mainly seepage or "bleeding" of saturated soil mantle.
Sediment carried	High—may reach 60 percent of volume.	Low—in relation to water volume.

Watershed Protection Requirements

Since 1920, much research work has been done on high mountain watershed lands to determine the relation between ground cover (including plants and litter), precipitation, surface runoff, and erosion.

After floods, field investigations have been made to determine flood-source areas, their condition, and their specific contribution to runoff and sedimentation. From these many analyses it has been determined that heavy flooding has occurred when the hydrologic balance on as little as 2 to 10 percent of the watershed has become deteriorated. It has also been noted that such deterioration is primarily due to a reduction of cover to the extent that each area of land was unable to receive and dispose of water through the process of infiltration.

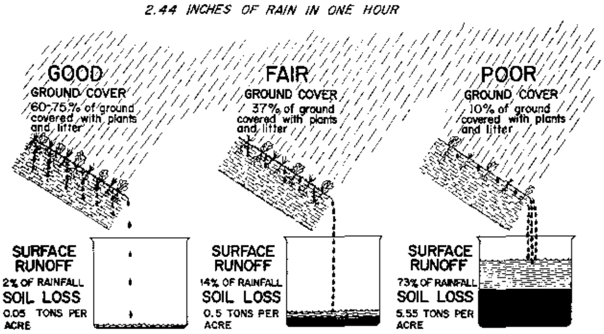

FIGURE 2. — The effect of watershed condition on rainstorm runoff and erosion, Subalpine Range, Ephraim Watershed, Utah.

Research efforts have covered a wide variety of soil conditions and vegetal types. Results indicate that in the intermountain area, a minimum of 60 to 70 percent ground cover is needed to control effectively surface runoff of water and erosion occasioned by torrential summer rainstorms. The same studies have also indicated that when ground cover has been reduced below 60 to 70 percent, overland flow and soil losses increased at an extremely rapid rate. The relation of ground cover to surface runoff and eroded soil for different soil-vegetation complexes is shown in figures 2, 3, and 4.

Determining Type of Watershed Rehabilitation

After an analysis of a flood source area to determine the type of erosion, type of flooding, and ground cover condition, it is then possible to plan the watershed treatment required. In most cases the immediate objective is to restore the watershed site to a condition where precipitation is received and disposed of without the occurrence of oversurface flows of water (*4, 9*). Based on several factors, watershed rehabilitation efforts fall into the following general categories:

1. Where sufficient native plants are available to furnish a seed supply, adequately fertile soil is present, ground cover density exceeds 40 percent, and a definite erosion pattern of rills and gullies is not evident, restoration of the hydrologic balance can be obtained by means of natural revegetation. This process may be slow; in most instances, very conservative management practices, such as rest-rotation grazing and light use by livestock, are required.

2. Where natural revegetation cannot be expected because of lack of seed, but where soil is productive and slopes do not exceed 30 percent gradient, artificial revegetation, using approved range seeding methods, are necessary to obtain needed plant cover. This method of rehabilitation requires careful selection of plant species, intensive farming methods, and complete protection from use after treatment until the vegetation is well established. Often it is desirable to supplement this treatment with the installation of a series of contour furrows to prevent surface runoff.

3. Where both plants and soil fertility have been destroyed so completely that a protective cover cannot be established by categories 1 or 2 above, the soil must be stabilized and surface runoff controlled by mechanical devices until the plant cover can be restored. To achieve this, a system of contour trenches and gully plugs is constructed and areas of soil disturbed by construction activities are seeded to grasses or planted to trees or shrubs (fig. 5).

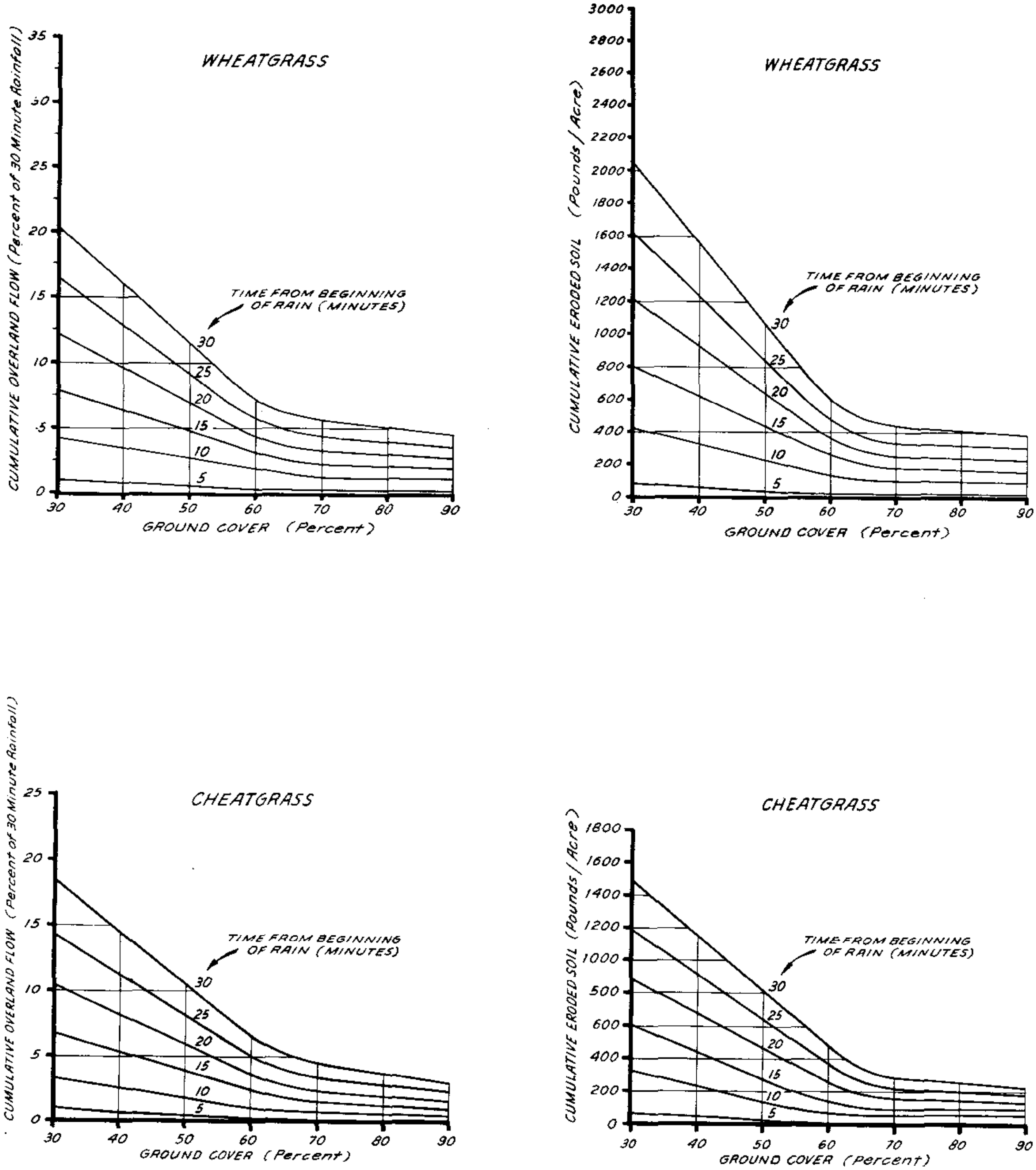

FIGURE 3. — Cumulative overland flow and soil erosion from wheatgrass and cheatgrass sites on soil derived from granite at different ground cover densities by successive 5-minute periods. Based on a simulated rainfall of 1.87 inches for 30 minutes (*12*).

Contour Trenching

The principle of contour trenching as a soil conservation measure is very old, but the use of trenches to secure soil stabilization on high

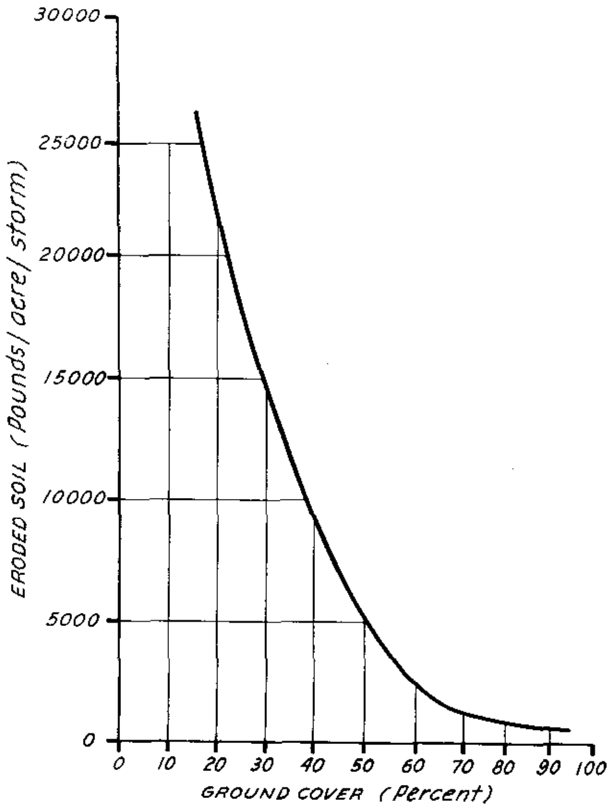

FIGURE 4. — Relation of eroded soil to ground cover density on experimental watershed A, subalpine-herbaceous range, Utah. Based on simulated rainfall of 1.5 inches per hour for 20 minutes (*10*).

mountain watersheds and to prevent floods is relatively new (*11*).

In 1933 the Intermountain Forest and Range Experiment Station, U.S. Forest Service, was given the responsibility of devising the most efficient and effective methods for the control of floods and erosion originating on forest and range lands (*2*). Development of the trenching system to get water into the ground where it falls, thus preventing surface runoff, erosion, and sedimentation, has proved most effective. In addition, the application creates favorable moisture conditions in the soil that hasten the restoration of plant cover needed to stabilize the soil further.

The principle of contour trenching has proved so sound and effective that several thousand acres of badly eroded flood-source areas in the intermountain west have been treated and many more thousands of acres are scheduled for treatment. Since its inception nearly 30 years ago, the criteria guiding application of the contour trenching system and the construction and design techniques have been greatly improved upon. Some of these criteria are discussed here.

Contour trenching is a precision-type job that requires a combination of close analysis of potential surface runoff, recognition of site adaptability, and careful construction. Failure to recognize or give full consideration to any one of these three items can cause failure of the work. Careful consideration of them can provide complete control of surface runoff and erosion from treated areas occasioned by high-intensity summer rainstorms.

The contour trench system consists of a series of zero-grade insloping-type trenches spaced sufficiently close to hold a predetermined amount of surface runoff. Small check dams or baffles are constructed across the trenches at intervals of about 35 feet to segment them. These baffles are slightly lower than the fill-dike to allow water to flow along the trench without overtopping the trench. Runoff calculations are obtained by using runoff curves developed for different vegetation and soil types (fig. 6).

The following formula relates rainfall, trench spacing, and capacity aids in designing contour trench systems for various conditions:

$$\text{Rainfall} \times \frac{\text{Estimated runoff (percent)}}{100} \times \frac{\text{Trench interval (ft.)}}{12} = \text{Trench capacity (cu. ft./lineal ft.)}$$

Considerable care is needed in selecting sites that are adaptable to the contour trench system. Soil depth, mass stability of soils, rock

FIGURE 5. — Contour trench system installed on a deteriorated watershed for flood prevention and watershed protection purposes. Slope gradients vary from 30 to 70 percent. Evaluations made subsequent to construction indicate the trenching system has materially reduced downstream sedimentation.

outcroppings, and slope gradient all influence the decision of whether to trench or not.

Because the trenching system is a device to hold water until it can be disposed of by infiltration, a minimum of soil depth is necessary. Also, soil is necessary to provide a favorable seedbed for the establishment of vegetation on the soils disturbed by trench construction.

Normally, areas that have 24 to 30 inches of soil development above the unaltered parent material can be trenched successfully.

Mass stability of the soil is another factor determining the applicability of the trenching system. Areas with a history of mass soil movement or slumping should be avoided. Likewise, sites having a substratum of impervious clay soils should be avoided even though slumping is not obvious.

The pattern and disposition of rock outcroppings within the headwaters of a drainage also exert an influence on the decision to trench. Since each trench of the system is in itself a reservoir, the trench pattern should be continuous across the slope and extend to the upper limits of the flood-source area. If rock outcroppings at the head of a drainage are contributing to oversurface flows of water and such outcroppings preclude trench construction, there is a possibility that runoff from the upper slope will exceed the capacity of the trench, causing the trench to fail. A similar situation can occur when working across the slope and rock outcroppings prohibit a continuous run of the trench.

Many areas containing rock outcroppings have been successfully trenched. The main point to remember is that each trench must be capable of storing and disposing of the water deposited into it from the land above. Under no circumstance should water from an upper trench be diverted into a lower trench nor should water from a trench be diverted to a natural channel.

Once it has been determined that a site is adaptable for the contour trenching system, construction can begin. Stages of the construction process are shown in figures 7 to 11.

The construction process, although not com-

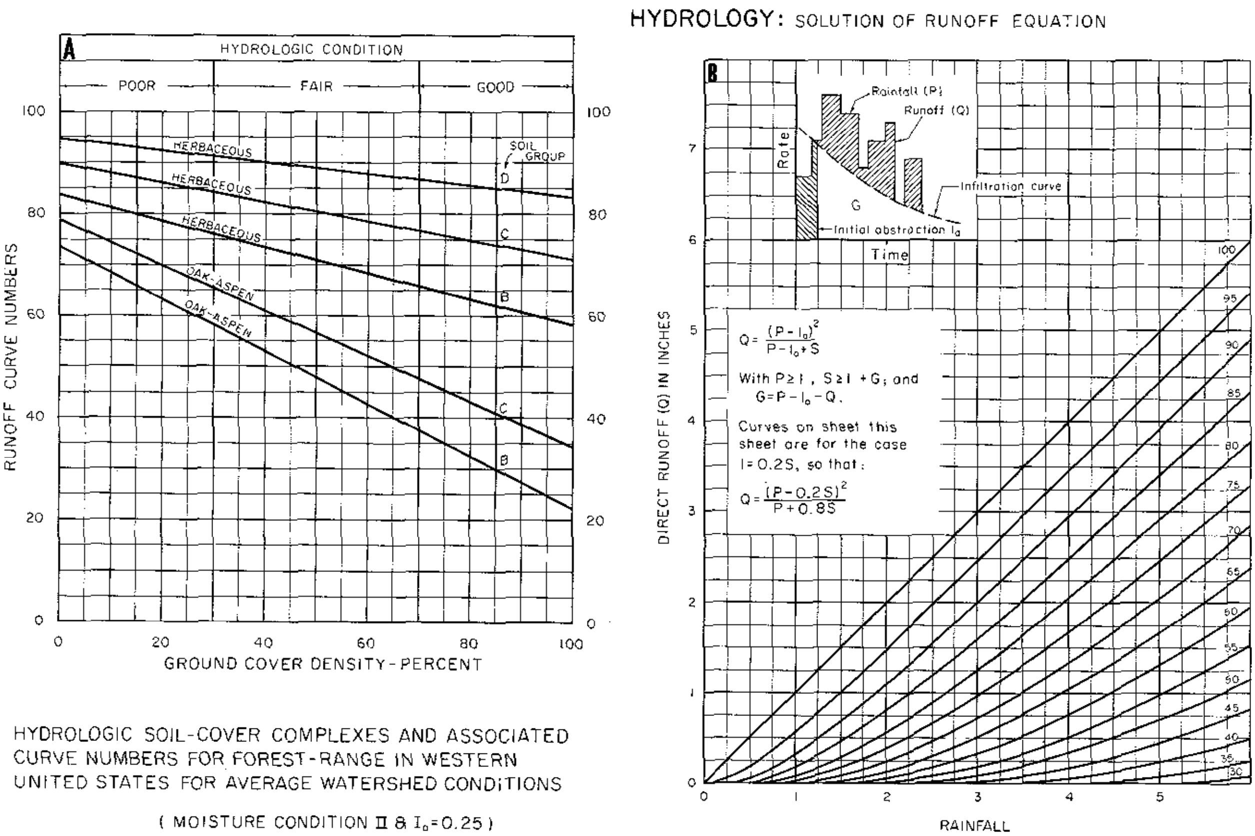

FIGURE 6.—*A*, Based on soil group, vegetal type, and ground cover density, curve number (fig. 6, *B*) is selected for solution of the runoff equation. *B*, With runoff curve number selected from figure 6, *A*, surface runoff can be computed for various rainfall intensities (*13*).

plex, requires an understanding of certain facts involving a knowledge of several skills and disciplines. Failure to apply these skills and disciplines to the specific characteristics of the site to be treated can result in an unsatisfactory job. On the other hand, skillful application can result in a satisfactory job that will provide permanent flood control measures. Some of the more important facets of the construction job are enumerated below:

1. Contour trenching is a precision job, and each trench must be on a zero grade. Accordingly, each trench must be laid out on the contour, with a hand level and common builder's lath for stakes. Stakes must be placed frequently enough that they can be easily followed by the tractor operator and to keep the machine on level grade across undulating terrain. Each high and each low point need be staked to avoid undulations in the trench.

2. The horizontal spacing interval, as determined from the formula, should be fairly

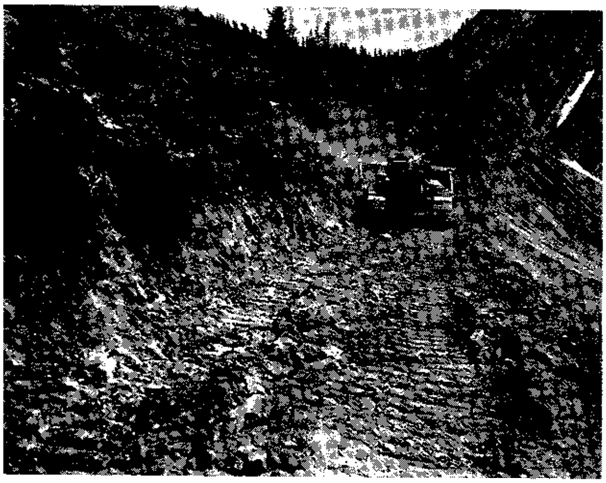

FIGURE 7. — On steep terrain, the first step of contour trench construction is building a level work platform on which the tractor operates. The platform need be no wider than necessary to accommodate the equipment safely.

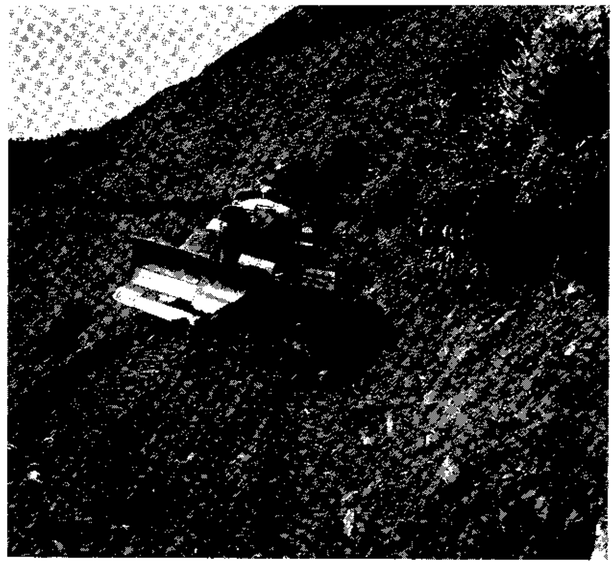

FIGURE 9. — The trench is constructed along the platform by a cut-and-fill operation. With the use of full angle and tilt of the blade, excavated dirt spills under the outer track of the machine, where it is packed to form the outer dike of the trench.

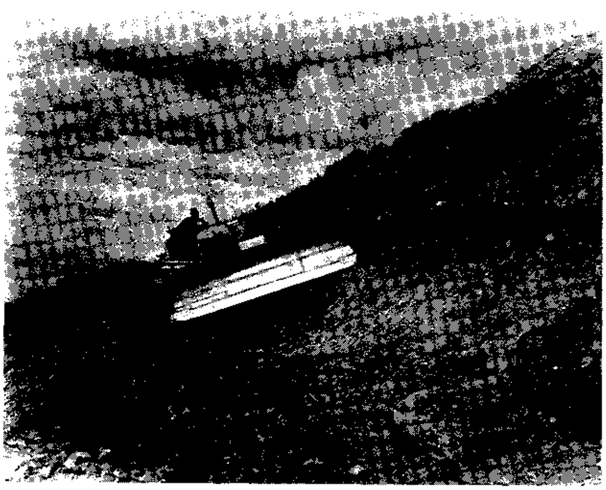

FIGURE 8. — After the platform is constructed, the upper 2 feet of the steep vertical cutbank are knocked down to aid in backsloping.

FIGURE 10. — Trench on 70-percent slope completed to standard except for cross dams or baffles, which are constructed as the tractor backs out.

FIGURE 11. — Completed trench after construction of cross dams or baffles. Trench has a storage capacity of 7 to 10 cubic feet per lineal foot of trench. Cross dams are lower than trench dike, to allow equalization of stored water in trench and to prevent spill over the trench.

constant. To prevent trenches from converging because of increasing slope gradients, staking should commence on the steepest slope to be treated. If slope gradient lessens and the trench interval increases beyond 30 percent, short trenches will be needed to fill in the gap.

3. Powerful crawler-type tractors with full-angle and tilt dozer blades are essential to successful contour trench construction. If the work is in rocky terrain or in tight soils, a rear-mounted hydraulic ripper is recommended. Because most work is done at high elevations where equipment efficiency is less, tractors with over 140-drawbar horsepower are advisable. Experience gained from high elevation work indicates a lower unit cost per lineal foot of trench when larger size equipment is used.

4. Well-trained and competent equipment operators and job supervisors are essential for a successful operation. Several days of training for new crews by personnel experienced in trenching work are advisable. Inexperience and improper job supervision can result in a situation worse than that originally existing.

5. Live watercourses and seep areas should be avoided. Contour trenches are designed primarily for collecting and disposing of over-the-surface flows of water from rainstorms. They will not function properly if continually saturated from live water sources.

6. All areas of soil disturbance caused by construction activities need to be revegetated with adaptable plant species. The continued effectiveness of the trenching system depends upon stabilizing the cut-and-fill slopes caused by construction as well as the establishment of adequate ground cover between the trenches. In most instances, natural revegetation occurs rapidly between trenches, since soil movement has been arrested and soil moisture conditions improved.

Effectiveness of the Contour Trenching System

A few quantitative and many qualitative evaluations have been made to determine the effectiveness of contour trenching to control flooding (figs. 12 and 13). Perhaps the most exhaus-

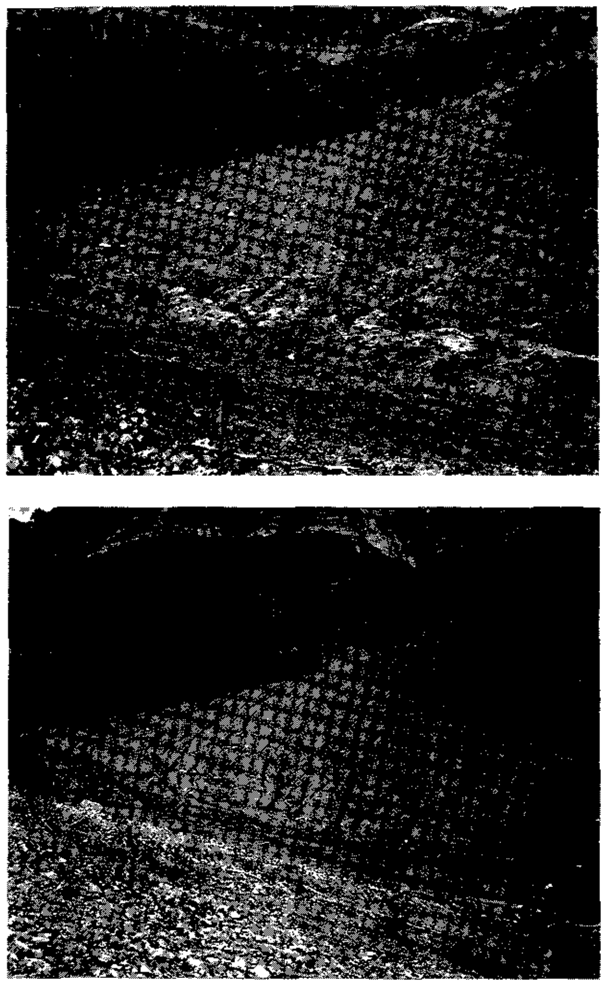

FIGURE 12. — Top, severely depleted watershed in Upper Dry Creek, with ground cover density of less than 40 percent in 1957. Bottom, the same area after a high intensity summer rainstorm in 1958. Oversurface flow of water established a gully pattern, concentrated runoff, and contributed to downstream flood and sedimentation.

tive and best instrumented study was conducted in the Davis County Experimental Watershed, Utah, where an intensive system of trenches was constructed in the early 1930's.

The nonflooding behavior of these rehabilitated watersheds has been evaluated (*5*) and is particularly significant when one considers that during two storms greater rainfall rates were attained than had ever been recorded in the State of Utah. During a rainfall of 1.14 inches on July 10, 1936, a rate of 5.04 inches per hour for a 5-minute period was registered. On the evening of August 19, 1945, when 1.09 inches of rain fell, rates at several of the recording gages exceeded 6.00 inches per hour for a 5-minute period, and at one a rate of 6.80 inches per hour was registered (table 1).

The storm on July 10, 1936, produced no floods from the treated watersheds, but the same rainfall caused mud-rock floods in four drainages within the area that had not been treated. Rehabilitated watersheds again on August 19, 1945, when subjected to the unusually high rainfall rate of 6.00 inches per hour, disposed of the precipitation without erosion or runoff of flood proportions.

The findings of the Davis County evaluations have been further corroborated by numerous field investigations of comparable watersheds during and immediately after high intensity rainstorms. In all investigations, treated watersheds were compared with contiguous nontreated watersheds. Duration and intensity of precipitation in each watershed were judged to be comparable. In every case it was found that contour trenches significantly reduced surface

FIGURE 13. — Left, system of contour trenches constructed on Dry Creek flood-source area in fall of 1958. Trenches break up gully pattern. Right, Dry Creek area 3 years after installation of contour trench system (1961). Seeded grasses well established on soils disturbed by construction activities. Improved soil moisture condition between trenches have contributed to reestablishment of native vegetation.

TABLE 1.—*Summer storm rainfall and resultant overland flow and soil losses from Parrish plots, Davis County Experimental Watershed, Utah*

Storm dates	Total rainfall	Nonflood-source area		Flood-source area		Artificially denuded	
		Overland flow	Soil eroded	Overland flow	Soil eroded	Overland flow	Soil eroded
	In.	*Pct.*	*Cu. ft./acre*	*Pct.*	*Cu. ft./acre*	*Pct.*	*Cu. ft./acre*
July 10, 1936	1.14	0.7	0	42.8	181.5		
July 16, 1936	.89	.4	0	43.4	153.6		
July 28, 1936	1.21	.2	0	33.0	83.2		
Aug. 18–20, 1945	3.09	.5	0	24.3	92.8		
July 10, 1950	.70	.9	0	12.6	(1)	61.3	215.3
Aug. 19, 1951	1.15	.6	0	8.4	(1)	46.6	186.2
Aug. 4, 1954	1.17	.4	0	3.8	(1)	31.3	91.3
Aug. 19–20, 1959	.98	.6	0	2.3	(1)	43.7	98.4
Sept. 3, 1960	.63					31.0	110.0
Aug. 25, 1961	.64					28.6	89.2
July 13–24, 1962	2.59					39.0	401.3

[1] Trace.

water runoff into stream channels, reduced peak discharge of streams, and effectively reduced soil erosion and resultant downstream sedimentation.

Summary

Several methods of obtaining soil stabilization on high mountain watersheds are available to the land administrator. These are (1) intensive management practices, (2) revegetation coupled with intensive management practice, and (3) contour trenching. Each method recognizes the fundamental relation existing between land cover and hydrologic behavior and reflects the importance of maintaining the productivity of the site for the production of forage, fiber, wildlife, and recreation.

The application of each method requires a careful analysis of the (1) geologic norm, (2) type of flooding, (3) watershed protection requirements, and (4) adaptability of the site for treatment.

Of the methods described, contour trenching has proved most effective in controlling flooding, and sedimentation occurring from badly deteriorated mountain watersheds. The application of this method is not a panacea for all flood-source areas but has proved effective in controlling flooding from badly deteriorated lands occasioned by high intensity summer rainstorms.

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EMERGENCY MEASURES TO CONTROL EROSION AFTER A FIRE ON THE SAN DIMAS EXPERIMENTAL FOREST

[Paper No. 19]

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Southern California is in urgent need of better solutions to its flood and erosion problems. Its steady population growth has resulted in intensive urban development on the debris cones at the mouths of mountain canyons. The Mediterranean climate, which attracts thousands of newcomers to the State, favors the growth of a highly inflammable vegetative cover (chaparral) on the mountains. It also frequently produces weather conditions that promote widespread wildfires. Such fires damage watersheds on steep mountain slopes that often lie above densely populated cities. This hazard justifies flood and erosion control measures that may not be necessary in most parts of the United States.

The U.S. Forest Service is conducting a broad research program in southern California to test several flood and erosion control measures for use after fire on mountainside slopes and in small tributary channels. This study is in progress at the San Dimas Experimental Forest, which has been devoted to watershed management research since 1933. Owing to the difficulty of burning watersheds under controlled

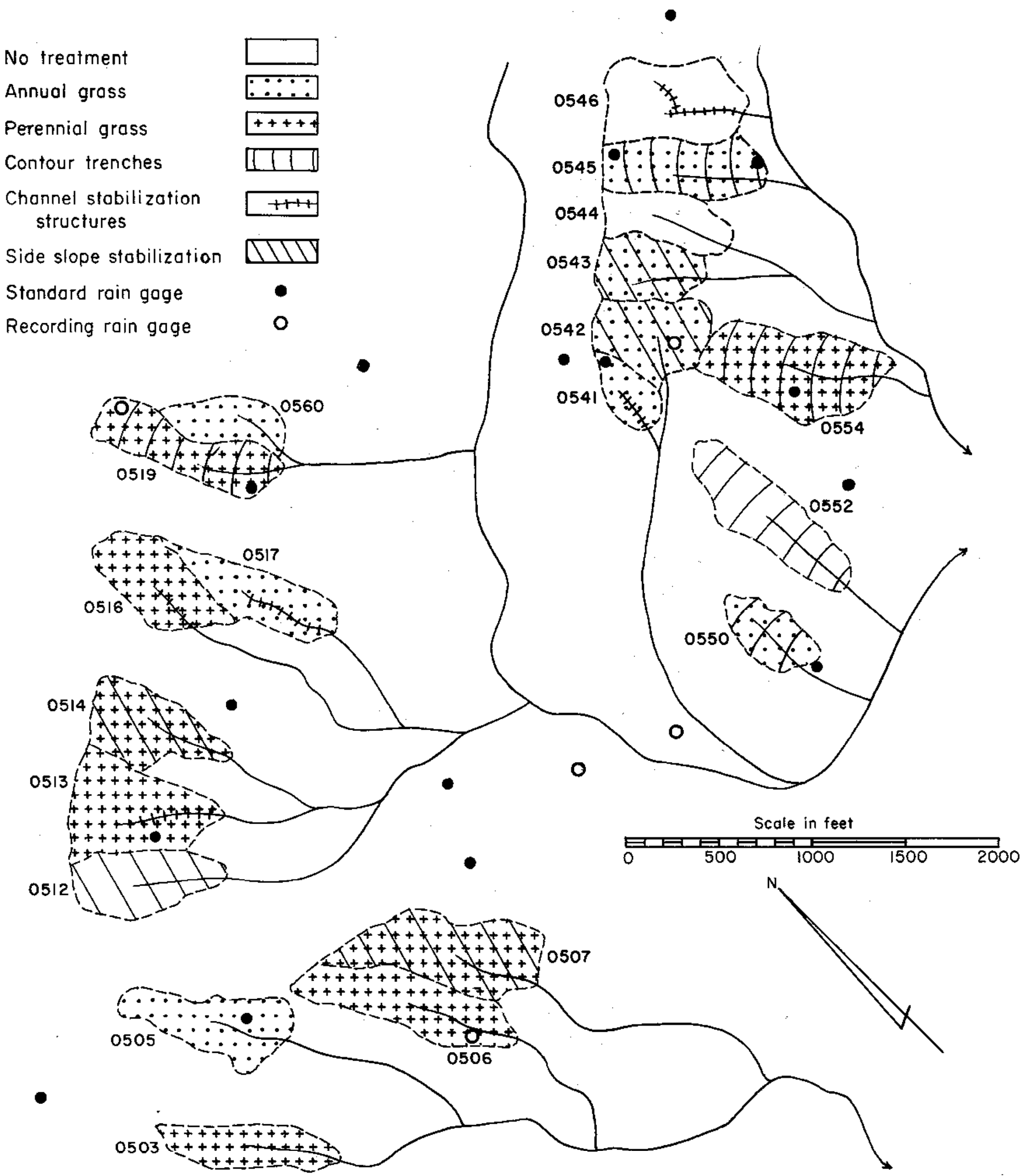


Figure 1. — Location of treatments on experimental watersheds testing erosion control measures.

conditions, earlier studies of erosion after fire had been limited to plots or to analyses of the effect of wildfires in the area.

In 1960 a wildfire swept most of the 17,000-acre Experimental Forest. It destroyed much valuable research underway, but it also presented an opportunity to study flood flows and erosion rates from completely burned watersheds. To exploit this opportunity, Federal, State, and county agencies undertook a cooperative emergency research program.

This paper reports on a continuing study begun during the dry winter of 1960-61, and covers data collected during the four major storms of the 1961-62 season.

Methods

We are seeking to obtain a quantitative evaluation of several mechanical and vegetative land treatments as "first aid" for burned chaparral watersheds.

Selection of Watersheds

The 20 watersheds used in this study were chosen to be as similar as possible in size (about 5 acres), shape, aspect, and erodibility (fig. 1). Even so, considerable variation existed within the group. To reduce the effect of this variability upon our study, we grouped watersheds into five erodibility classes based on three independent appraisals of their relative erodibilities.

The appraisers used slope, channel gradient, rockiness, and amount of colluvial soils as indicators of the relative erodibility of the watersheds. Treatments were then assigned to the watersheds so that apparent erodibility was balanced among treatments; that is, no treatment could be applied to all the high erodibility groups.

Instrumentation

The streamflow from each experimental watershed is measured in a 30-foot trapezoidal flume. Debris is trapped and measured behind earth-fill dams that can hold about 60 cubic yards per acre. Precipitation is measured in 5 intensity rain gages and 16 nonrecording gages distributed throughout the study area.

Selection of Treatments

In southern California broadcast sowing of annual grasses is the most widely used method of rehabilitating watersheds after a fire. Eight of the watersheds were sown to a mixture of annual grasses (Wimmera 62 ryegrass, *Lolium rigidum:* and blando brome, *Bromus mollis*) — four at the rate of 2.5 pounds per acre and four at 20 pounds per acre.

Perennial grasses — often suggested for use — were also tried. Eight watersheds were seeded to a mixture of perennial grasses (intermediate wheatgrass, *Agropyron intermedium;* pubescent wheatgrass, *A. trichophorum;* tall wheatgrass, *A. elongatum;* hardingrass, *Phalaris tuberosa stenoptera;* big bluegrass, *Poa ampla;* smilograss, *Oryzopsis miliacea*) and small amounts of the annuals, blando brome and Wimmera ryegrass — four at the rate of 4.5 pounds per acre and four at 20 pounds per acre. Four watersheds were left unseeded.

The areas sown to perennials were sprayed with 2,4-D and 2,4,5-T during the springs of 1961 and 1962 to help establish perennial grass by reducing competition from brush species.

Precipitation after sowing was light (total of 6.29 inches, 16 storms) during the 1960-61 season. Consequently, we had scant cover from seeded species. To correct this shortage, broadcast sowings were repeated in the fall of 1961.

In addition to the broadcast sowings, three mechanical erosion control measures were being tested. Chosen from measures currently in use in Western United States, each treatment combats the movement of water and soil at a different place along the route from raindrop impact to the debris basin. These mechanical treatments were distributed among the watersheds orthogonal to the broadcast sowings (see tables 2 and 3).

Side slope stabilization. — This treatment consisted of planting barley and fertilizer in hand-hoed rows at 2-foot intervals on the contour (150 pounds of barley and 140 pounds of diammonium phosphate per acre). Its objective was to create closely spaced barriers to the overland flow of water and debris. This treatment was compared with other mechanical measures because we were merely using plants as a means of obtaining the desired pattern of obstructions. The barley plants undoubtedly also promoted infiltration and reduced rainfall impact.

Contour trenching. — This method is being used in Idaho and Utah under somewhat different conditions of climate and soil. It has the effect of breaking up surface flow, increasing depression storage, encouraging the infiltration of storm runoff, and trapping sediment and debris. In this study the trenches were put in as close together as the terrain would permit (40 feet on the gentler slopes to 90 feet on the steeper slopes). The trenches provided storage for about 3 inches of rainfall. Storms of large size or of very high intensity may overtop the trenches. In order to provide for this situation, each trench was drained either into the stream channel or into another trench below. This drainage system consisted of about six 12-inch half-round downspouts for each treated watershed.

Channel stabilization. — Channel stabilization was attempted by building small gravity channel check dams from soil cement. In the watersheds so treated, a system embodying both natural and artificial controls was designed to stabilize the channel in those portions with less than 30 percent normal gradient. This treatment attempts to lessen channel downcutting and, thereby, helps stabilize the toe of colluvial soils resting on side slopes.

The Analysis

A multiple linear regression model was used in analyzing the data. Nine separate analyses were made — each based on the flood peaks or debris production of an individual storm, except one analysis that used total annual debris production as a dependent variable. Several continuous variables were included in analyses in addition to the class variables used to express treatment effects. The vegetation variable expressed differences in natural vegetative recovery of the watersheds. The other continuous variables gave a further description of the inherent differences of the watersheds. The model tested was:

$$Y = a + \sum_{i=1}^{4} b_i M_i + \sum_{i=4}^{9} b_i V_i + b_{10} N + b_{11} R + b_{12} S + b_{13} C + b_{14} A$$

in which Y is the dependent variable expressed as cubic feet per second per acre for flood peaks or cubic yards per acre for debris production.

a is the mean response of the experimental watersheds.

M_i are the four mechanical treatment variables taking a value of 0 or 1, depending on the presence or absence of the individual treatments.

V_i are the five vegetative treatment variables treated in the same manner as the M_i.

N is the vegetative cover of the watersheds due to the residual native vegetation and the recovery of native plants (includes burned brush stems and litter). The cover was obtained by using visual estimates of cover on clusters of four 1-square-foot quadrats distributed in a stratified (on aspect) random fashion in the watersheds. About 140 square feet of each watershed was sampled. Expressed as a percent, the native plant cover at the time of the first two storms ranged from 3.7 to 16.5 percent, with a mean value of 7.1 percent. Estimated native cover for the third and fourth storms ranged from 2.3 to 29.9 percent, with a mean of 13.2 percent. This variable was included to allow for differences in natural vegetative recovery of the watersheds.

R is the percent of the soil surface covered by rocks greater than one-half inch in diameter. This variable ranged in value from 0.4 to 15.3. The mean was 7.4 percent. This variable was intended to index the effect that armoring the surface of the watershed with rocks might have on erodibility and storm runoff.

S is the mean slope of the watershed as determined by averaging the slopes at the vegetative sampling plots. This variable ranged from 37 to 69 percent with an average of 54 percent.

C is the mean channel gradient of the watersheds measured from 1:4000 scale aerial photographs. Gradients vary from 17 to 44 percent with an average of 27 percent.

A is the area of the watershed above the flume for flood peak analyses and the area above the debris dam for debris production analyses. The average area above the flumes is 4.67 acres (range: 1.38 to 7.31 acres). The average area above the debris dam is 5.68 acres (range: 2.26 to 9.57). As Anderson reiterated in a recent paper "most of the variables which we neglect to put in our analyses and many of our mistakes in choice of functions hide in the area variable."[1] We included area in our analyses as index-of-ignorance variable. In each of the regression analyses four models were tested for each set of dependent variables: The first analysis included all independent variables; the second omitted the continuous variable; the third omitted the vegetative treatment variable; and the fourth omitted the mechanical treatment variables.

[1] ANDERSON, H. W. A MODEL FOR EVALUATING WILDLAND MANAGEMENT FOR FLOOD PREVENTION. Pacific Southwest Forest and Range Expt. Sta. Tech. Paper 69, 12 pp. 1962.

Results [2]

Storms

Four of the 22 storms during the 1961-62 season were long and intense enough to produce responses in the experimental watersheds that could be analyzed (table 1). Analysis of the catch of rain gages indicated there were no appreciable differences in the amounts or intensities of rainfall among the watersheds. Consequently, rainfall variables were not included in the regression analyses. The average concentration time of the watersheds is about 8 minutes. The 10-minute intensities shown in table 1 have recurrence intervals of 2.1 years, 1.1 years, 0.5 year, and 0.8 year. The recurrence intervals for the maximum 24-hour precipitation are 0.5 year, 0.6 year, and 1.0 year.

TABLE 1.—*Rainfall intensities and amounts for major storms of hydrologic year 1962* [1]

Storm date	Maximum rainfall intensity for duration of—						Total storm precipitation
	5 min.	10 min.	15 min.	20 min.	30 min.	60 min.	
	In./hr.	*In./hr.*	*In./hr.*	*In./hr.*	*In./hr.*	*In./hr.*	*Inches*
Nov. 20, 1961	2.16	1.70	1.38	1.21	1.16	.99	2.47
Nov. 30 to Dec. 3, 1961	1.80	1.32	1.09	.96	.91	.73	4.58
Jan. 20 to Jan. 23, 1962	1.38	1.10	.92	.82	.79	.70	4.75
Feb. 7 to Feb. 12, 1962	1.59	1.24	.96	.81	.63	.39	9.27

[1]Average of gages in vicinity of study watersheds.

Storm of November 20, 1961

The first storm of the season had rainfall of high intensities. This downpour resulted in high flood peaks and heavy debris from the watersheds with no mechanical treatment and in moderately high peaks and moderate amounts of debris from watersheds modified by channel, check dams, or treated side slopes. The responses were small from the contour-trenched watersheds, because the storm failed to exceed the storage capacity of the trenches. During this storm, the channel-stabilizing dams continued to be filled with debris. Thus, additional channel storage was available that, consequently, reduced the flood crests of these watersheds.

Storm of November 30 to December 3, 1961

During the second storm of the season, most of the channel structures filled with debris to the level of the spillway. This storm was the first since the study was begun to exceed the storage capacity of contour trenches. Several contour trenches failed, causing an increase in flood peaks and debris production from these watersheds, although rainfall was less intense during this storm (table 1).

Storm of January 20 to 23, 1962

The third storm was the gentlest and failed to reveal any dramatic effects of treatment differences. The general relations between mechanical treatments appear to be continuing.

Storm of February 7 to 12, 1962

The last storm of the season lasted 5 days and provided about two to four times as much precipitation as any other storm (table 1). During most of the storm, the rain fell at relatively low intensities (0.25 in./hr.). The peak flows were in response to short bursts of high-intensity rainfall on the fourth day of the storm.

Additional contour trenches failed during this storm, because storage capacity was greatly exceeded. With rare exceptions check dams that stabilized channels were filled with debris. In many cases, debris cones extend upstream to the toe of the next higher dam, indicating that the design profile had been reached.

The channel-stabilized watersheds had the highest flood peaks, continuing what appears to be a trend toward higher relative crests in comparison with the other treatments. The watersheds with stabilized side slopes, on the other hand, seem to be maintaining lower relative peaks. In this storm their average was about two-thirds the average of all the other watersheds.[3]

Seasonal Results

Two measures of practical importance to the land manager are the total annual production of debris (the debris to be disposed of, table 2) and the highest flood peak for the year (the peak to be guarded against, table 3).

As the row means in tables 2 and 3 show, watersheds seeded to low density perennial grasses had higher peaks and heavier debris production. Debris production appears to have been reduced by the high density sowings. But whether this is a true effect is questionable, because the vegetative cover from seeded grasses in all watersheds was very low. The best cover was obtained in the watersheds having high density ryegrass where the seeded annual grass cover amounted to 1.8 percent in the spring of

[2] The authors wish to acknowledge the assistance of Donald W. Seegrist, statistician, Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif., for conducting the regression analyses and statistical tests.

[3] Detailed data on flood peaks and debris production for each storm are available from the Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, 110 North Wabash Avenue, Glendora, Calif.

TABLE 2.—*Total debris production by treatments during hydrologic year 1962*

Broadcast sowing treatments	Mechanical treatments				
	No mechanical treatment	Contour trenches	Channel stabilization	Side slope stabilization	Mean [1] response
	Cu.yd./acre	*Cu.yd./acre*	*Cu.yd./acre*	*Cu.yd./acre*	*Cu.yd./acre*
No broadcast seeding	29.0	16.7	13.8	9.9	17.4
Low density annual grass	39.7	1.8	25.4	5.8	18.2
High density annual grass	31.4	6.7	8.4	9.1	13.9
Low density perennial grass	35.6	26.6	26.4	8.6	24.3
High density perennial grass	26.0	6.9	23.3	8.7	16.2
Mean response [2]	32.3	11.7	19.5	8.4	18.0

[1] Row effects significant at the 0.23 level.
[2] Column effects significant at the 0.03 level.

TABLE 3.—*Highest flood peaks by treatments observed during hydrologic year 1962*

Broadcast sowing treatments	Mechanical treatments				
	No mechanical treatment	Contour trenches	Channel stabilization	Side slope stabilization	Mean [1] response
	Cu.ft./sec./acre	*Cu.ft./sec./acre*	*Cu.ft./sec./acre*	*Cu.ft./sec./acre*	*Cu.ft./sec./acre*
No broadcast seeding	2.1	1.7	1.2	3.8	2.2
Low density annual grass	6.0	1.6	2.8	1.1	2.9
High density annual grass	2.5	1.4	3.3	1.8	2.2
Low density perennial grass	3.6	7.4	7.7	2.5	5.3
High density perennial grass	3.9	0.7	3.0	1.8	2.4
Mean response [2]	3.6	2.6	3.6	2.2	3.0

[1] Row effects significant at the 0.23 level.
[2] Column effects significant at the 0.64 level.

1961 and 9.9 percent in the spring of 1962. Average total vegetative cover, exclusive of barley, on all watersheds amounted to 7.7 percent and 17.3 percent for the same periods, the majority of it being native species. In watersheds with the side-slope treatment, barley accounted for another 7.0 percent of cover in the spring of 1961 and 13.9 percent in the spring of 1962.

The mechanical treatments produced more striking contrasts, particularly in debris production. Debris yield from the watersheds with no mechanical treatment averaged about 30 cubic yards per acre when allowance is made for the effect of the continuous variables (table 4). The side-slope-stabilized watersheds yielded about 35 percent of this amount, the contour-trenched watersheds 40 percent, and the channel-stabilized watersheds 65 percent. The highest peaks (table 3) form two groupings according to mechanical treatment: (1) those from watersheds with side-slope control (contour trenches and furrow planting of barley), and (2) those from watersheds without control (channel stabilization and no mechanical treatment). This grouping held during each of the four storms studied.

The regression equations calculated from each of these two analyses are shown in table 4. The debris regression accounted for 90 percent of the variability in the data (i.e., $R^2=0.90$) and the other regression accounted for 74 percent of the variability in peak flow. Figures 2

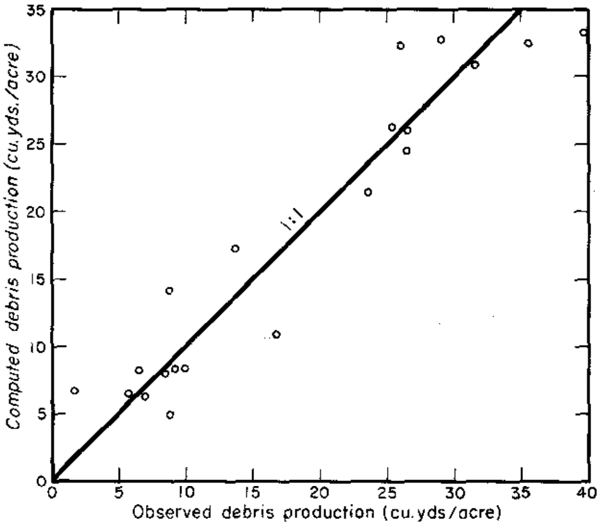
TABLE 4.—*Regression equations for predicting tota annual debris production and highest annual flood peak*

Total debris regression coefficients	Peak flow regression coefficients	Independent variables
Cu. yd./acre	*C.f.s./acre*	
$Y=+7.48$	$Y=-2.31$	Constant.
$+11.99$	$+0.57$	If no physical treatment.
-5.96	-0.45	If contour trenched.
$+1.40$	$+0.78$	If channel stabilized.
-7.42	-0.90	If side slope stabilized.
-1.75	-0.82	If no broadcast sowing.
$+1.51$	$+0.10$	If sown to low density annual grasses.
-4.27	-0.60	If sown to high density annual grasses.
$+7.03$	$+2.16$	If sown to low density perennial grasses.
-2.53	-0.83	If sown to high density perennial grasses.
$+0.04x$	$-0.08x$	Native vegetative cover.
$+0.78x$	$+0.10x$	Exposed rock.
$+0.35x$	$+0.07x$	Slope.
$-0.37x$	$+0.09x$	Channel gradient.
$-0.73x$	$-0.18x$	Area.

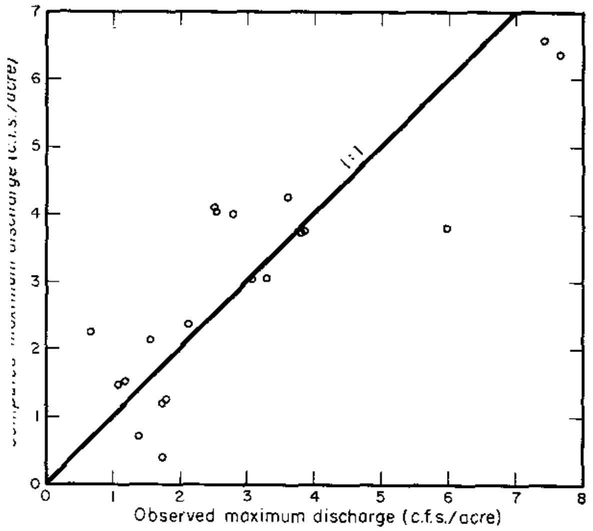
and 3 illustrate the precision of our predictioı equations.

Discussion and Conclusions

The perennial grass seeding appears to b unsuited to our soils and climate. The poor es tablishment of perennial grass (never mor than 1.7 percent cover in this experiment could not offset the reduction in native cover owing to herbicidal chemicals needed to assis that establishment. Watersheds seeded by lov



'IGURE 2.—Actual vs. predicted annual debris production (1962).



IGURE 3.—Actual vs. predicted highest annual flood peak.

ensity perennials tended to have higher flood eaks and greater debris yields than the other atersheds.

Annual grass seeding, on the other hand, may e justified as an emergency erosion control easure. It had no apparent effect on flood eaks, but may have helped reduce debris. Due the low cost of this treatment (about 1/100 e cost of the mechanical treatments) and the se and speed with which it can be applied, nd managers appear to be justified in gambling on the success of the grass crop.

But there are difficulties in relying solely on broadcast seeding for erosion control in arid regions. To grow a grass crop, an area must have enough rainfall, properly distributed. Storms must be of several days' duration for initial establishment of grass and spaced every few weeks for continued growth. Dry autumn winds, common to this area, can disperse the seed, causing a patchy catch. Also, the grass rarely provides enough cover to do much good during the first year.

We found that the first year's seeding was almost a complete failure. We reseeded the watersheds in the fall of 1961 and had a respectable response by the third and fourth storms. By July 1962, the watersheds of high density annual grass had an average cover of 10.3 percent. The seed produced by this grass promises greater effectiveness from the treatment during the coming season than past performance.

Contour trenches do not appear suited to the terrain and climate of the test watersheds, although the rather limited data do not clearly reflect this fact. By the end of the 1962 season all watersheds had several broken trenches, with little likelihood that the eroding breaks could heal before they produce large amounts of debris. The trenches were necessarily underdesigned because of the steepness of the watersheds. That is, they were not spaced closely enough to provide sufficient storage for the runoff from larger storms. The test results should not be interpreted to mean that contour trenches would be ineffective if they had adequate storage. Our experience during the November 20 storm indicates that closely spaced trenches can be eminently successful in controlling erosion and in reducing peak discharge.

While trenching may not be a dependable control method under our conditions, an increase in depression storage on the side slopes would be highly effective if a method were used that was not so subject to failure. For this reason the trenches in three watersheds were repaired and strengthened so that the effects of increasing side-slope storage could be studied further in future seasons.

The reduction in debris obtained in the channel-stabilized watersheds is greater than the amount currently used to compute cost/benefit ratios for projects with this erosion control measure. However, the associated higher flood peaks argue for a closer look at this erosion control measure.

In our small watersheds, the increase in peaks may come from reduced channel roughness and shorter channel lengths caused by debris filling the rough crooked channels between the check dams. This effect would probably not be so pronounced in larger watersheds. In our case, however, the storage of debris behind the stabilizing dams during this season was probably a much larger fraction of the total debris produced than in large watersheds. These ambiguities point to a need for further study of this treatment, particularly in larger watersheds.

Side-slope stabilizing by contour furrow planting appear to be the most effective erosion control measure. But the expected effective life of this treatment is only about 4 years. Also, side-slope stabilization is difficult to establish on rapidly eroding areas, such as dry erosion chutes or steep faces undergoing rapid weathering. However, in the majority of cases these limitations may not be serious. Usually most of the area in any watershed can be treated. Using the estimates of Rowe, Countryman, and Storey [4] of debris after fire, with a recurrence of fire in 30 years, we find that 67 percent of a watershed's erosion takes place during the 4 years that the treatment for side-slope stabilization usually persists under conditions in southern California.

The relative superiority of the side-slope-stabilized and contour-trenched watersheds over the channel-stabilized watersheds supports the thesis that, immediately after a fire at least, erosion control measures that prevent the concentration of water or debris are most effective. Barley planted to help stabilize side slopes also provides considerable protection against raindrop impact. From these tests we conclude that preventing the initiation of erosion is the key to postfire erosion control.

[4] Rowe, P. B., Countryman, C. M., and Storey, H. C. HYDROLOGIC ANALYSIS USED TO DETERMINE EFFECTS OF FIRE ON PEAK DISCHARGE AND EROSION RATES IN SOUTHERN CALIFORNIA WATERSHEDS. U.S. Forest Service Pacific Southwest Forest and Range Expt. Sta., 49 pp., illus. 1954.

VEGETATIVE CONTROL OF STREAMBANK EROSION

[Paper No. 20]

By Donald A. Parsons, *hydraulic engineer, USDA Sedimentation Laboratory, Soil and Water Conservation Research Division, Agricultural Research Service* [1]

Vegetation may protect a streambank in at least three ways. Perhaps the most important of these is the reduction of water speeds and tractive forces at the soil surface to a value below that required to cause erosion. Second in importance is, perhaps, the protection given to the bank material as a buffer against ice, logs, and other transported materials. The stalwart barrier of trees standing along the edge of a stream prevents the impact of the transported materials with the soft material of the bank. Or, in another way, the tough but pliant shrub-type materials, bending with the forces involved, act as skid surfaces for the transported materials as they are deflected by the banks of streams of all sizes.

Third, close-growing vegetation will contribute to bank stability, within a narrow range of conditions, by inducing deposition. Subsequent to a rare flood that has caused damage but not complete destruction to the vegetative cover, the deposition that occurs in minor floods helps to maintain the bank.

Since the ability of the flood flows to erode the boundary is related to the water speeds near the boundary, it is instructive to measure velocity variations in a vegetated waterway. W. O. Ree (*6*) did this for 8-inch long, dormant bermudagrass. His diagram is reproduced in figure 1, along with the velocity distribution in a comparable, uniform bare channel. The vegetation

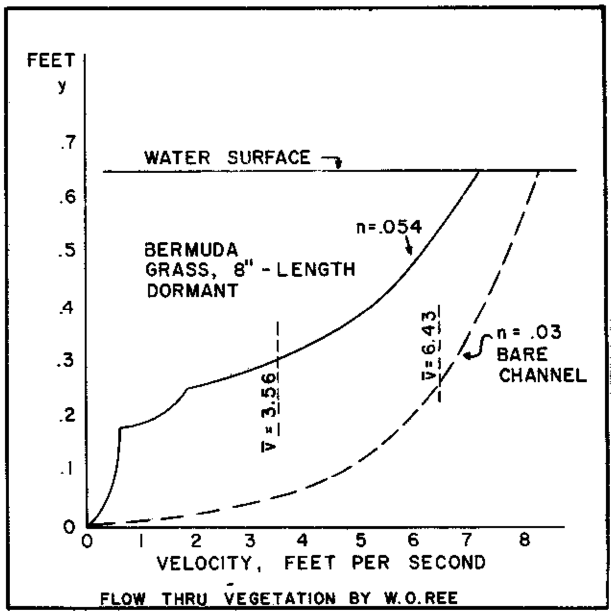


FIGURE 1.—Flow through vegetation (after W. O. Ree).

markedly reduces the water speeds near the soil surface. The rate of change of velocity with distance from the boundary also is less near the boundary with vegetation than without, indicating that the fluid shear stress at the boundary is therefore lower.

These low rates of change of velocity near the ground surface and the higher rates of change

[1] Research in cooperation with the University of Mississippi and Mississippi State University.

above the bent, waving grass suggest that the drag or tractive force is divided into two parts. The smaller part in this instance is at the ground surface; the larger part is on the grass tops, transmitted through the stems to the soil mass in contact with the roots.

These results and concepts are important to the understanding of the true functions of vegetative covers. Such an understanding permits a determination of the qualities that suitable vegetative materials should have.

Lessons From the Spartanburg, S.C., Data

As a further aid to judgment of the pertinent qualities of vegetation, an analysis is here made of data from bermudagrass channel flows at the Outdoor Hydraulic Laboratory operated by the Soil Conservation Service near Spartanburg, S.C., for the period 1936-41.

The conditions of the vegetation, the channel geometry, and the hydraulic features of the tests have been published by Ree and Palmer (7), but the author has taken the liberty of making the following additional interpretations of these data.

Figures 2 and 3 demonstrate that an empirical relationship of variables is found that well represents most of the flows for widely differing channel and vegetative conditions. The formula is for Chezy's C.

$$C = 23 \log Re + A \log \frac{hc}{6500} - 98 \qquad (1)$$

$V = C(RS)^{1/2}$=mean velocity; R=hydraulic radius; S=energy gradient; $Re = VR/\nu$=Reynolds number; h=average length of the vegetation top growth, inches; c=the number of stems per square foot; A is a parameter dependent upon the stage of growth and other conditions of the vegetation. Inclusion of the Reynolds number implies that viscosity was a factor affecting the depth and velocity. This is not known, and the data are hardly suitable for determining this.

Figure 4 shows the influence of the total length of bermudagrass per square foot, hc, on Chezy's C, and the manner of derivation of A. Figure 5 shows the variation in A with time of year and state of the vegetation. The retarding effect of the vegetation and therefore its ability, in part, to protect the soil surface, is shown by these two figures to be dependent upon the height and count of the grass and upon whether

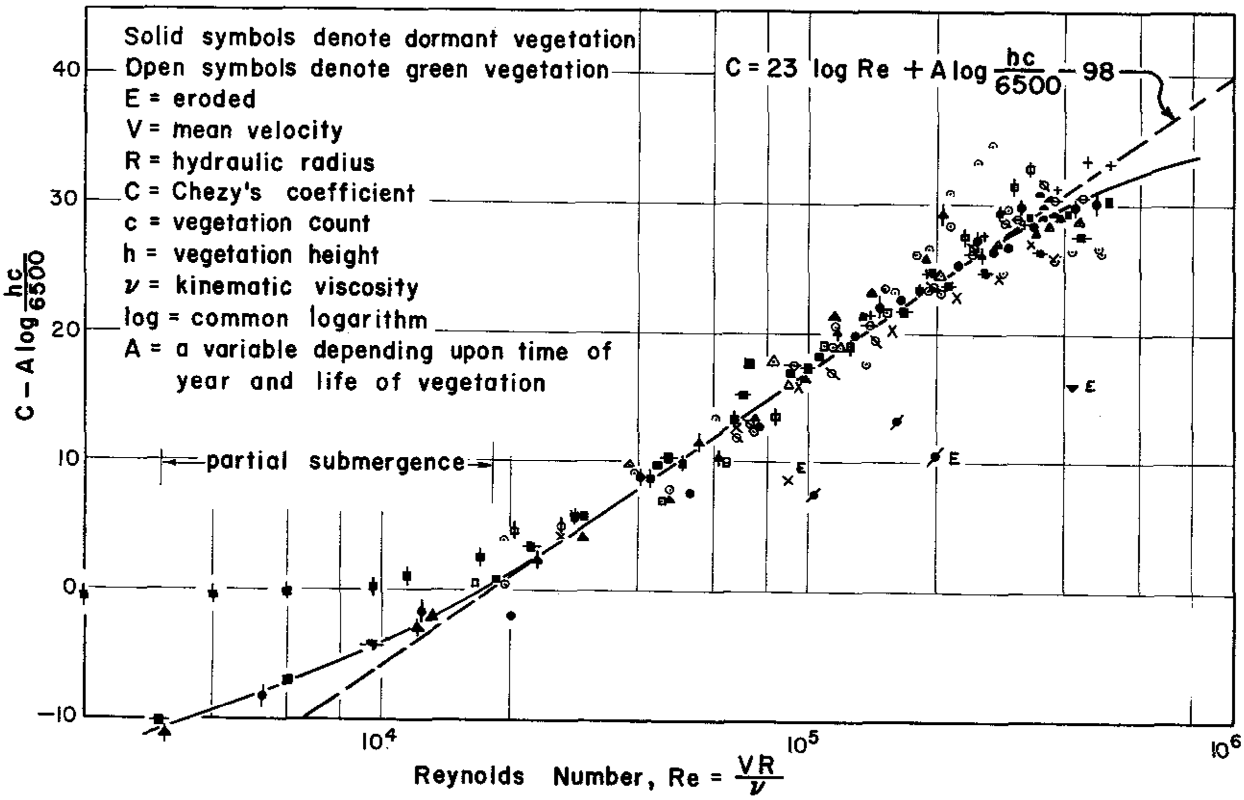


FIGURE 2.— Bermudagrass channels, Spartanburg, S. C.

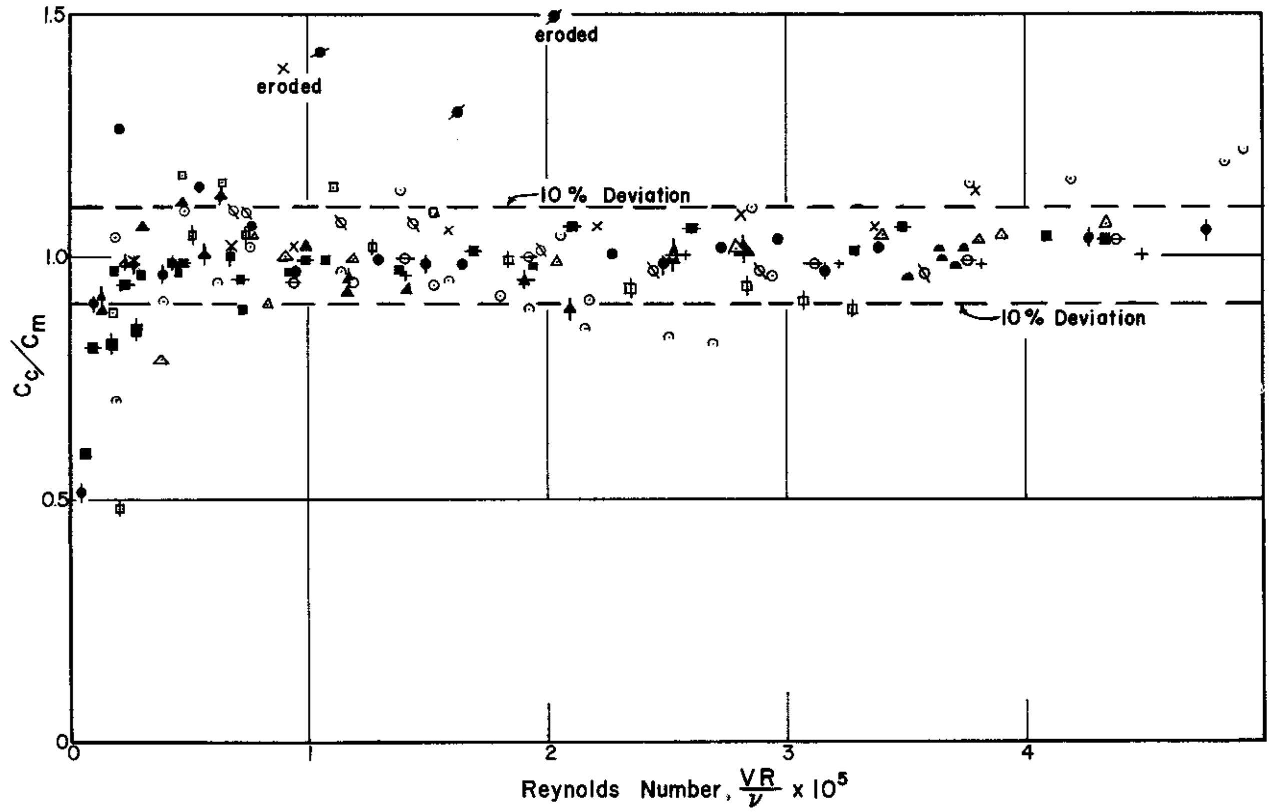


FIGURE 3. — Ratio of calculated to measured values of Chezy's *C*.

the grass is green or dormant. Figure 5 also shows that, other things being equal, the vegetation is most effective when it is young, sturdy, and resilient. After it is killed in the fall, a progressive decrease in effectiveness occurs with time. Its effectiveness is least in late winter and early spring.

Observations

Although there may not yet be good quantitative measurements of the effectiveness of vegetative linings, some things can be stated that are helpful to a better understanding of the use of vegetation in streambank protection work. These, for the most part, are elementary facts and deductions derived from extensive observations over several years. Some come from the findings of hydraulic laboratory tests.

(1) Streambanks that are eroding and need protective measures have little, if any, vegetation on the face of the bank.

(2) If vegetation is to be used to protect such a bank, it must be developed on the bank face between floods.

(3) To establish vegetation quickly, the conditions for growth must be good. Fertilization, mulching, and watering are often needed. Sterile, compact subsoil materials should be scarified and mixed with productive materials.

(4) The portion of an actively eroding bank that is under prolonged submergence is not a favorable place for the development of any known vegetative material. It follows that this part of the bank should be protected by other means. A possible exception would be for shallow depths in very small channels of low velocity where exposed roots and overhanging tops may be capable of reducing the boundary velocity below that needed to scour bare soil.

(5) Since time is required for the development of resistance by vegetation, there is risk of failure because of floods, unless temporary auxiliary protective measures are employed, as, for example, the anchored brush mats along the Winooski River in Vermont (*2*).

(6) The risk of failure during the development stage decreases with increasing elevation on the bank, growth conditions being the same, because of the probable increase in the period before submergence occurs.

(7) The length of time required for effective establishment and development of resistance varies greatly among the kinds and varieties of vegetation. Woody materials are slower than

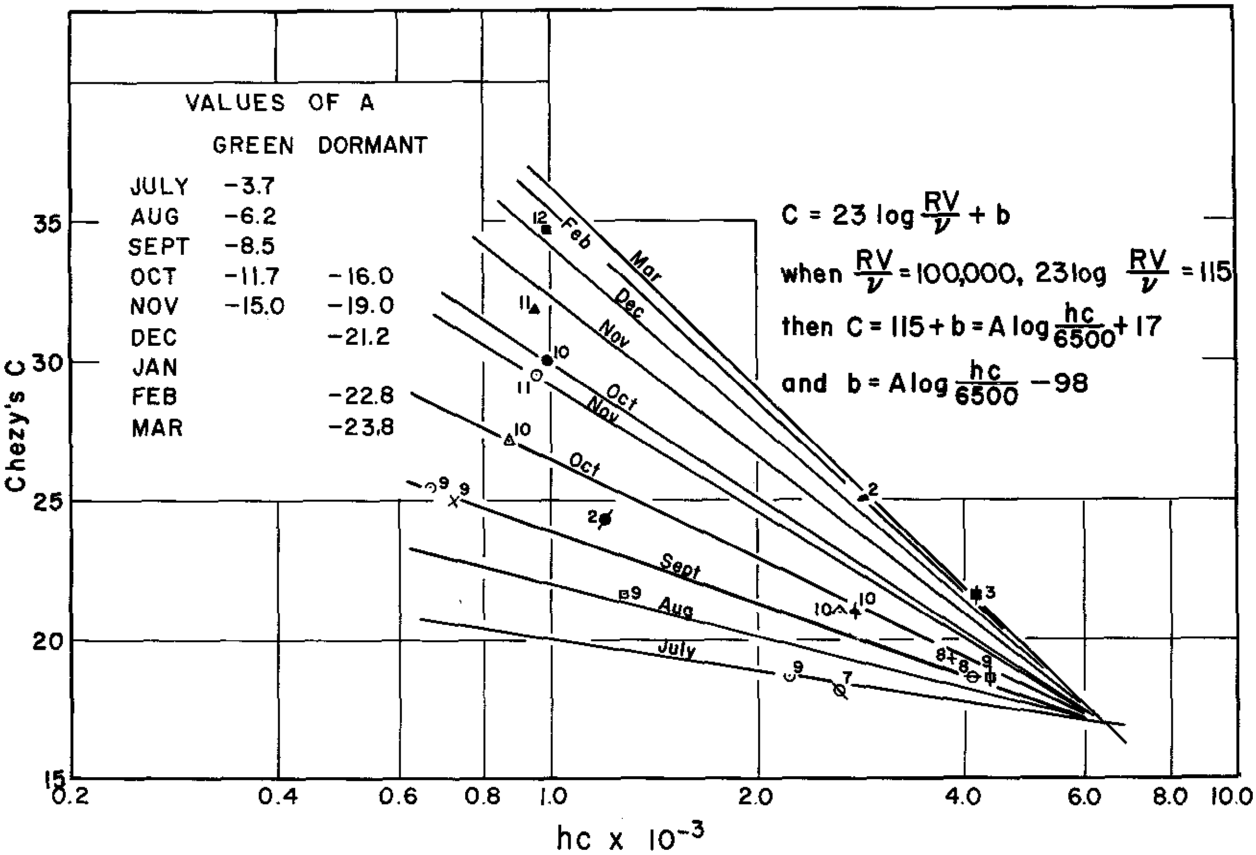


FIGURE 4.—Variation of Chezy's C with vegetation count and height at $Re = VR/\nu = 100{,}000$ (Spartanburg bermudagrass channels).

the grasses. Grass mixtures should include a variety that is quick to become effective, even though at maturity it may not be the most desirable. In the Northeast, an addition of ryegrass to the seed mixture has been good for this purpose.

(8) Since the dependence upon a vegetative lining for protection implies having it on the bank at the time of the flood, the time of its initiation (seeding, planting, etc.) in relation to the beginning of the dormant season becomes important. Protection against dormant season flood should not be expected of late-planted materials.

(9) The principal function of a vegetative lining is to keep the fast moving water and transported coarse materials away from the soil surface. Therefore, the lengths, number per unit area, and physical qualities of the tops are, with few exceptions, the most important attributes of the lining.

(10) Once the soil surface beneath the tops has started to erode, exposing some of the roots, the lining has started to fail.

(11) Time is also an important element in the destruction of most streambank linings. It is usually best to think of the destructive process as an erosion, i.e., a little bit at a time, and at different rates for different conditions.

(12) The roots are also important. They should be sufficiently extensive to resist the pull of the tops resulting from the drag of the flow. Also, in case of partial failure, they help to retard the water speeds when exposed and, if not too severely damaged during a flood, may again support growth. Unlike vegetation generally, the roots of some willows and some of the other kinds of riparian vegetation, when once established, not only persist but thrive in water flowing at moderate speeds.

(13) Vegetative linings possess a healing ability under some conditions. The subsequent recovery of growth, following partial failure in an extreme flood, may induce sedimentation and bank buildup during the lesser floods that follow. The kind and quantity of the sediment load of the stream is undoubtedly a factor in this.

(14) The flow-retarding ability of the vegeta-

tion and thereby its ability to protect the soil surface is also dependent upon its toughness and resilience, things generally associated with growth and life. Aside from the vulnerable period during establishment, the critical periods are generally the dormant periods. If floods occur during the dormant season, it is desirable to select those types and varieties that retain much of their strength, resilience, and perhaps some life in the tops during this period. An excellent grass for the Northeast is creeping red fescue.

(15) Legumes are generally weak in retarding flow, and should be used only if they promote better growth of the other species in the mixture or have the ability to grow and persist where other materials do poorly.

(16) Low-growing woody materials, such as small types of willow, appear to have favorable qualities. If they can be induced to grow along the concave banks of streams, where protection is really needed, they act as skid surfaces for ice and transported debris. They must be pliable and capable of quick recovery from severe mauling. Brittle materials could offer little protection. Isolated, tough, bushy materials are undesirable because they are a major obstruction to the flow, causing high, destructive water speeds in their immediate vicinity. Early spring, when moisture and temperature conditions are favorable, has been found best for planting the woody vegetation.

(17) The mixture of woody and herbaceous materials should be such that the soil surface is protected, either by a very dense stand of shrubs or by shade-tolerant grass in a less dense stand of woody growth.

(18) Although the strength or resisting abilities of vegetative linings along streambanks have not been evaluated, there is some helpful information available about sod-type of growth in small waterways. From the data of Ree and Palmer (*7*), allowable values of shear stress for bermudagrass linings can be deduced.

Equivalent Stone Sizes for Bermudagrass and Woody Vegetative Linings

The notion of an equivalent stone size for describing the resistance of vegetation to destruc-

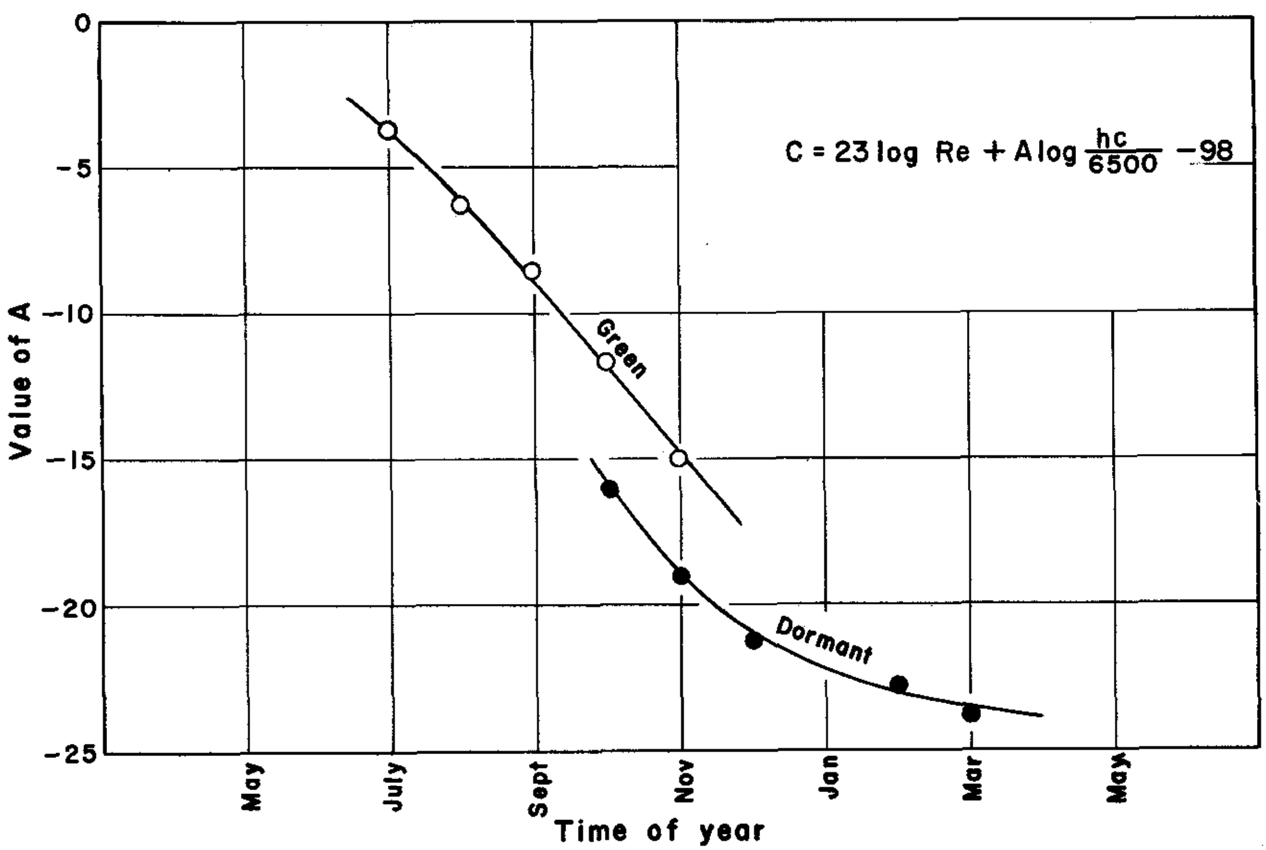


FIGURE 5. — Seasonal variations of *A* (Spartanburg bermudagrass channels).

tion by flowing water seems to have utility. Ree and Palmer (*7*) specifically give only allowable velocities for vegetated waterways, but their tabulated values of slopes and hydraulic radii for their many tests make it possible also to compute the allowable or limiting shear stresses and to derive the equivalent stone sizes given in table 1.

TABLE 1.—*Equivalent stone sizes for bermudagrass linings*

Condition of bermudagrass	Allowable shear stress	Equivalent stone diameter
	Lb./sq. ft.	*In.*
Fair stand, short,[1] dormant	0.9	2
Good stand, kept short, dormant	1.1	2
Good stand, long,[2] dormant	2.8	5.5
Excellent stand, kept short, green	2.7	5.5
Good stand, long, green	3.2	6.5

[1] Less than 5 inches high.
[2] Greater than 8 inches high.

The equivalent stone sizes of table 1 are based upon the relation that critical shear stress in pounds per square foot is equal to one-half the stone diameter in inches, the conversion factor being based upon tabulations of data from hydraulic laboratory tests and other sources by Chang (*1*), Lane (*3*), and others. The critical shear stress values shown are for Cecil sandy loam soil.

The existing information on the resistance of good sod during the dormant season indicates an equivalent stone size of from 2 to 5 inches, but there is practically no comparable information for woody materials. The single bit of evidence is for an excellent 3-year growth of basket willow and grass along Bennettsville Creek, New York (*4*). Here a stone size equivalent of a little less than 6 inches is indicated. Although this information is less than desirable for evaluating woody vegetative streambank linings, it does serve on a contingent basis to give the order of magnitude of the bank protection offered.

Some Practical Limitations

The role of vegetation in the regimen of streams varies with the size and slope of the stream, the frequency and duration of floods, the climate, the sterility or productivity of the soil materials along the stream edge and their inherent erodibility, the bed material texture and transport rates, land use, and presumably other things. The list of factors affecting the utility of vegetative materials for streambank protection are large; yet the range is not so large and complex that areas or situations cannot be delineated wherein certain kinds of vegetation are ideal for bank protection.

On the smaller streams of perhaps 100 feet or less in width and with moderate to low width/depth ratios, mature vegetation along the banks affects the average water speeds in floods and thereby the erosive agent. The transport capacity of the floodflows for bed material is also affected. Changes in this streambank growth by purposeful destruction, trimming, mowing, or spraying will affect the water velocities and thereby the channel capacity, the sediment transport capacity, the ability to scour the bed and the banks, and the meandering tendency. Utilization of these practices in timely maintenance can provide the most economical means for obtaining satisfactory channel conditions. Overdoing these things can result in a wildly meandering or severely degrading channel.

There are some cases on smaller streams where the effects of grazing and trampling by livestock along the edge of the stream are sufficient to induce objectionable streambank erosion. Close grazing and trampling reduce the protective capacity of vegetation. Fencing, along with the good fortune of having lower than normal floodflows for a few years, may be the least costly, effective corrective measure. However, experience has taught that annual fencing repair costs can be appreciable, and effective maintenance of fences for protection of streambank vegetation has been hard to obtain.

The very great importance of the studies of vegetative streambank linings, and the ascertainment of the portions of the bank where they are suitable, can be obtained by comparing costs. After shaping the bank, it costs about 20 cents per square yard of bank area to establish a herbaceous lining, 50 cents for a combination shrub and grass lining, and $4 or $5 for 12-inch-thick stone riprap. These costs are based upon experiences in western New York State in the protection of streambanks that were subject to floodwater erosion.

Many of the thoughts that have been expressed herein, along with others in regard to the use of vegetation along Buffalo Creek, New York, have been ably reported in a paper by Harry Porter and Leon Silberberger, entitled "The Use of Vegetation in Streambank Stabilization," given at the 1958 meeting of the Soil Science Society of America; also, "Streambank Stabilization" by the same authors (*5*). A recent article describing the use of vegetation in streambank protection is by Stanton and McCarlie (*8*).

Summary

Some factual information about the resistance of vegetation to destruction by floodflows

is given along with many observations and deductions about the role of vegetation in streambank erosion.

Little-publicized basic information, obtained by W. O. Ree, about the variation of water speeds within a flow of water over vegetation is again presented.

The retarding effect of grass on the flow of water as it varies with grass density, length, age, and time after frost is shown.

The protective ability of grass and woody vegetation in terms of equivalent stone size and the guiding principles for successful use of vegetation for streambank erosion control are given.

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SOME ASPECTS OF FLUVIAL MORPHOLOGY INFLUENCING INVESTIGATIONS OF CHANNEL STABILITY

[Paper No. 21]

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Introduction

Proper identification, correlation, and sampling of representative soil materials facilitates the design of stable channels. Improvements may be made over many miles and intensive investigation can be costly, unless an interpretation of the fluvial morphology is possible. This interpretation is defined as a determination of the depositional environment in which the alluvium has accumulated to a depth at least as great as the proposed channel investigation. Stratigraphic correlation of deposits by depth and width across the valley would be part of the interpretation of fluvial history.

Interpretation of depositional environment is not only important for purposes of correlation but also because the mode of accumulation does much to establish the stability characteristics of the resulting deposit, if not immediately, then perhaps with time. Channel deposits are noncohesive because of the absence or scarcity of clay or fine silt that could act as a binder. On the other hand, flood plain deposition offers the greatest opportunity for a stable soil to develop, assuming relatively quiet water when fine material accumulation occurs. Fan sediment occupies an intermediate position from the standpoint of texture, since small particles are forced to deposit along with the coarse in the spreading flow.

This paper presents data available from channel and damsite investigations in alluvial valleys and on fans where the depositional environment is believed to be identifiable. An analysis of the data is made for the purpose of quantitatively establishing the distinction between channel, fan, and flood plain deposits. Problems associated with a quantitative distinction between such sediments are also discussed.

Data on Fluvial Sediments

Table 1 lists the available data from 32 stream valleys in 7 Western States. The amount of such data from each valley varies considerably. Nevertheless, the data are representative of specific valleys, if they are not necessarily a fair sample of all alluvial soils in the west. A major separation of the information is between channels, fans, and flood plains. The flood plains are further subdivided into sediments deposited in recent years and those of older but variable history. For the most part, they include sediments with profile development. They either occur in valleys known to have a very slow rate of accumulation because of low sediment yield or because of dissection of the flood plain by valley trenching.

Stream slopes were obtained in many cases from topographic sheets, some of which were of small scale and large contour interval. They should therefore be considered as approxima-

TABLE 1.—*Size distribution of fluvial sediment by depositional environment, Western States*

Depositional environment	No.	Stream	County	State	Stream slope	Size distribution				Plasticity index	Coefficient of sorting[1]	Rate of particle-size increase[2]
						25 pct. finer	Median	75 pct. finer	<.005 mm.			
					Ft./ft.	*Mm.*	*Mm.*	*Mm.*	*Pct.*			
	1	Adobe Creek	Lake	California	0.003	0.90	4.00	12.00	...	...	3.67	0.222
	2	do	do	do	.003	1.50	5.20	10.00	...	...	2.58	.170
	3	do	do	do	.003	1.60	8.50	22.00	...	...	3.70	.408
	4	do	do	do	.003	3.50	15.00	27.00	...	...	2.78	.471
	5	Arroyo Grande	San Luis Obispo	do	.005	.75	2.80	7.00	...	...	3.06	.124
	6	do	do	do	.004	.36	7.00	15.50	2	...	6.54	.303
	7	Beaver Creek	Marion	Oregon	.0016	.20	4.00	40.00	7	11	14.10	.796
	8	do	do	do	.0016	.82	3.50	80.00	...	...	9.78	1.584
	9	Boise River	Canyon	Idaho	.0024	.14	.21	.27	...	...	1.39	.003
	10	do	Ada	do	.002	.48	.82	1.70	...	...	1.88	.025
	11	Calleguas Creek	Ventura	California	.0013	.10	.22	.31	...	...	1.76	.004
	12	do	do	do	0013	.29	.41	.43	...	...	1.28	.003
	13	Cebada Canyon	Santa Barbara	do	.007	.25	.35	.55	...	...	1.48	.006
	14	Corbett Canyon	San Luis Obispo	do	.015	.045	.16	.45	12	...	3.16	.008
	15	Cottonwood Gulch	Ada	Idaho	.023	.58	1.20	2.60	...	...	2.12	.041
	16	Elk Creek	Boise	do	.015	.80	1.80	3.40	...	...	1.85	.084
	17	Frye Creek	Graham	Arizona	.016	.48	1.30	3.20	...	...	2.58	.054
	18	do	do	do	.016	1.20	4.80	14.00	...	...	3.42	.256
	19	Gabbert Canyon	Ventura	California	.016	.70	1.00	2.00	...	...	1.69	.026
	20	Graveyard Wash	Graham	Arizona	.007	.19	.32	.50	...	...	1.62	.006
Channels	21	do	do	do	.007	.42	1.00	2.70	...	...	2.54	.046
	22	Green River	King	Washington	.001	.10	.145	.18	...	...	1.34	.002
	23	do	do	do	.001	.15	.196	.25	...	...	1.29	.002
	24	Grimes Creek	Ventura	California	.014	.48	.80	1.35	...	...	1.68	.017
	25	La Posta Creek	San Diego	do	.010	.30	.43	.90	...	...	1.74	.012
	26	do	do	do	.009	.54	1.09	1.82	...	...	1.84	.026
	27	Limekiln Creek	Los Angeles	do	.021	.13	.72	6.00	5	...	6.80	.117
	28	do	do	do	.021	.55	1.80	5.00	2	...	3.12	.089
	29	Las Posas	Ventura	do	.006	...	...	1.30	...	...	1.44	.010
	30	Main Street Canyon	Riverside	do	.040	.78	1.60	3.90	...	...	2.21	.156
	31	Moore Creek	Boise	Idaho	...	.80	2.10	3.40	...	...	1.85	.048
	32	Simi Wash	Ventura	California	.008	.39	.55	.95	...	...	1.56	.011
	33	Skokomish River	Mason	Washington	.003	5.80	12.00	38.00	...	...	2.46	.648
	34	do	do	do	.004	7.40	24.50	94.00	...	...	3.56	1.721
	35	do	do	do	.002	4.80	11.30	28.00	...	...	2.42	.466
	36	Stockton Wash	Graham	Arizona	.004	.32	.50	.71	...	...	1.49	.008
	37	do	do	do	.004	.13	.39	1.49	...	...	2.91	.027
	38	Tar Springs Creek	San Luis Obispo	California	.015	.14	.21	.47	3	...	1.84	.007
	39	Upper Meadow Valley Wash	Lincoln	Nevada	.003	.028	.54	1.50	...	...	2.31	.029
	40	do	do	do	.0066	.38	2.80	13.30	...	...	5.90	.260
	41	do	do	do	.011	3.20	9.00	16.50	...	...	2.27	.270
	42	do	do	do	.011	2.60	13.00	20.30	...	...	2.78	.350
	43	Antelope Valley	Los Angeles	California	.114	.067	.21	.43	8	...	2.49	.007
	44	Deer-Day	San Bernardino	do	.050	.57	5.00	51.00	...	...	9.40	1.07
	45	do	do	do	.050	.57	4.00	20.00	...	...	5.90	.39
	46	do	do	do	.050	.90	7.50	32.00	...	...	5.90	.622
	47	do	do	do	.050	.70	8.50	38.00	...	...	7.70	.747
Fans	48	Etiwanda Creek	do	do	.047	.60	2.35	15.00	...	...	5.00	.288
	49	do	do	do	.047	.25	1.40	24.00	...	...	9.84	.474
	50	Grove Creek	Utah	Utah	.120	.035	[3].90	13.00	9	8	19.35	.259
	51	do	do	do	.120	.040	[3].75	14.00	8	5	18.65	.279
	52	do	do	do	.120	.026	[3].24	2.60	10	4	10.00	.052
	53	Adobe Creek	Lake	California	.0025	.034	.08	.18	8	...	7.29	.003
	54	do	do	do	.002	.03	.07	.18	3	...	7.74	.003
	55	Santa Rosa Creek	Sonoma	do	.003	.025	.06	.17	11	...	2.60	.003
Flood plains—modern	56	Upper Meadow Valley Wash	Lincoln	Nevada	.006	.050	.50	2.50	3	...	7.08	.049
	57	do	do	do	.006	.0065	.02	.08	10	11	3.56	.0015
	58	do	do	do	.006	.021	.04	.18	7	...	2.92	.0032
	59	do	do	do	.006	.05	.32	3.00	5	...	7.72	.059
	60	do	do	do	.003	.029	.06	.18	7	...	2.48	.003
	61	Adobe Creek	Lake	California	.003	.03	.07	.16	7	3	7.30	.003
	62	do	do	do	.003	.03	.11	.50	9	4	12.80	.009
	63	do	do	do	.002	.016	.03	.062	12	23	1.97	.0009
	64	do	do	do	.0025	.012	.039	.11	12	12	3.02	.0018
	65	Beaver Creek	Marion	Oregon	.0022	.02	.16	1.20	12	5	7.76	.0236
	66	do	do	do	.0022	.0075	.035	.13	21	10	4.16	.0024
	67	do	do	do	.0016	.008	.031	.066	22	14	2.88	.0012
	68	do	do	do	.0016	.0029	.023	.055	28	18	4.36	.0014
	69	Green River	King	Washington	.001	.015	.019	.24	...	...	4.00	.0045
	70	do	do	do	.0005	.009	.02	.035	17	6	6.20	.0005
	71	do	do	do	.0007	.018	.031	.055	8	...	1.39	.001
	72	La Posta Creek	San Diego	California	.010	.17	.24	.74	...	...	2.09	.011
Flood plains—recent to mature soil development	73	do	do	do	.009	.18	.52	1.05	...	...	2.41	.017
	74	do	do	do	.009	.10	.18	.40	...	...	2.00	.006
	75	Monroe Creek	Sevier	Utah	.06	.23	2.90	30.00	...	...	11.50	.595
	76	do	do	do	.06	.25	1.50	14.00	...	...	7.50	.274
	77	do	do	do	.06	3.60	8.50	24.00	...	...	2.60	.428
	78	Snohomish River	Snohomish	Washington	.001	.014	.045	.45	11	...	5.57	.009
	79	do	do	do	.001	.036	.085	.12	9	...	1.83	.007
	80	Sutherlin Creek	Douglas	Oregon	.004	.035	.071	.17	...	...	2.20	.0027
	81	do	do	do	.003	.028	.052	.11	10	4	1.98	.0003
	82	do	do	do	.003	.0065	.030	.29	23	37	6.69	.0028
	83	Upper Meadow Valley Wash	Lincoln	Nevada	.012	.02	.055	.31	16	14	3.95	.005
	84	do	do	do	.012	.035	.21	3.00	11	9	9.25	.06
	85	do	do	do	.012	.13	.40	.90	3	...	2.62	.015

[1] $\sqrt{Q_3/Q_1}$.

[2] $\frac{Q_3-Q_1}{50}$

[3] Size distribution not adjusted for 15-20 percent of samples over 6 inches.

tions of the gradients. A comparison of these with stream gradients in other parts of the country would no doubt show the western stream slopes to be substantially higher. This is believed to be one explanation for the relatively small amount of fines in the flood plain deposits shown on the table in the column giving the percentage of material less than 5 microns in size. This factor is also related to the generally low plasticity indices. The particle sizes of which 25, 50, and 75 percent are finer, by weight, completes the information from the classification of materials. Computed data on the table include Trask's Coefficient of Sorting,[1] which is obtained from the formula $\sqrt{Q_3/Q_1}$, where Q_1 (1st quartile) is the particle size of which 25 percent are finer (D_{25}) and Q_3 (3d quartile) is the size of which 75 percent are finer (D_{75}). The sorting coefficient approaches 1.0 as the two quartiles become more nearly equal.

The last column on table 1 is a value for rate of particle size increase, which is the quotient obtained from the formula $\frac{Q_3-Q_1}{50}$, where Q_3 and Q_1 are the same as above and the divisor is the percentage difference between the two quartiles.

Analysis of Data

Streamflow characteristics as related to settling velocities of particles were considered as a means of obtaining a numerical differentiation between environments of deposition by size distribution. Channelized flow conveys the coarsest particles available, but the degree of sorting varies, however, from place to place and from flow to flow, depending upon the magnitude and duration of the discharge, as well as the availability of material. There should, however, be a range of particle sizes that reflects the dominance of the velocity component as the transporting and depositing agent. Similarly, the characteristics of flood plains, where flows are usually elevated above the area of coarse material transport and where water viscosity and local turbulence are important, should dictate the limits of particle sizes carried and deposited.

The coefficient of sorting is indicative of the environment of deposition under the above-cited conditions, but in a general sense only. For example, in table 1, the average coefficient for channels is about 3.0, for fans 9.4 (with 2 of the 10 items looming very large in the average), and flood plains about 4.8. The sequence is in the anticipated order, but individual sample data of one group exceed the averages in others.

[1] TRASK, P. D. STUDIES OF RECENT MARINE SEDIMENTS, CONDUCTED BY THE AMERICAN PETROLEUM INSTITUTE. Natl. Res. Council Bul. 89, pp. 60-67. 1932.

This is to be expected, since, during the alluvial process, time for sorting prior to deposition is frequently insufficient, with fines being forced out of suspension with the coarse particles in velocities otherwise sufficiently strong for continued transport. Dispersion and loss of water are also reasons for unpredictable sorting patterns; but it is predictable that sorting will be poor on fans.

In searching for a more specific numerical indicator of the depositional environment in alluvial valleys, it was concluded that the average increase in particle size could serve to bracket the conditions under which sedimentation occurs. For example, a relatively large average increase in size for each 1 percent added between the 1st and 3d quartile should indicate a rather high velocity but variable flow during the depositional process. On the other hand, when there is a small average increase in size, the flow involved should have been relatively uniform rather than widely fluctuating in velocity and related flow conditions. A streamflow under high velocity but very irregular conditions would occur on a gravel wash or on a fan. Flow in a well-defined channel of uniform depth provides a definitive particle size and indicates general movement as bedload.

The most appropriate quartile to use in conjunction with average rate of size increase to segregate depositional environments was obtained by graphical means. Figure 1 is a plotting of the D_{75} and average rate of size increase. The nearly perfect correlation on log-log paper demonstrates the dominance of the D_{75} on the average rate of size increase. It also demonstrates that use of the coarser fraction does not offer a means of graphically segregating environments of deposition. Figure 2 is another plotting using the median, or D_{50}, with greater success in segregating channel, fan, or flood plain deposition. Figure 3, which shows the relationship between the D_{25} and the rate of particle size increase, makes a relatively clear-cut distinction between depositional environments.

The location of a few samples in an environment different from that given in the table can, at least in considerable measure, be explained. Classification by depositional evironment was made on the basis of topographic position. It does not follow, however, that such a position precludes the accumulation of sediment under the conditions of another streamflow regime. For example, the single flood plain sample shown within the channel envelope on figure 3 (No. 75) belongs with the high-velocity streams only by the broadest generalization. The sample was obtained from the streambank in an intermountain valley, Monroe Creek, Utah, where the slope is about 6 percent. It is logical to assume

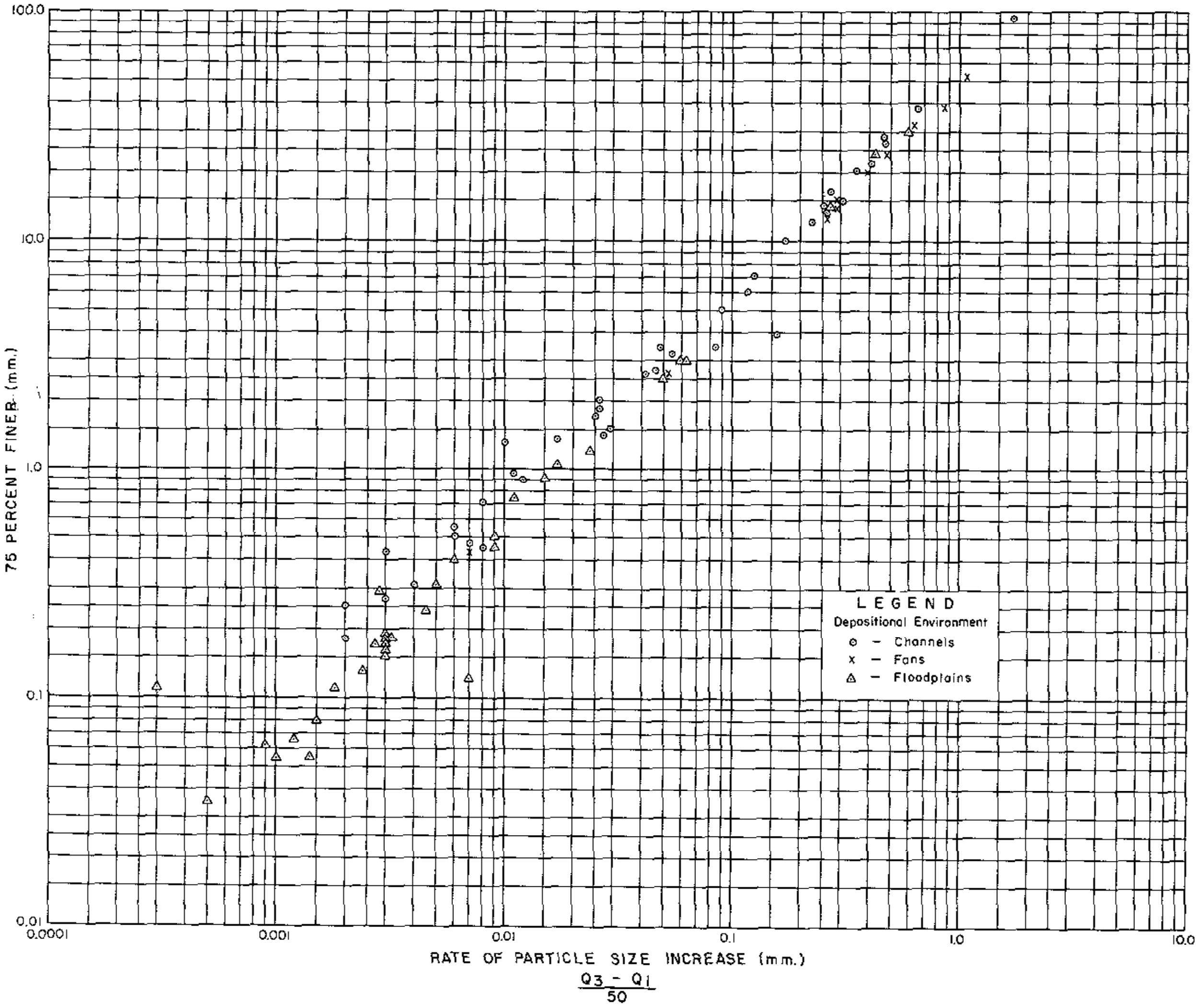

FIGURE 1. — **Relationship of particle size increase to size of which 75 percent is finer.**

that this deposit could have accumulated under channel flow conditions.

Similarly, one of the two channel events shown to be within the fan envelope occurs along a stream as it emerges from a mountain canyon. The site is located on Upper Meadow Valley Wash, Nev. The same is true for the channel sample (No. 27), in Limekiln Canyon, Calif., that is not within any of the envelopes. It is not unlikely that the sediment in each case accumulated under spreading fan conditions, although both samples were obtained from channels with insufficient capacity for even moderately large flood events. The other channel sample within the fan envelope on figure 3 (No. 6) is from Arroyo Grande channel in California. It was obtained near the mouth at the Pacific Ocean, where the presence of a beach barrier of littoral drift causes deposition of finer sediment at the D_{25} level than the average rate of particle increase of channel deposits would indicate.

One of the three samples identified as being from channels but which are plotted within the boundary of the flood plain envelope is from Stockton Wash, Ariz. (No. 37). This sample was obtained from a depth of 39 feet below the present channel. In this actively wandering stream, the flood plain deposits are certain to occupy varied positions with depth. An Upper Meadow Valley Wash sample identified as being from a channel (No. 39)), but is within the flood plain envelope, was obtained from near a place where the confined flow capacity is completely lost.

A sample from a fan deposit is located within but near the boundary of the flood plain envelope. This (No. 52) and the two lowest D_{25} plottings within the fan envelope (Nos. 50 and 51) are from Grove Creek fan in Utah. As shown in footnote 3 of table 1, from 15 to 20 percent of the size distribution of these samples does not include materials over 6 inches in diameter. The Antelope Valley fan sample (No. 43) is derived from weathered shale on the slope above and may be properly classed as colluvium.

Post-Depositional Influences on Particle-Size Distribution

Changes in particle-size distribution can occur after deposition that may alter the indicated environment of accumulation. These changes include:

1. Deposition of finer or coarser sediment among the particles accumulating under a different flow regime. For example, voids between gravel depositing under a channel flow regime are filled with fine sediment during receding flows.
2. The process of eluviation or movement of fine particles downward in the profile. This process, over time and with sufficient rainfall, results in accumulations of clay size particles in a subsoil.
3. Weathering, or breaking down of particles by physical or chemical means.
4. Filling of voids by chemical precipitates such as calcium carbonate.

The first post-depositional process described is believed illustrated by samples Nos. 7 and 8

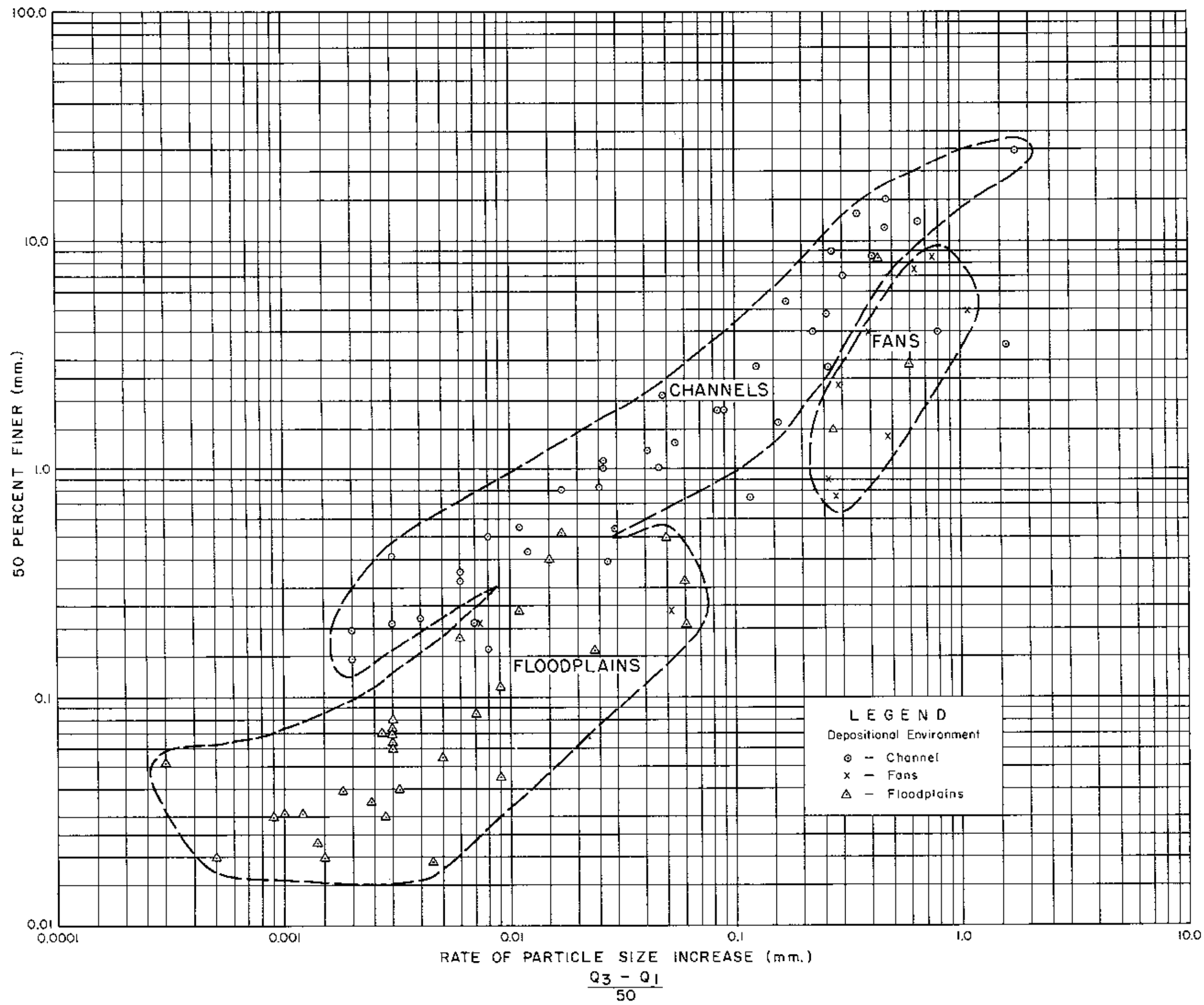

FIGURE 2.—Relationship of particle size increase to size of which 50 percent is finer.

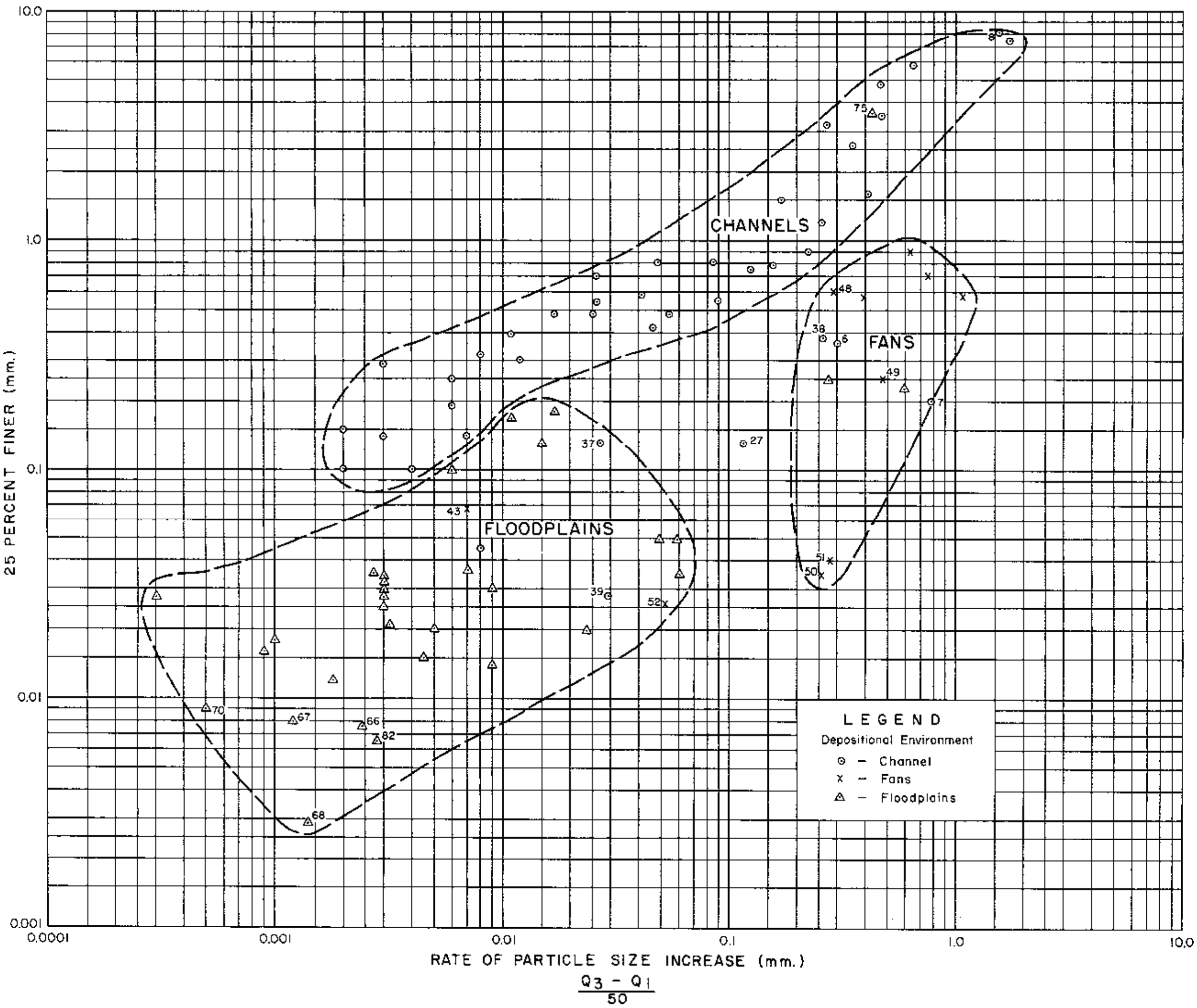

FIGURE 3. — Relationship of particle size increase to size of which 25 percent is finer.

on Beaver Creek, Oreg. The gravels in these samples were deposited by an ancestral Santiam River channel, which formerly occupied the lower Beaver Creek Valley. Fine sediment was subsequently deposited on top of the gravels. Perhaps because of a more protected site further up the creek valley, sample No. 7 had a considerable amount of fines deposited in the gravel voids. The mixing of sediment from two depositional environments places the plotted point within the confines of the fan envelope. Sample No. 8, obtained from the same gravel horizon near the mouth of the present creek, has a normal position in relation to other channel deposits.

Examples of a combination of the second and third post-depositional processes described are the older fine alluvium in Beaver and Sutherlin Creek Valleys in Oregon (Nos. 66, 67, 68, and 82) and Green River, Wash. (No. 70). The high proportion of fines relative to the rate of particle size increase is believed indicative of post-depositional eluviation and weathering. Age alone, however, does not necessarily result in alteration of deposits. The deposit at a depth of 50 to 60 feet on East Etiwanda fan in southern California is not significantly different from the one near the surface. This illustrates the slow rate of change in material characteristics in semiarid and arid climates.

Relation Between Depositional Environment Determinations and Channel Stability Investigations

It has been pointed out that stratigraphic correlation of beds whose environment of deposition has been determined within an alluvial valley facilitates investigations pertaining to channel stability. It is now proposed to illustrate this by three examples from stream valleys listed on the table. These are, in increasing order of complexity, Skokomish River, Wash.; Adobe Creek, Calif.; and Green River, Wash. The early history of the Skokomish and Green River valleys reflects their proximity to the ocean base level. During a period of much lower sea level their valleys were eroded by glacier and stream action.

The Skokomish Valley was backfilled with gravel outwash to which has been added in more recent times, stream gravels and fine flood plain alluvium. The river moves back and forth across its relatively wide valley, cutting the banks on the outside on bends, rebuilding on opposite slip-off slopes. As shown by figure 4,*A*, the separation between gravel and fine alluvium is sharp and occurs at about the same elevation across the valley. This is a characteristic of gravel-floored valleys whose channels move by lateral erosion and accretion. Gravel outwash deposited on top of fine alluvium during flood flows drops back to the bedload platform as bank erosion engulfs the deposit. The fluvial characteristic of this valley will be maintained until a shift in base level occurs, due either to sea level change or earth movements. In this instance, the identification of the depositional environment of the two major sediment types and their correlation is straightforward.

Adobe Creek Valley, of which a part is shown on figure 4,*B*, is similar to Skokomish River Valley in some characteristics. That is, the stream moves laterally across the valley with the shifting gravel surface as the pivot. For several reasons, including lack of vegetative entrapment, the accretion is not proceeding as at Skokomish River Valley. About halfway through its course from foothills to Clear Lake, the stream enters a new environment, consisting of fine, relatively erosion-resistant sediment. This sediment may have accumulated at a time of higher lake level. In any event, the gravel flooring of the stream was introduced into the downstream reach by a conveyance channel cut into the fine alluvium. Borings made adjacent to it fail to reveal other channel-type deposits at the same level, indicating that natural changes in alinement are probably made by sudden evulsion rather than by lateral erosion. Item Nos. 1 to 4 in table 1 are the data on channel samples, and Nos. 53 and 54 are modern flood plain sediments. Item Nos. 61 to 64 are the old sediments in which the lower channel is being confined.

The Green River Valley has apparently had a chequered history during the postglacial epoch. Mullineaux[2] has described the geomorphic history of this valley and the adjacent and substantially larger White River, which in times past has joined the Green River in flowing to Puget Sound. The valley has backfilled with clean medium-sized sand overlain by discontinuous cross valley beds of silty sand, silt, clayey silt, and peat, at depths germane to present problems of stratigraphic correlation. A detailed analysis of a recent channel stability investigation has not yet been made. The research reported by Mullineaux and the character of the sediment obtained from borings indicate, however, that the valley was probably at one time nearly covered by a sandy wash with the channel shallow and wide. Depressions near the valley boundaries provided a suitable environment for lush vegetative growth from which peat subsequently formed. This environment was followed by or overlapped one favorable to the accumulation of fine flood plain deposits; then lateral erosion in a highly meandering channel dissected these sediments at various places and replaced them with fine sands, silty sands, and silts. The old meander pattern is still visible on aerial photographs. Natural levee deposits, such as exist along the banks of the present channel, may have contributed to the discontinuity of the bedding. Figure 4,*C* is a schematic representation of the described features in the Green River Valley.

Conclusions

A method has been described for differentiating between channel, fan, or flood plain deposits in the alluvial valleys from which data are available. The procedure involves a determination of the rate of particle size increase and plotting this value in relation to the size of which 25 percent is finer. The 25-percent size proved to be the best of the three levels of size distribution tested.

The described procedure is believed to be most helpful in segregating environments when deposition could have occurred either from transport as suspended material or as bedload.

It was pointed out that the correct interpretation of the fluvial morphology based on size distribution must consider postdepositional influences and that these influences can be reflected in differences in behavior and in deviations from the average position on the graph.

Finally, the fluvial morphology of three stream valleys was briefly discussed, in order to demonstrate the relation between environments of deposition and the stratigraphy of alluvial valleys. A balanced study of all the factors is important in the planning and design of channel improvements.

[2] MULLINEAUX, D. R. GEOLOGY OF THE RENTON, AUBURN AND BLACK DIAMOND QUADRANGLE, WASHINGTON. U.S. Geol. Survey Open File Rpt., 202 pp. 1961.

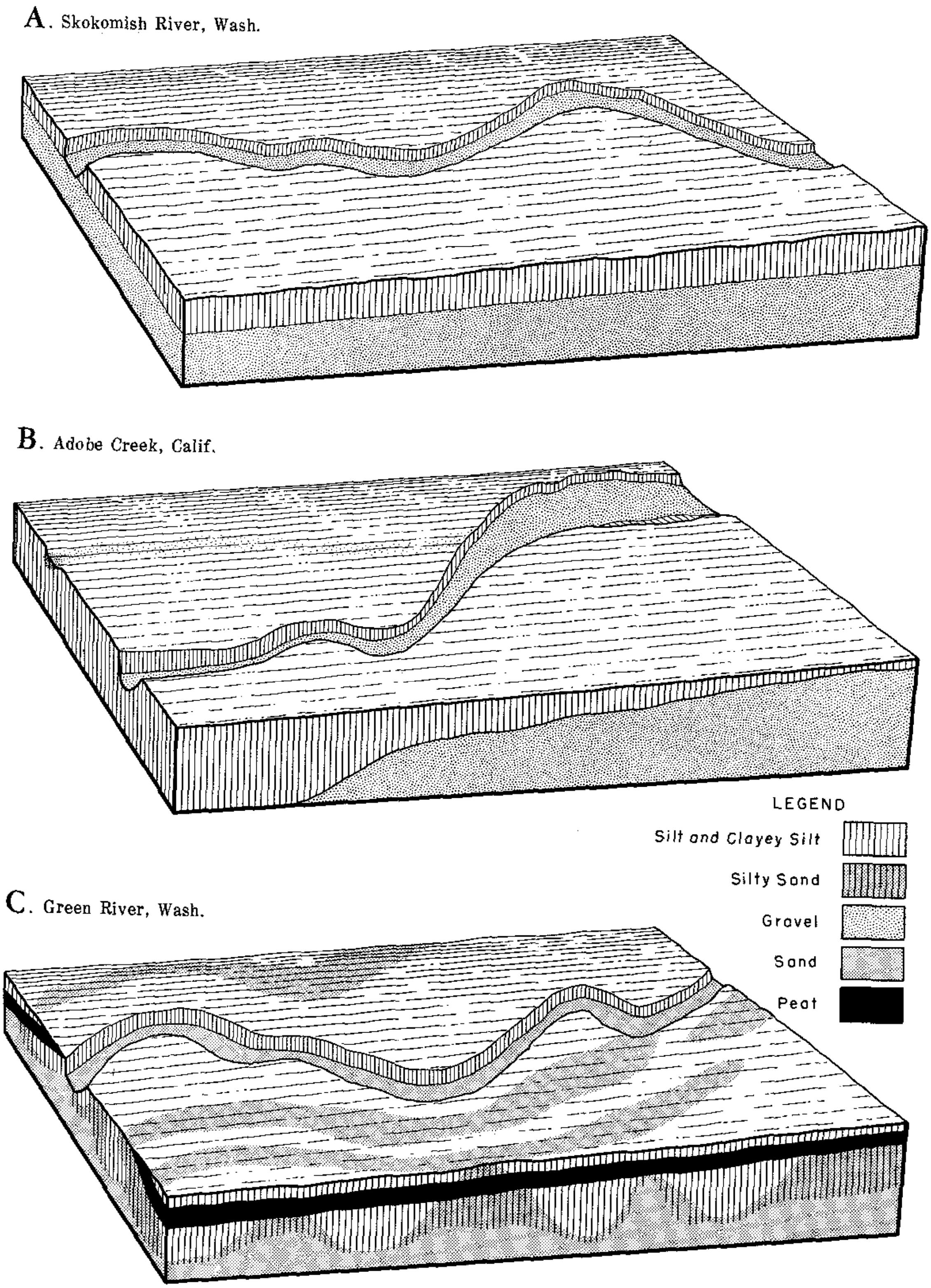

FIGURE 4. — Stratigraphy of alluvial deposits in three western streams.

SUSPENDED SEDIMENT CONCENTRATIONS IN A MICHIGAN TROUT STREAM AS RELATED TO WATERSHED CHARACTERISTICS

[Paper No. 22]

By W. DAVID STRIFFLER, *research forester, Lake States Forest Experiment Station, Forest Service*[1]

Introduction

The northern forested region of the Lake States has long been noted for the many fine quality streams and lakes that originate there. The quality of the water in these streams has generally remained high as long as the natural stream channels have not been disturbed. However, few streams have escaped disturbance in some manner. The net result has been to increase the sediment load carried by these streams.

The disadvantages of sediment in the streams are well known. However, in northern Michigan streams, one of the chief causes for alarm is the effect upon the trout resource. This effect is well documented (*2*, *4*).

The purpose of the study reported here was to examine the suspended sediment concentration in a representative northern Michigan watershed and evaluate the sediment load with respect to geology, soils, land use, and other watershed characteristics.

The Area

The watershed selected for this study is the Tobacco River watershed located in the central part of Michigan's lower peninsula (fig. 1). It includes areas representative of both the northern forested region and the southern agricultural region of the State. Therefore, the wide variety of geological formations, soils, and land-use types offers a broad range of sediment-producing conditions. The river basin is divided into three main branches, all of which head up in the forested upper watershed and then flow through the agricultural lower watershed (fig. 1). The waters of the river are largely considered marginal trout producers, although the upper parts of all three branches are classified as trout waters.

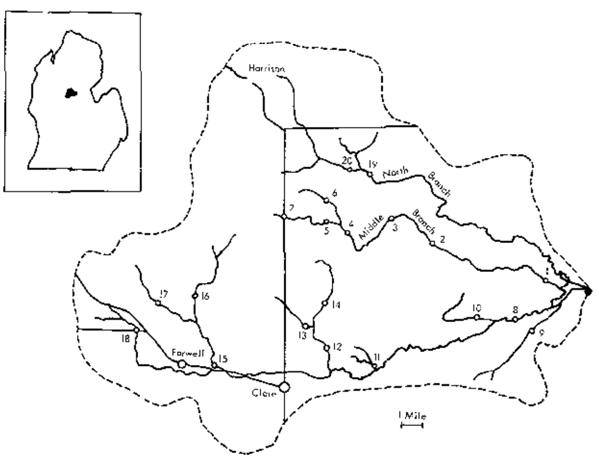

FIGURE 1. — Sampling stations on 20 small watersheds within the Tobacco River basin. Location of the basin in Lower Michigan is shown in the upper left corner.

Geology

The entire watershed is covered by a deep mantle of glacial drift. Four major types of surface deposits are commonly recognized. They include moraine, outwash plains, till plains, and glacial lake bed plain (fig. 2). The main streams flow through each of these from west to east.

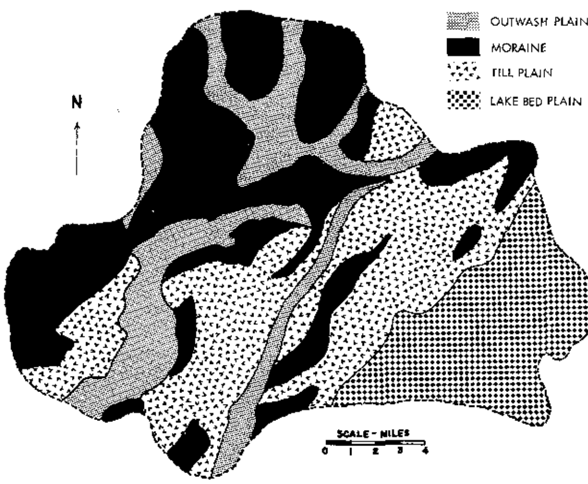

FIGURE 2. — Surface geology, Tobacco River Watershed. (After Martin (*9*)).

Within the morainal headwaters on the west, the landscape is hilly to rolling, soils are sands or sandy loams, and streams are small and widely separated, and they have a uniform flow. Intermingled outwash plains consist of ancient glacial drainage channels where soils are largely stratified sands and gravels. Such deposits are generally level and frequently form channels for present-day streams.

[1] This study was conducted in cooperation with the Michigan Water Resources Commission, the Michigan Conservation Department, and the University of Michigan.

The till plain deposits occur within the central part of the watershed. They vary from level to rolling and are composed of heavy clays and clay loams. Streams are more finely branched than in moraine or outwash areas and exhibit a wide range of flows during the year.

Lakebed plains occur in the eastern end of the watershed. They are broad level plains composed of sand but underlain by lacustrine clay at varying depths. Surface drainage is almost nonexistent except for artificial drains and the main branches of the Tobacco River.

Soils

Although no detailed soil surveys of the watershed area exist, a generalized map of major soil associations within the watershed is available (*10*). Primary soil mapping units (fig. 3) include six soil associations. Soil associations are closely related to the geologic deposits from which they develop.

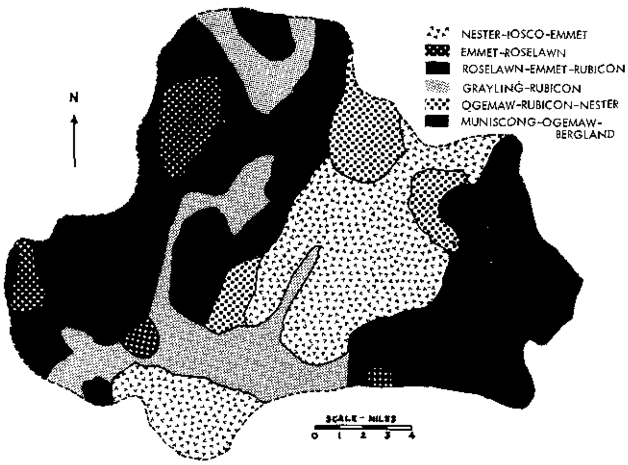

FIGURE 3. — Major soil associations, Tobacco River Watershed. (After Veatch (*10*)).

SA– 7–*Nester-Iosco-Emmet.* This is primarily a till-plain derived soil consisting of a friable, bouldery till overlain by a thick cover of eluvium ranging from clay loam to sandy loam. Topography is rolling with numerous basin depressions.

SA–16–*Emmet-Roselawn.* These are upland morainal soils that vary in their surface composition according to the nature of the underlying drift, although sandy loams and loams predominate. Topography is rolling to hilly with irregular drainage features and numerous basin depressions.

SA–22–*Roselawn-Emmet-Rubicon.* These soils are also morainal soils and differ from SA-16 only in that surface soils are sands rather than loams and sandy loams. This association occupies 29 percent of the Tobacco River watershed.

SA–24–*Grayling-Rubicon.* These are the major soil types developed on the deep sandy outwash plains. Soils are medium to coarse sands with varying degrees of profile development. Relief is generally flat.

SA–35–*Muniscong - Ogemaw - Bergland.* These are lake plain soils and characteristically consist of sand and gravel deposits underlain by clay. Surface soil may include areas of dry sands or clays, but wet sands predominate.

SA–48–*Ogemaw-Rubicon-Nester.* This association occurs on both till plain and outwash plain deposits. The distinguishing characteristic of these soils is a clay subsoil overlain by sand and gravel. The clay may lie at shallow depth or may come to the surface. The topography ranges from level to undulating with occasional basin depressions.

Land Use

Land use within the watershed is closely related to the surface geology and soils. Moraines with deep sandy profiles and sandy surface soils are largely forested. Till plains are largely agricultural with use divided between cultivation and pasture land. Outwash plains are divided between pasture and forest. The use of lake plains depends upon the depth of the sand mantle and the drainage within a particular area. Where the clay beds come to the surface, cultivation predominates, but where the sand mantle is deep or surface soils very wet, forest and pasture lands predominate. For purposes of this study, land use was classified into four types:

Cultivation.—Land area devoted to cultivated crops. Primary crops include corn, small grains, and other crops requiring annual tillage.

Pasture land.—The land area devoted to sheep or cattle pasture. Hay lands were also included in this category.

Wild land.—Included abandoned farmland, brushland, or other predominantly open land not devoted to any specific use.

Forest land.—Land area supporting a forest cover. Major forest types in the watershed included northern hardwoods, lowland hardwoods, oak, aspen, and small areas of pine plantations.

Methods

The primary objective was to relate the suspended sediment concentration in the stream to streamflow, land use, soils, geology, and the other watershed characteristics measured, by means of a multiple regression analysis. To accomplish this, 20 sample watersheds within the Tobacco River basin were selected, each representing different conditions with respect to size and watershed characteristics. Suspended sediment samples and stream discharge measurements were collected at irregular intervals between September 1960 and April 1962. Hydrologic events occurring during the sampling period included two snowmelt periods and several major rainstorms with return intervals of about 5 years. A total of 840 sediment measurements were made, about half of them during snowmelt or stormflow periods.

Several notable studies have used techniques similar to this (*1, 2, 3, 5, 6, 7*). The one major difference in this study is the form of the dependent sediment variable. All the studies cited used some expression of sediment yield over a period of time, while in this study the individual observations of sediment concentration or sediment discharge rates form the dependent variable.

The 21 variables used in the analysis are summarized in table 1. Sediment concentrations represent the average stream sediment concentrations at the time of sampling. Sediment samples were collected with the US DH–48, US DH–59,[2] and automatic single-stage samplers. Sediment discharge rates were computed from sediment concentration values. Stream discharge rates were determined from stage-discharge curves prepared for each sample watershed. Watershed areas were measured from aerial photographs. Channel lengths were measured on a large scale (1:22,240) base map of the watershed. Stream channel gradients were determined either from USGS topographic quadrangle sheets (scale 1:62,500, 10-foot contour intervals) or from direct measurement with a precision surveying altimeter. The number of road crossings was also determined from the large-scale base map. The length of eroding banks was determined from a stream survey and plans report by the Fish Division, Michigan Conservation Department. The proportion of each sample watershed classified in the various geologic types and soil associations was measured directly from the soil and geology maps (figs. 2 and 3). Land use classification was based on aerial photographs and a field survey. Values of these variables for the individual sample watershed are presented in table 2. Various combinations of these variables were also included in the analysis.

TABLE 1.—*Summary of watershed variables used in the analysis of 20 small watersheds*

Symbol	Definition	Units	Range	Mean
Sed p.p.m.	Sediment concentration	P.p.m.	1–3800	115
Sed Q	Sediment delivery rate	Lb./sq. mi./day	0.1–157,800	1,340
Q	Stream discharge rate	C.f.s./sq. mi.	.001–13.168	1.641
R/F	Rising/Falling stage	Rising = 1; falling = 2		1.645
A	Area of watershed	Sq. mi.	1.0–134.3	21.8
CL	Length of permanent channels	Miles	0.3–34.9	6.6
CG	Gradient of main channel	Feet/mile	5–61	23.4
EB	Total length of eroding banks	100's of feet	0–62	10
RC	Road crossings	Number	0–83	10.7
Mor	Moraine	Percent	0–94	50
Out	Outwash	..do	0–42	18
Till	Till plain	..do	0–96	26
Lake	Lake plain	..do	0–100	6
SA–7	Nester–Iosco–Emmet Soil Association	..do	0–100	19
SA–16	Emmet–Roselawn Soil Association	..do	0–50	7
SA–22	Roselawn–Emmet–Rubicon Soil Association	..do	0–100	44
SA–24	Grayling–Rubicon Soil Association	..do	0–44	18
SA–35	Muniscong–Ogemaw–Bergland Soil Association	..do	0–100	6
SA–48	Ogemaw–Rubicon–Nester Soil Association	..do	0–58	6
Cult	Cultivated land	..do	0–45	10
Past	Pasture land	..do	0–42	18
Wild	Wild land	..do	6–37	26
For	Forest land	..do	9–68	44

The multiple regression analysis was computed on the University of Michigan IBM 709/7090 computer, with a standard program known as the Westervelt Modified General Motors Multiple Regression Program. This is a stepwise analysis that selects and analyzes the most important variables among the data. A multiple regression coefficient, coefficient of determination, and *F* level are computed for each variable entering the analysis. In this manner, only the most important variables are included in the analysis while nonsignificant variables are dropped.

[2] Two sediment samplers developed by the Inter-Agency Sedimentation Project, St. Anthony Falls, Minn. *See* paper No. 25.

Results

In the multiple regression analysis, all the 23 variables listed in table 1 plus 7 interaction forms of these variables were tested against sediment concentration (p.p.m.) and sediment discharge rates (lb./day/sq.mi.). In the test against sediment discharge rates, they were found to be significantly related to 6 of the 28 variables. These six, accounting for 75 percent of the variation (equation 2, table 3), included stream discharge (*Q*), whether the stream was rising or falling (*R/F*), eroding banks (*EB*), and three of the soil associations (*SA*–22, *SA*–24, *SA*–48). In the test against sediment concentration (p.p.m.), the same six variables as above, plus the land use variable, cultivation, were significantly related. Fifty percent of the variation was explained by the seven variables (equation 1, table 3). These two equations permit the individual effects of the included variables to be evaluated. Fourteen variables remain that, since they are not included in the analysis, must either have no significant relation with stream sediments or else the relation is obscured by the variables included.

To determine the effects of these remaining variables, only selected variables were used in a series of analyses. In this manner the specific effects of the geologic types, soils groups, and land use types were evaluated. Regression equations derived from these analyses are also included in table 3. Only statistically significant variables are included in the equations.

Discussion of Significant Variables

Streamflow Variables

A large proportion of the total variation was explained by the two streamflow variables, discharge (*Q*) and whether the stream was rising or falling (*R/F*). When sediment concentration (*Sed p.p.m.*) was used as the dependent variable, 43 percent of the variation was explained by rising/falling stage. Less than 1 percent was explained by stream discharge (*Q*). When sediment discharge rates were used as the dependent variable, 52 percent of the variation was explained by stream discharge, while 20 percent of the variation was explained by rising/falling stage. These values indicate that, in northern Michigan trout streams, sediment concentrations greatly increase on the rising stage and that sediment discharge rates increase with increasing streamflow rates. This relation is illustrated in figure 4.

The strong relation between sediment and streamflow variables suggests stream discharge may be an important eroding agent as well as the vehicle of transportation. The consistently high significance of eroding banks in the analy-

TABLE 2.—*Summary of watershed characteristics for sample watersheds*

Station	Area	Total channel	Channel gradient	Road crossings	Eroding banks	Surface geology				Soil association (SA)						Land Use			
						Moraine	Outwash	Till	Lake	7	16	22	24	35	48	Cultivated	Pasture	Wild	Forest
	Sq. mi.	*Miles*	*Ft./mi.*	*No.*	*100 ft.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*
1	36.6	37.5	11	23	38	40	17	36	8	43	2	26	13	9	7	11	26	28	34
2	27.4	23.6	14	19	28	49	21	30	0	40	3	36	18	0	3	10	26	28	34
3	22.8	16.8	13	13	15	59	25	16	0	30	3	45	22	0	0	7	23	32	37
4	15.2	7.5	12	7	0	73	24	2	0	7	4	58	31	0	0	3	12	36	48
5	8.3	3.9	15	4	0	70	28	2	0	0	0	62	38	0	0	4	11	37	47
6	4.7	1.7	19	0	0	90	10	0	0	0	14	57	29	0	0	1	3	37	57
7	1.0	.3	17	0	0	92	8	0	0	0	0	56	44	0	0	0	0	35	65
8	134.3	93.0	17	83	62	22	18	48	12	28	5	31	22	11	3	13	23	26	35
9	8.1	8.2	5	5	0	0	0	0	100	0	0	0	0	100	0	7	18	30	44
10	2.3	3.7	14	2	0	0	0	3	97	11	0	0	0	89	0	22	28	24	24
11	3.4	5.7	29	5	10	17	0	83	0	100	0	0	0	0	0	45	37	6	9
12	16.3	13.0	18	14	20	7	16	77	0	40	0	16	22	0	22	23	38	22	14
13	4.8	2.7	25	3	0	3	1	96	0	14	0	28	0	0	58	22	42	16	18
14	5.8	3.6	20	5	0	29	14	57	0	52	0	22	20	0	6	26	33	22	17
15	28.6	16.7	33	8	1	42	42	16	0	0	8	66	26	0	0	2	8	26	62
16	20.6	7.7	53	3	0	54	35	11	0	0	7	70	23	0	0	1	5	25	68
17	3.7	2.3	61	0	0	948	0	6	0	0	0	100	0	0	0	0	2	30	67
18	5.1	4.7	28	1	0	92	6	2	0	0	50	50	0	0	0	3	19	23	50
19	48.1	21.4	27	11	27	67	32	1	0	0	14	57	22	0	7	2	8	18	68
20	38.9	14.7	28	8	0	64	36	0	0	0	19	53	28	0	0	2	6	19	67

TABLE 3.—*Summary of multiple regression equations*

Equation No.	Equation	Correlations
1......	$\log SED_{ppm} = 3.066 + 0.191 \log Q + 0.135 \log EB - 0.003\ SA/22 - 0.007\ SA/24 - 0.003\ SA-48 + 0.001\ Cult - 0.765\ R/F.$	$r=0.72,\ S_y=0.420$
2......	$\log SED_Q = 3.831 + 1.190 \log Q + 0.134 \log EB - 0.003\ SA/22 - 0.007\ SA/24 - 0.003\ SA-48 - 0.764\ R/F.$	$r=0.87,\ S_y=0.419$
3......	$\log SED_{ppm} = 2.996 + 0.131 \log Q + 0.154 \log EB - 0.767\ R/F - 0.002\ (Mor+Out).$	$r=0.70,\ S_y=0.426$
4......	$\log SED_Q = 3.729 + 1.128 \log Q + 0.153 \log EB - 0.780\ R/F - 0.002\ (Mor+Out).$	$r=0.87,\ S_y=0.425$
5......	$\log SED_{ppm} = 3.038 + 0.141 \log Q + 0.134 \log EB - 0.778\ R/F - 0.003\ (SA-16 + SA-22 + SA-24).$	$r=0.71,\ S_y=0.425$
6......	$\log SED_Q = 3.771 + 1.138 \log Q + 0.131 \log EB - 0.778\ R/F - 0.003\ (SA-16 + SA-22 + SA-24).$	$r=0.87,\ S_y=0.424$
7......	$\log SED_{ppm} = 1.421 + 0.011\ Past.$	$r=0.24,\ S_y=0.528$
8......	$\log SED_Q = 2.244 + .005\ Past.$	$r=0.08,\ S_y=0.848$
9......	$\log SED_{ppm} = 2.027 - 0.006\ (Wild+For).$	$r=0.23,\ S_y=0.528$
10......	$\log SED_Q = 2.470 - 0.003\ For.$	$r=0.07,\ S_y=0.849$
11......	$\log SED_{ppm} = 2.897 + 0.138 \log Q + 0.093 \log CL - 0.002\ (Mor+Out) - 0.781\ R/F + .003 \log EB \times (Cult+Past).$	$r=0.71,\ S_y=0.424$
12......	$\log SED_Q = 3.630 + 1.134 \log Q + 0.093 \log CL - 0.002\ (Mor+Out) - 0.781\ R/F + 0.003 \log EB \times (Cult+Past).$	$r=0.87,\ S_y=0.424$
13......	$\log SED_{ppm} = 1.409 + 0.007\ Past + 0.001 \log EB \times (Mor+Out) + 0.002 \log EB \times (Cult+Past).$	$r=0.28,\ S_y=0.575$
14......	$\log SED_Q = 1.371 - 0.212 \log CL + 0.325 \log EB + 0.009\ (Mor+Out) + 0.021\ Past.$	$r=0.30,\ S_y=0.813$

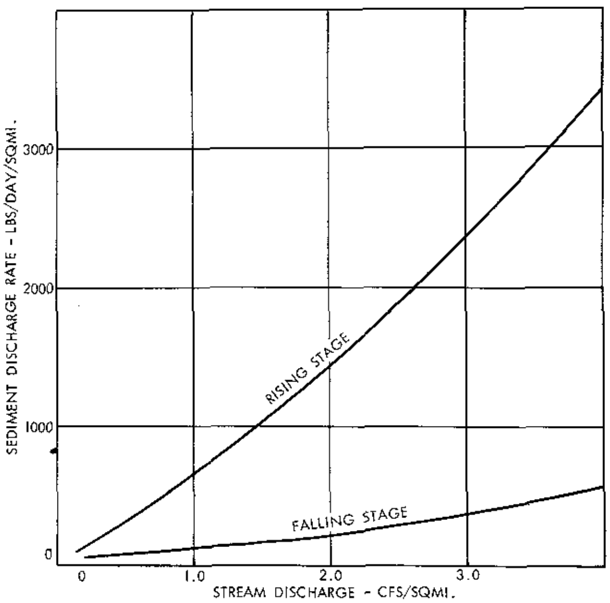

FIGURE 4. — General relation between stream discharge and sediment discharge rate for northern Michigan trout streams.

sis supports this conclusion. As the stream rises, after a rainstorm or snowmelt period, an increasing area of streambanks becomes subject to the stream action. Sediment immediately available to the stream includes loose soil material that has accumulated at the foot of the bank since the last storm flow and sheet erosion directly from the face of the bank during the storm. Additional sediment becomes available as the stream rises and begins to cut into the bank. All these processes tend to cause high sediment loads on the rising stage and at higher discharge rates. However, as the stream recedes, the decreased energy in the stream is no longer sufficient to cause bank cutting and, since all loose soil material has already been removed, that part of the sediment load derived from the channel is greatly reduced.

Channel Length

The variable, channel length (*CL*), representing the total length of all permanent stream channels within each sample watershed, was significantly related to sediment concentration and sediment discharge rate in equations 11 and 12. This raises the question as to whether watershed area is actually the value being considered, since channel length and area are closely correlated. However, since the area variable was included in these problems and rejected as nonsignificant, some other explanation is indicated. Actually, there are two reasons that channel length becomes significant. First, total channel length is related to the length of eroding banks within a watershed. It is reasonable to expect that the greater the length of the permanent channels within a watershed, the greater the length of eroding banks. Therefore, the inclusion of channel length may be a reflection of the high significance of eroding banks. Second, as the density of channels within a watershed increases, there is a greater opportunity for sediment derived from sheet erosion to reach the channels. The inclusion of channel length as a significant variable might also be due to this relationship. This suggests that a drainage density value for each watershed, as suggested by Horton (*8*), might be a much better variable to use than channel length.

Geology

If equations 3 and 4 are used, the contribution of sediment from the combined moraine and outwash geologic types can be evaluated. By differences, the contribution of the remaining land area, till plain and lake plain, can also be evaluated. The sources of sediment derived from the land surface, excluding sediment derived from eroding banks, is (1) 53 percent from moraine and outwash (68 percent of area); and (2) 47 percent from till and lake plain (32 percent of area). The range of average sediment discharge rates that might be expected from a theoretical "average" watershed with 100 percent moraine plus outwash is 442 lb./day/sq. mi. as compared to 700 lb./day/sq. mi. from the same watershed with 100 percent till plain.

Soils

Soil associations may also be evaluated with respect to sediment contribution (equations 5 and 6). In this problem, the soil associations were combined into similar type groups. *SA*–16 + *SA*–22 + *SA*–24 formed the group of sandy soils, whereas *SA*–7 + *SA*–48 formed a group of heavier textured loam and clay soils. *SA*–35, the lake plain soils, remained separate. Sediment contribution from the various soil groups is as follows: (1) 48 percent from *SA*–16 + *SA*–22 + *SA*–24 (69 percent of the area); and (2) 52 percent from *SA*–7 + *SA*–48 + *SA*–35 (31 percent of the area). These values represent erosion from the land surface and do not include sediment originating from streambank erosion. The range of average sediment discharge rates that might be expected from the "average" watershed with 100 percent *SA*–16 + *SA*–22 + *SA*–24 would be 369 lb./day/sq. mi., and the same watershed with 100 percent *SA*–7 + *SA*–48 would yield 736 lb./day/sq. mi.

Land Use

The effect of the various land use types upon the amount of suspended sediment in the streams can also be evaluated (equations 1, 7, 8, 9, 10). The proportions of suspended sediment originating from upland erosion and to be attributed to the use types are: (1) 13 percent from cultivated land (10 percent of area); (2) 42 percent from pasture land (18 percent of area); (3) 17 percent from wild land (28 percent of area); and (4) 28 percent from forest land (44 percent of area).

In this analysis, the proportion of sediment derived from pasture land is much greater than from cultivated land. This is probably due to differences in topography and length of overland flow to the stream. In the Tobacco River watershed, the cultivated areas are primarily confined to the level or gently sloping upland till plain areas, whereas much of the land along stream bottoms is pastured. Streambottom lands characteristically have rough topography with short steep slopes, and discharge surface runoff directly into the stream.

Land use effects are illustrated in figure 5. This shows the relation between land use type and sediment as it occurs. Since land use is so closely related to soil type and topography, this relation merely points out the important sediment contributors and cannot be used to predict the results of land use changes.

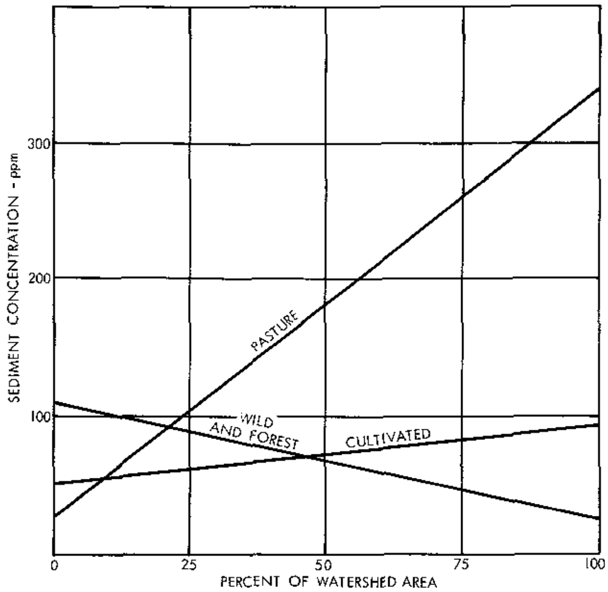

FIGURE 5.— General relation between land use and sediment concentration in the Tobacco River Watershed.

Eroding Banks

One of the more important sources of suspended sediment in the watershed is streambank erosion. Estimates of its contribution range from 26 to 30 percent of the average sediment load with an average of 28 percent (equations 1 to 6).

Erosion from streambanks represents one source of suspended sediment that can be effectively controlled in northern Michigan trout streams. To determine potential reductions within those sample watersheds containing eroding banks (watersheds 1, 2, 3, 8, 11, 12, 19), the values of the watershed characteristics for each sample watershed (table 2) were inserted into equations 3 and 4 and average sediment values computed both with and without the variable for eroding banks. Potential reductions in the average sediment load ranged from 30 to 47 percent (table 4). Whether such reductions can actually be attained remains to be tested.

TABLE 4.—*Predicted sediment reductions by stabilizing eroding banks*

Sample watershed No.	Eroding banks	Average sediment		Predicted sediment		Potential reduction
	100 feet	*P.p.m.*	*Lb./day sq. mi.*	*P.p.m.*	*Lb./day sq. mi.*	*Percent*
1	38	91	677	52	388	43
2	28	74	803	44	482	40
3	15	58	612	38	405	34
8	62	86	573	46	305	47
11	10	67	589	47	477	30
12	20	89	542	56	342	37
19	27	89	544	54	328	39

Conclusions

Several conclusions may be drawn from this study. First, the study demonstrates that watershed characteristics can successfully be evaluated with respect to their influence upon stream sediment concentrations or sediment discharge rates by using individual suspended sediment observations from the sample watersheds rather than total sediment yields as the dependent variables. An added advantage is that a large number of comparisons is possible for any group of sample watersheds.

In northern Michigan, a broad range of surface geology, soils, and land use may occur within major watersheds. In this study, geology, soils, and land use are interrelated to such an extent that any one factor may be used in the prediction equations with similar results.

Sediment derived from upland erosion may be attributed to several sources. The most important sources of suspended sediment are the upland areas with heavier textured surface soils or the surface geologic types from which heavier textured soils develop. Specifically, within the Tobacco River watershed, 47 percent of the average suspended sediment load comes from till plain and lake plains that occupy 32 percent of the area, whereas 53 percent comes from moraine and outwash plain that occupy the remaining 68 percent of the area. A similar division was obtained, using soil association mapping units. Thus, 52 percent of the suspended sediment load comes from *SA*–7, *SA*–48, and *SA*–35 that occupy 31 percent of the area, while 48 percent comes from *SA*–16, *SA*–22, and *SA*–24 occupying the remaining 69 percent of the area.

Sediment yield also varies with land use. In the Tobacco River watershed, pasture lands are the most important sediment producers, probably because of the proximity of a large share of the pasture land to the streams. Streambottom pasture lands characteristically have many short steep slopes and comparatively short lengths of overland flow to the stream. Pasture land, occupying 18 percent of the land area, yields 42 percent of the sediment, whereas 13 percent comes from cultivated land (10 percent of area) and 45 percent comes from forest and other wild land occupying the remaining 72 percent of the area.

Of all sediment sources, eroding banks, which yield about 28 percent of the suspended sediment load, represent a source that the land manager can effectively control. In trout streams with forested drainage areas, eroding banks may be the most important source of sediment. Bank stabilization practices may, therefore, be one means of reducing sediment concentrations in these streams and improving the stream as a trout habitat.

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MEASUREMENTS OF THE SHEAR RESISTANCE OF COHESIVE SEDIMENTS

[Paper No. 23]

By FRANK D. MASCH, *associate professor, Civil Engineering, University of Texas;* WILLIAM H. ESPEY, JR., *hydraulic engineer, U.S. Geological Survey;* and WALTER L. MOORE, *chairman and professor, Civil Engineering, University of Texas, Austin*

Abstract

A rotating cylinder test apparatus designed to measure low shear stresses is described. This apparatus gives a value of the true shear stress on a sediment sample and a measurement for this shear which is independent of such uncertainties as roughness changes and boundary layer growth. The apparatus is also analyzed in view of the work on rotating cylinders by Taylor and others. A standard test procedure is outlined, and results of tests on several laboratory samples are presented.

Introduction

When concerned with stable channel design or localized scour in beds of cohesive sediments, fluvial hydraulicians often resort to selecting either a critical tractive force or a safe permissible velocity so that no undesirable erosion will occur. These methods involve choosing the hydraulic variables so that certain critical shear forces or critical velocities are not exceeded. Etcheverry (*1*), Fortier and Scobey (*2*), Lane (*3*), and others have published tables and graphs summarizing these critical shears and velocities.

While it is generally understood that the scour resistance of a cohesive sediment will depend in some fashion on the properties of the sediment, the relative significance of such parameters as density, moisture content, percentage of clay, Atterberg limits, vane shear, etc., is not fully known. In 1962, Moore and Masch (*4*) summarized much of the existing work on scour in cohesive materials and presented some test results of their own. More recently, Carlson and Enger [1] reported on tests performed at the U.S. Bureau of Reclamation in which soil samples were set into a test well flush with the bottom of a circular tank and water circulated over the sample with a rotating impeller. Critical tractive forces were measured and correlations made with several soil properties.

It is not entirely clear as to whether tractive force measurements made on soil samples set into a section of a smooth-bottom flume or tank are actually representative of the shear that would cause erosion in a cohesive bed. As the flow over the bottom suddenly encounters the soil sample, there is an abrupt change in the bed roughness and velocity distribution. This is particularly true when the surface of the sample is eroding. Under these conditions, the average tractive force is not uniformly distributed over the sample and determinations of critical shear from point velocity measurements are not necessarily representative of the shear on the sample. Tests of this type seem to be preferred, probably because they appear similar to flow in natural streams. However, the similarity may end with the flow being parallel to the bed sample and the critical shear determined from this type test no more representative for a given type bed material than that determined from jet or other dissimilar type tests.

If the relations between the critical shear stress and the various properties of a cohesive material are to be investigated, the need for a way to measure a mean shear that is constant over the entire surface of the sample is evident. The purpose of this paper is to describe a test for determining the critical shear stress at which a stiff cohesive sediment will scour. The apparatus has been designed so that the distribution of the average shear over the sample is uniform. In addition, this average shear is measured directly rather than computed from other experimental data. It should be emphasized that it is not the purpose of this paper to present design criteria for stable channels in cohesive beds.

Development of Apparatus

In 1962, Moore and Masch (*4*) briefly described an apparatus then under fabrication at the University of Texas that could be used to measure directly the shear stress on a sample of a cohesive sediment. Since first reported, the apparatus has undergone some modifications and, in the course of its development, a procedure for measuring the critical shear on a sample has been worked out.

Test Apparatus

The test apparatus was built utilizing a rotating cylinder principle common to some types of viscosimeters. As seen in figure 1, a cylinder of stiff cohesive sediment 3 inches in diameter and 4 inches long was mounted coaxially inside a larger transparent cylinder that could be ro-

[1] CARLSON, E. J., and ENGER, P. F. TRACTIVE FORCE STUDIES OF COHESIVE SOILS FOR DESIGN OF EARTH CANALS. Amer. Soc. Civil Engin., Hydraul. Div. Conf. 11, Davis, Calif. 1962.

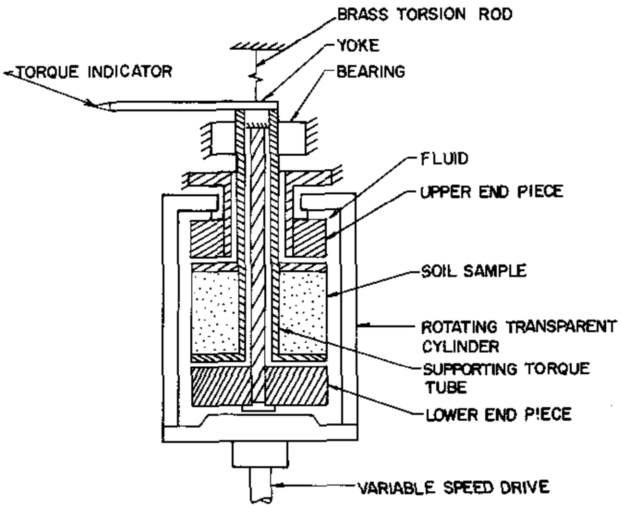

FIGURE 1. — Diagram of modified rotating cylinder test apparatus.

tated at speeds up to 2,500 r.p.m. The apparatus could be operated with either a 3.25- or a 4.20-inch diameter rotating cylinder, giving an annular spacing of either 0.125 inch or 0.60 inch, respectively. To transmit shear from the outer rotating cylinder to the surface of the soil sample, the annular space between the sample and the rotating cylinder was filled with water. Since the annular spacing between the sediment sample and the outer cylinder was constant and there were no abrupt changes in roughness on the area in shear, the stress was uniform at all points on the surface of the soil.

The sediment sample was stationary, but was mounted on a combination radial and thrust bearing so that the shear stress transmitted to its surface resulted in a slight rotation of the supporting tube. This rotation was in turn transmitted to a 0.060-inch diameter brass torsion rod 6 inches long attached through a yoke to the supporting tube. By measuring the deflection of a pointer connected to the yoke and calibrated to give the torque, the shear stress on the sample was obtained. To minimize the variation in shear stress at the ends of the cylinder, 3-inch diameter endpieces were mounted independently of the sample so that the shear applied to their surfaces would not contribute to the measured torque for the soil sample.

Nature of Flow in Apparatus

If the flow in the annular space between two concentric cylinders rotating at steady speed is considered to be parallel, i.e., only the tangential component of velocity not equal to zero, the flow can be analyzed by the Navier-Stokes equations. For the case in which the inner cylinder (radius r_1) is at rest while the outer cylinder (radius r_2) is rotating at an angular velocity of ω_2, Schlichting (*5*) gives the moment (T) transmitted by the rotating cylinder to the fluid as

$$T = 4\pi\mu h \frac{r_1^2 r_2^2}{r_2^2 - r_1^2} \omega_2 \qquad (1)$$

where h is the height of the cylinder. Equation 1 also gives the torque transmitted by the fluid to the sample. Since the shear is directly related to the torque, the shear stress on the inner cylinder or soil sample is given by

$$\tau_0 = 2\mu \frac{r_2}{r_2^2 - r_1^2} \omega_2 \qquad (2)$$

For equation 2 to be applicable, the flow in the annular space between the outer rotating cylinder and the fixed cylindrical soil sample must be that of a stable Couette flow. Generally, the flow in the annulus between rotating cylinders tends to be quite stable because of the effect of inertial forces. Fluid particles near the outer rotating boundary are kept from moving radially inward by large centrifugal forces, whereas those particles near the inner boundary do not move outward because of smaller centrifugal forces.

Schlichting (*5*) has compiled the work of Taylor and others on the critical Reynolds number at which the flow in an annulus between a fixed inner cylinder and a rotating outer cylinder becomes unstable. Figure 2 shows these results as a curve of the critical Reynolds number plotted as a function of the relative annular spacing s/r_2, where s is the annular spacing. For the two outer cylinders used in the soil test apparatus, the critical speeds for stable Couette flow from figure 2 are 344 r.p.m. for the smaller cylinder and 435 r.p.m. for the larger cylinder. These values are summarized in table 1.

From the data plotted in figure 2, the curve of limiting stability appears to be affected by eccentricity in the coaxially mounted cylinders. In those cases where good concentricity was maintained, the critical Reynolds number is seen to be much larger than the limiting curve passing through Taylor's data. To compare the critical Reynolds number for the soil test apparatus with the work of Taylor, the shear stress on a dummy soil sample was measured as a function of the rotational speed of the outer cylinder. The dummy cylinder, which was made of wood 3 inches in diameter and 4 inches long, was tested in the 3.25-inch diameter cylinder. This arrangement gave an annular spacing of 0.125 inch, which is almost identical to a test performed by Taylor in which the annular spacing was 0.122 inch. Results of the test on the sediment apparatus are plotted in figure 3

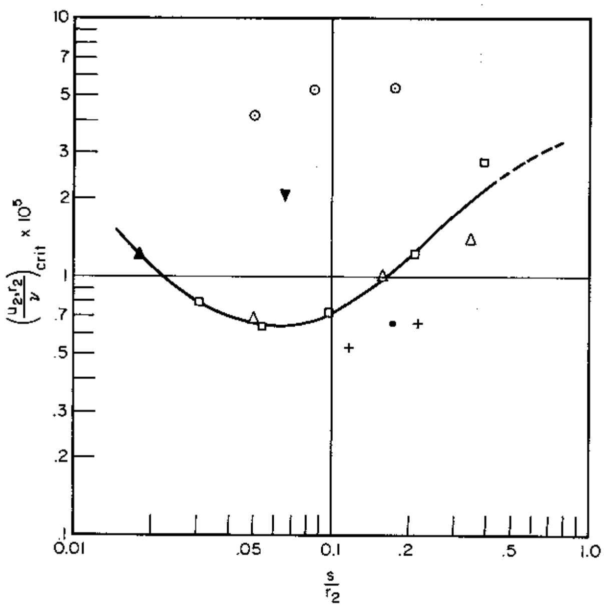

Figure 2. — Critical Reynolds number vs. relative annular spacing. (After Schlichting (*5*).)

where it is seen that the transition from a stable Couette-type flow to an unstable type flow occurs at a rotational speed of 680 r.p.m. This is nearly twice the value of 344 r.p.m. obtained from figure 2.

Taylor (*6*) presented his results for the 0.122-inch annular spacing in the form of two param-

Table 1.—*Critical speeds for stable flow for two cylinders used in soil test apparatus*

Item	Small cylinder	Large cylinder
Critical speed............r.p.m...	344	435
Inner radius (r_1)..........inches..	1.50	1.50
Outer radius (r_2)..........inches..	1.625	2.10
Annular spacing (s).......inch....	0.125	0.60
s/r_2........................	0.077	0.285
Critical Reynolds number.........	6.6×10^4	1.4×10^4

eters, $T/\rho N^2$ and $\rho N/\mu$ where both are given in the c-g-s system of units. These results along with those for the scour apparatus are shown in figure 4.

The fact that stable conditions exist for a greater range of speeds in the scour apparatus is attributed to better concentricity. It is significant that figure 4 is analogous to the conven-

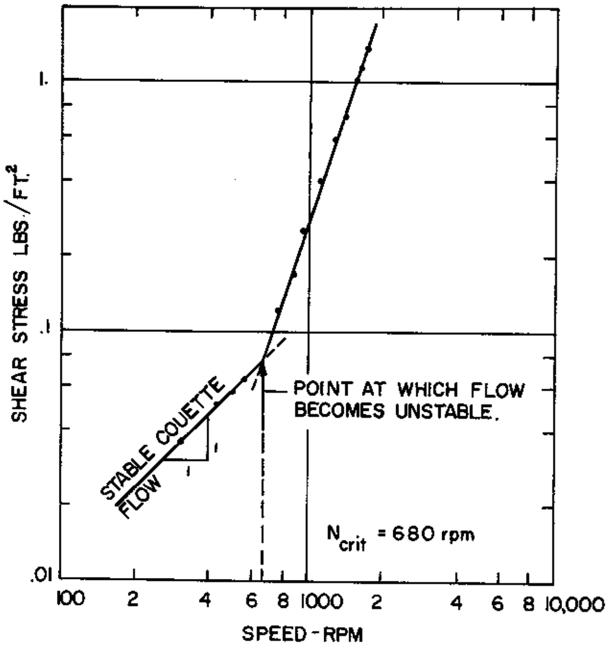

Figure 3. — Shear stress vs. speed.

tional skin friction-Reynolds number relation for flow over flat plates. For most cohesive sediments, the scour apparatus is operated in the unstable zone and the flow is not completely developed turbulent flow. Its operation is normally in the transition where the zone of turbulent flow probably does not extend across the full width of the annulus. This coupled with the

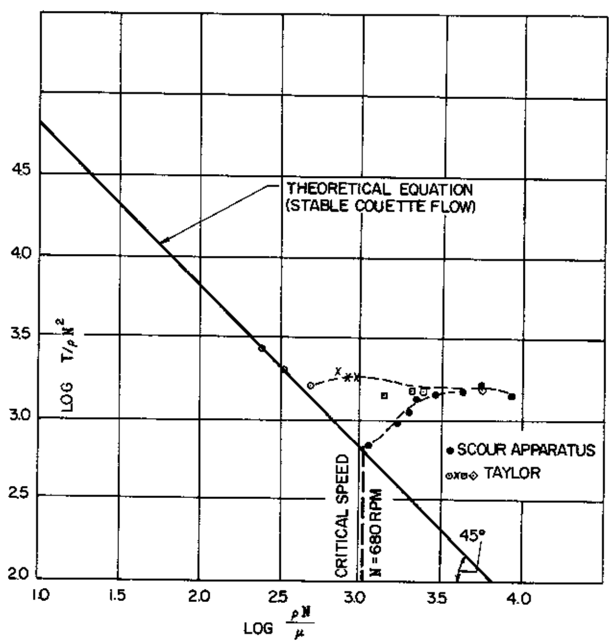

Figure 4. — $T/\rho N^2$ vs. $\rho N/\mu$. (After Taylor, 1960.)

fact that the inertial forces increase in the radial direction tend to make the turbulence level low and the instantaneous shear stress fluctuations on the surface of the soil relatively small. Thus the mean shear measured on the sample should be nearly equal to the maximum shear occurring at any point or at any time.

Test Procedure [2]

During the course of the development of the apparatus, two different test procedures were used to evaluate the critical shear on the surface of a sample of material. The first method consisted of loading the sample to a preselected value of shear over a period of 1 minute and allowing it to scour at this stress for 1 minute. The sample was removed from the apparatus and its weight loss determined. The sample was then replaced in the apparatus, loaded to a higher preselected value of shear in 1 minute, and allowed to scour at this higher stress for 1 minute, and the weight loss again determined. This same procedure was repeated in a systematic manner, each time with a higher value of shear stress. The weight loss was plotted as a function of the shear stress, and the range of stress at which an appreciable quantity of sediment was removed was noted.

The second method used to determine the shear at which scour began was visual. A sample of sediment was placed in the apparatus and the speed of the outer cylinder increased at a steady rate. By viewing the sediment sample through the transparent outer cylinder, it was easy to note the beginning of scour. The beginning of scour was also characterized by a sudden movement of the pointer attached to the torsion rod. When scour was observed, the deflection of the torsion rod was noted and the shear stress measured. This visual test was repeated several times and seemed to be independent of the rate of loading.

Discussion

Measurements of the critical shear causing scour on remolded samples of cohesive sediments were obtained by both test procedures outlined above. In all cases the samples were made from 100 percent Taylor marl and had moisture contents between 28 and 31 percent. The samples that were 3 inches in diameter and 4 inches long were extruded under vacuum with a Vac-Aire extruder, thus insuring that the sample was uniform and free of air voids.

Typical results of the first test procedure are shown in figure 5. At the very low shear stresses the rate of scour is very low. This small amount of scour is attributed to a slight flaking of material from the surface of the sample and probably depends on the condition of the surface of the sample. After a certain critical shear is reached, the rate of scour is suddenly increased. This is the critical shear at which scour is considered to begin. While this type of test does not give the exact value of stress at which the scour starts, it does define limits within which this critical shear must fall. The results of a series of these type tests are tabulated in table 2.

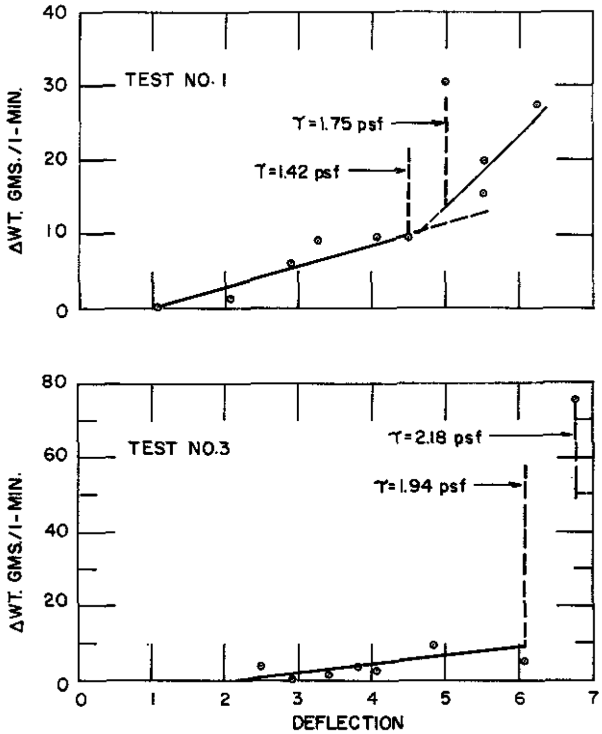

FIGURE 5. — Weight loss per 1 minute vs. deflection.

TABLE 2.—*Critical shear stress by visual test and by weight loss per minute*

Test No.	Critical shear stress range from first test method	Test No.	Critical shear stress from visual test	Moisture content
	Pounds per square foot		*Pounds per square foot*	*Percent*
1....	1.42–1.75	1...	1.74	28
2....	1.94–2.18	2...	1.96	31
3....	1.02–1.58	3...	1.48	31
4....	1.35–1.45	4...	1.74	31
5....	1.47–1.52	5...	1.58	31
		6...	1.82	28
		7...	1.74	30

Several tests that use the visual method for determining critical scour were run on the same material. These results are also summarized in table 2. Again, at the lower speeds it was pos-

[2] ESPEY, W. H., JR. A NEW TEST TO MEASURE THE SCOUR OF COHESIVE SEDIMENT. Master's thesis. On file, University of Texas library, Austin.

sible to observe what might be called a washing of the surface, i.e., the flaking of small soil particles from the surface of the sample. As the speed and the shear stress were increased, the sample was observed through the transparent cylinder until the critical shear was reached, at which time appreciable quantities of sediment came loose from the sample and the water in the annulus became cloudy. After a large quantity of material had scoured from the sample, it no longer conformed to a sample with a uniform shear stress distribution. At the point where scour occurs, separation of the flow develops, producing intense turbulence in the scour hole and downstream from it. The form drag produced by the hole results in tangential forces and thus increases the shear in the hole resulting in a reduction in the shear on the rest of the sample.

If the nature of the material tested is considered, the results obtained with the different test procedures are in fair agreement. In most cases, the visual test results fall within the range of shears obtained with the first test method. There is not enough variation in moisture content to tell whether any relation exists between it and the shear stress.

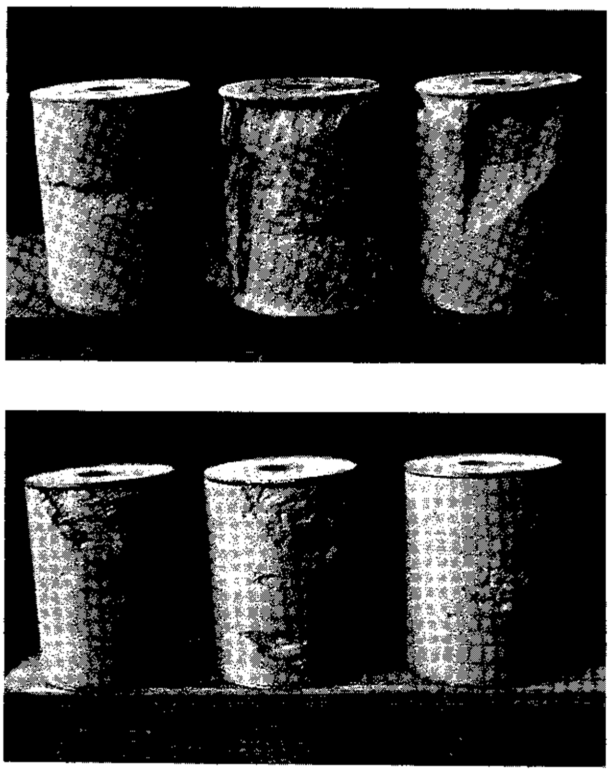

FIGURE 6. — Typical scour patterns.

Systematic failure of the various soils tested was not apparent. Figure 6 shows several typical scour patterns resulting from both types of scour tests. Those samples showing large amounts of scour were tested according to the first method outlined and were subjected to scour at shears greater than the critical value. Those samples showing only small amounts of scour were tested by the visual method. The failure of the sample at several different points supports the contention that the shear stress was relatively uniform over the entire sample.

Conclusions

Based on the results of the investigation outlined above, several conclusions appear to be justified. The rotating cylinder apparatus has been developed and test procedures outlined that enable the critical shear stress at which a given stiff cohesive sediment scours to be obtained. The test procedure is relatively simple and if the nature of the sediment tested is considered, it appears to give consistent results. The level of turbulence is believed to be low so that the average shear measured on the sample when erosion starts should be very near to the actual stress causing erosion, based upon studies of flow in the annular spacing between the soil sample and the rotating outer cylinder.

It now appears feasible to investigate the effect of the various properties of the sediment on the critical shear causing scour. Until a better understanding of the nature of scour is obtained, it is believed that basic studies of this type can best progress by performing tests on remolded sediments so that some control can be maintained over its properties.

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SURFACE RUNOFF AND EROSION AS AFFECTED BY SOIL RIPPING

[Paper No. 24]

By E. J. DORTIGNAC, *forester (research)*, and W. C. HICKEY, JR., *range conservationist (research), Rocky Mountain Forest and Range Experiment Station, Forest Service, Albuquerque, N. Mex.*[1]

Sedimentation is the most critical watershed problem in the arid and semiarid Southwest. It is particularly severe in the Rio Grande basin in New Mexico, where sedimentation depletes reservoir capacities, aggrades river channels, increases the need for maintenance of irrigation systems, damages land and crops, wastes water by evaporation and by evapotranspiration of nonbeneficial vegetation, and contributes to downstream salinity. The worst offender is the Rio Puerco tributary — since 1885 an estimated 600,000 to 800,000 acre-feet of soil has washed into the Rio Grande. Even now, the Rio Puerco, which yields only about 5 percent of the measured runoff above Elephant Butte Reservoir, produces almost half of the measured sediment inflow to the main channel. This damaging sedimentation must be controlled or reduced.

Past misuse and mismanagement has resulted in a deteriorated vegetation cover on the lower lying foothills, mesas, escarpments or bluffs, and valley floors. Over large areas, the once important and highly productive dominant grasses, such as alkali sacaton (*Sporobolus airoides* Torr.), galleta (*Hilaria jamesii* Torr.), black grama (*Bouteloua eriopoda* Torr.), Indian ricegrass (*Oryzopsis hymenoides* (Roen & Schult.) Ricker), and blue grama (*Bouteloua gracilis* (H.B.K.) Lag.), have been largely replaced by less desirable grasses and shrubs. The major change in the natural vegetation of these rangelands has occurred since 1860. Yet, deterioration of these lands had already been observed by explorers of the mid-nineteenth century. Abert (*1*), Simpson (*6*), and Whipple (*9*) observed gullies in the main Rio Puerco channel between 1846 and 1853.

The deterioration of the vegetation has been accompanied by a great reduction in ground cover, leaving most of the land with exposed or bare soil (fig. 1). Surveys and field studies indicate that bare soil and rock comprise 90 to 100 percent of the land area on deteriorated sites.

The resultant harsh microclimate (particularly on south and west exposures) makes rehabilitation of these lands a most difficult task. Management and proper grazing use cannot be expected to restore these lands to full productivity without supplemental mechanical treatments. Moreover, a good vegetation cover for

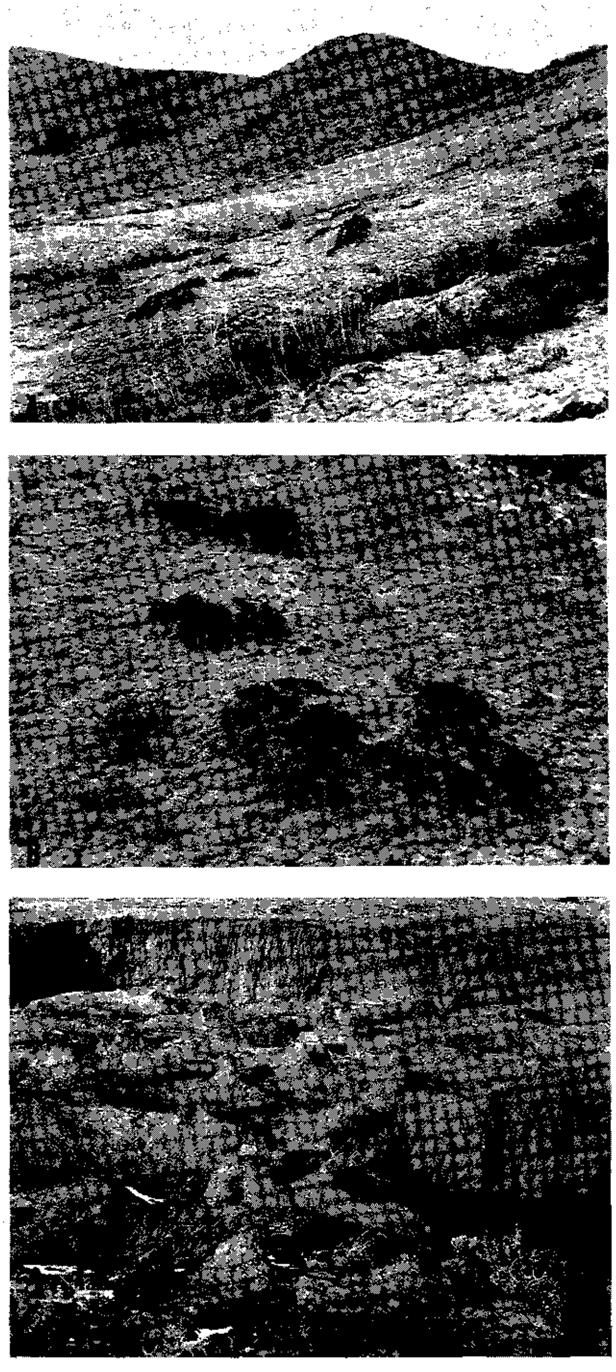

FIGURE 1. — Loss of vegetation and deterioration of the range: *A*, Dead alkali sacaton on shale hill; *B*, root crowns of dead alkali sacaton; and *C*, gully on alluvium downslope from the shale hill.

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[1] A cooperative study between the Bureau of Land Management, U.S. Department of the Interior, and the Forest Service, U.S. Department of Agriculture.

holding soil in place cannot be attained until desirable species become established in sufficient numbers to provide a continuous source of seed dissemination over these lands. Experience has shown that re-establishment of vegetation on deteriorated arid and semiarid rangelands is a slow process and that many years are required for full recovery.

Reseeding grass and browse has usually failed on the Upper Rio Grande basin rangelands below the big sagebrush (*Artemesia tridentata* Nutt.) belt or where average annual precipitation is less than 12 or 13 inches. Improvement of the severe microclimate on deteriorated sites in this semiarid climate is an essential first step in any program of vegetation restoration. An increase in soil moisture and a reduction in air and soil temperatures are the most important elements to be considered.

Improvement of the soil moisture regime may be accomplished by increasing the water retention capacity, the infiltration capacity, or both. Several soil treatments, such as basin listing, contour trenching, and pitting, are recognized methods of increasing the retention capacity and prolonging the time for infiltration. Depending on soil type and condition, this type of land treatment may or may not increase the rate of water intake. Yet the initial retention of water increases the time for infiltration, at least until the basins or soil openings become filled with sediment.

An increase in soil moisture usually results in greater production of forage, crop, or trees. Several reports indicate range pitting with modified disks that gouge out small, closely spaced basins has improved forage production and grazing capacity (*2*, *3*, *5*). Also, Rauzi (*4*) reported higher water infiltration on pitted rangeland. These studies indicated that 50 to 100 percent more water infiltrated in pitted areas than in adjacent nontreated areas and that a newly formed pit holds 0.3 inch of rain. Measurements of the average size of pits made by several types of mechanical equipment in New Mexico indicate that basins when first formed hold 0.25 to 0.50 inch of water. Subsequent sediment-laden surface runoff may soon fill the pits with soil and reduce their effectiveness for water storage. However, the establishment of more desirable hydrologic plant species or an increase in the ground cover as a result of pitting usually contributes to higher infiltration capacities. Moreover, on certain soils with impermeable layers near the surface, a rotary pitter with a long tooth can loosen and open this layer to water intake and prolong the effectiveness of the pit.

Valentine (*8*) reported that five selected types of structures to check runoff water from semidesert range (New Mexico Experiment Station's Experimental Ranch) failed to improve the vegetation cover on the sites where installed. One of the treatments included large ripper furrows made with a road ripper. This implement dug a broad, flat furrow about 6 inches deep and 24 to 30 inches across. Soil factors, such as erodibility and low moisture retention capacity, were thought to be responsible for the lack of vegetation improvement under all treatments tested.

Soil ripping increases the water storage capacity of the land until the fissures become filled with washed-in or blown-in soil and until weathering levels the roughened surface (fig. 2). Soil ripping may derive its greatest hydrologic benefit by increasing the water absorbing area and by allowing surface runoff water to penetrate directly into the less permeable subsoil. This latter condition is extremely important when shallow soils are underlain with

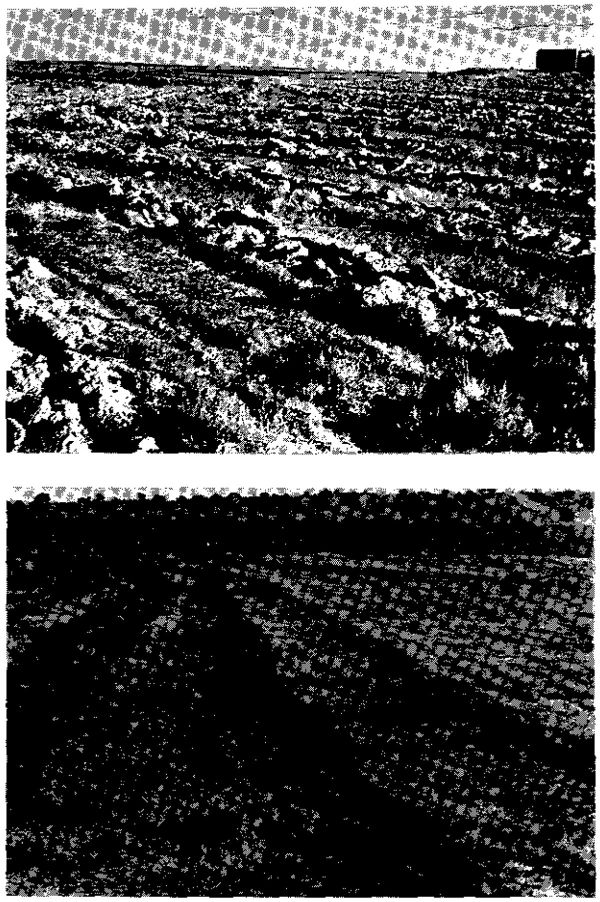


FIGURE 2. — Temporary water-storing dams or terraces formed in the soil-ripping operation.

impervious parent material or developed B horizons.

The reported study is an attempt to evaluate the effectiveness of soil ripping with a Jayhawk Soil Saver on surface runoff, erosion, and vegetation response.

Location of Study

The study area is a seriously deteriorated site in the Rio Salado drainage that enters the Rio Jemez, 2 miles south of San Ysidro, N. Mex. This site probably represents the poorest range and hydrologic condition in the Rio Jemez and adjacent Rio Puerco basins (fig. 3). Ground cover in the summer of 1958, when the site was selected, averaged less than 2 percent. Annual forbs comprise the main vegetation. There were few living alkali sacaton plants, but numerous dead plants indicated this grass species previously covered most of the shale hills, colluvium, and alluvium (fig. 1).

Soils are derived from Mancos shale, an Upper Cretaceous marine deposit of high salinity. This parent material is covered by 10 inches to 8 feet of soil on the northeast exposure and mostly exposed shale on the southwest aspect. Mancos shale disintegrates quite rapidly when immersed in water. Laboratory tests showed that 1- to 2-pound samples of hard shale, obtained with a pick, dispersed completely within 10 minutes after immersion in a vessel containing tap or distilled water. This instability is conducive to rapid weathering when this shale rock is exposed to the elements of climate.

The clay mineral has been identified as illite, a hydrous mica. Derived soils are silty clay and silty clay loams. The alluvium on both aspects is cut by numerous fingering gullies, a result of the past high surface runoff over the area (fig. 4). Vertical gully walls are common in this soil type.

Annual precipitation averaged about 8.3 inches during the 3 years. About 70 percent of the precipitation was received mostly in high-intensity rainstorms (maximum rate recorded was 4.5 inches per hour for 3 minutes) between April 1 and December 1, while the balance was largely snowfall (table 1).

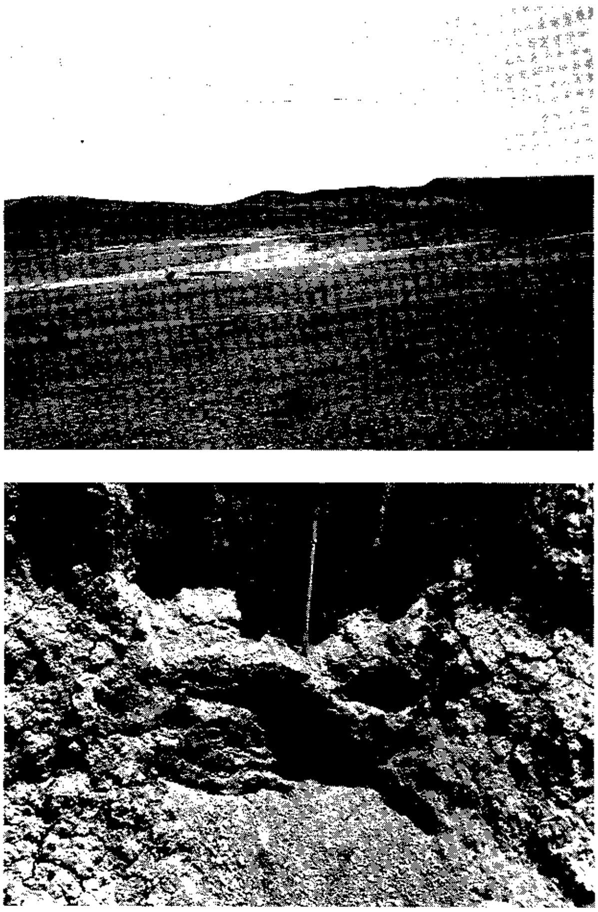


FIGURE 3. — General view of southwest aspect and close-up of shale soil of study area.

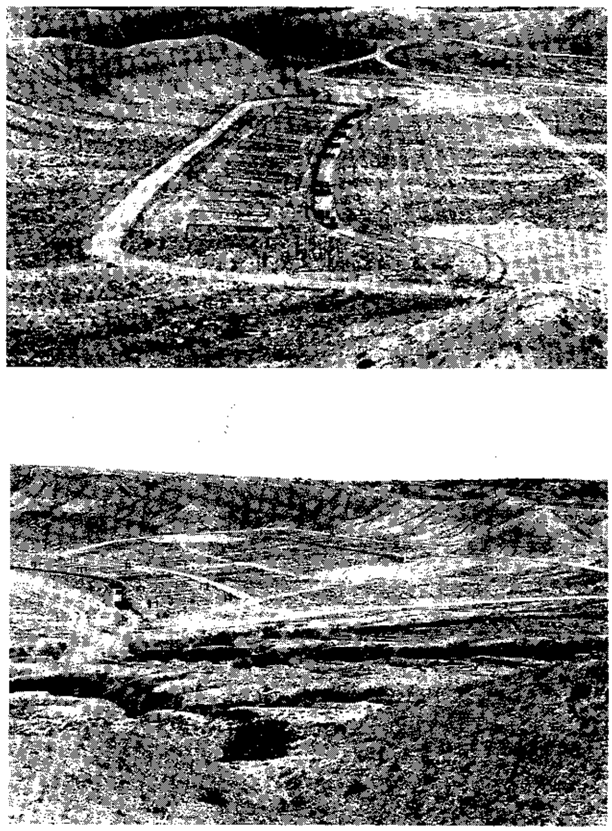


FIGURE 4. — General views of northeast aspect, the ripping site, and fingering gullies.

TABLE 1.—*Precipitation at experimental site in the Rio Salado drainage, 1958-61*

Year	December 1 through March 31	April 1 through November 30
	Inches	*Inches*
1958–59	1.66	5.31
1959–60	3.89	6.45
1960–61	1.87	5.74
Average	2.47	5.83

The long-term average annual precipitation, estimated from the isohyetal map of the Rio Puerco, is about 10 inches (*7*). Accordingly, below average precipitation occurred during this study.

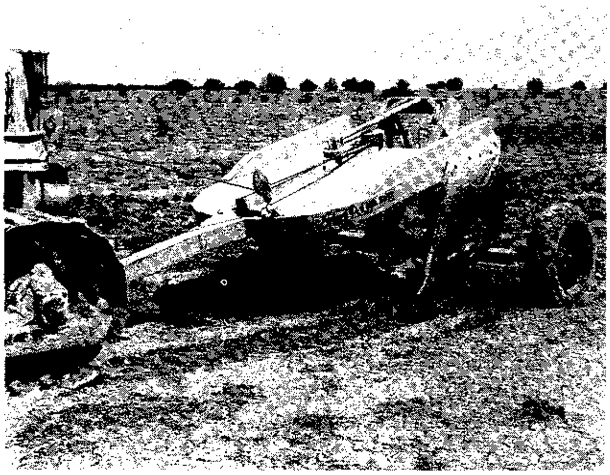
Method of Study

Soil Ripper (Jayhawk Soil Saver)

The soil ripper (Jayhawk Soil Saver) (fig. 5)[2] was developed and first used in Kansas. A revolving auger behind the chisel rotates clockwise as the ripper is pulled through the soil profile. Field excavations have shown that this ripper forms rather large openings in the subsoil which provide an appreciable increase in the water-holding capacity and in the water-absorbing area.

The Jayhawk Soil Saver required a D-8 tractor on these and similar soils. The depth of ripping varied from 24 to 30 inches, depending on soil bulk density, soil moisture, and depth to the parent material. Soil rips were spaced 7 feet apart.

The soil ripper in action (fig. 5) and the land surface after treatment (fig. 2) indicate the soil treatment possibilities with this equipment. Some residual vegetation is destroyed during soil ripping, but this loss may be more than offset by the grass recovery (fig. 6).



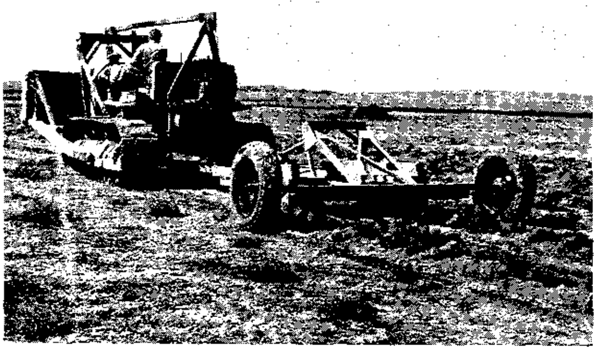


FIGURE 5. — Soil ripper (Jayhawk Soil Saver) pulled by a D-8 tractor.

FIGURE 6. — Grass recovery 1 year after treatment with the soil ripper; untreated area at extreme left.

In field trials conducted in Wyoming, Rauzi and Lang (*5*) found that pitting with the offset disk removed approximately one-third of the existing vegetation, but the increased volume of growth on the remaining plants exceeded the production from the nontreated areas. Less vegetation is destroyed in soil ripping than in soil pitting with offset disks.

Field Installations

Surface runoff plots were installed on the upper and lower slopes of a northeast and a southwest exposure below a shale hill (fig. 7). Plots on the upper slope were placed near the base of the shale hills, whereas those on the lower slope were about 200 to 300 feet above the gullies (fig. 8). Depth of soil increases in proceeding downslope from the shale hill toward the gullies. Slope gradient averages 10 percent

[2] More recently Bureau of Land Management technicians have modified the Jayhawk Soil Saver by adding a range seeder and two duckfoot cultivators on both sides of this soil ripper. The present study covers ripping with the unmodified Jayhawk Soil Saver.

FIGURE 7. — Runoff plots on southwest aspect below the shale hills.

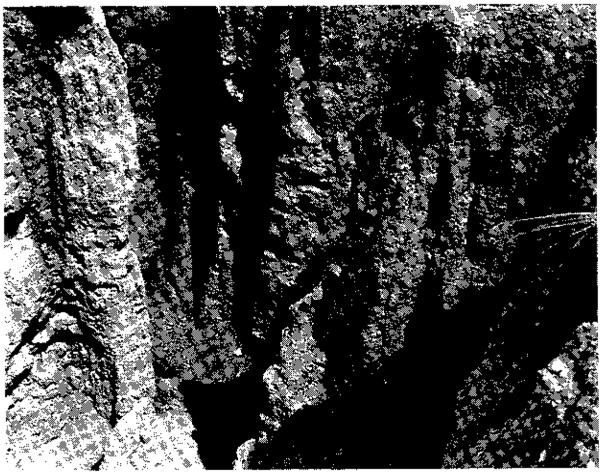


FIGURE 8. — Gully below the shale hills and runoff plots.

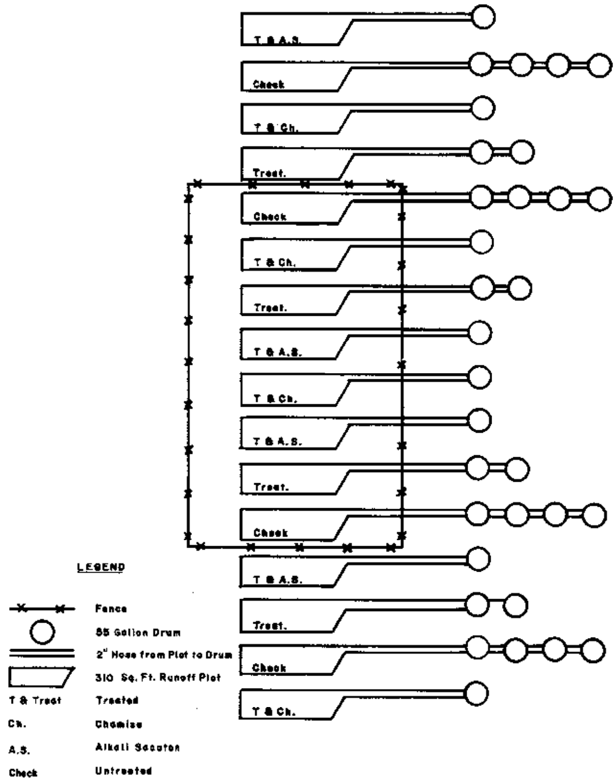


FIGURE 9. — Plot layout for one slope and one exposure.

on the northeast aspect and 6 percent on the southwest exposure.

The design provides for a comparison of the effect of soil ripping by exposure and slope position. In addition, two closures to exclude rabbits and livestock (proof exclosures) were constructed at each of the above positions to provide a replication of these treatments by slope position and exposure. Four separate treatments, representing untreated soil (the control), soil ripping, soil ripping with seeding to alkali sacaton, and soil ripping with seeding to chamiza, or fourwing saltbush (*Atriplex canescens* (Pursh) Nutt.) were installed for each above-mentioned condition (fig. 9).

In all, 64 surface runoff plots were installed at this location. Plots are 10 x 30.5 feet, with the length parallel to the slope. Plot materials and construction details have been described.[3]

The overall plot layout was staked in the field prior to soil ripping, which was done on the contour. The soil ripper was lifted out of the soil before crossing the check or "no treatment" plot zones. Timbers were laid to prevent soil compaction by the tractor and the ripper on the untreated area. A 10-foot buffer or isolation strip separates the individual plots.

It was necessary to seal the soil fissures formed by the Jayhawk Soil Saver on both sides of each plot.[4] This was accomplished by using a steelplate (3/8 x 8 x 40 inches) with a piece of 3/8-inch angle iron welded to the top (fig. 10). The pointed end of this plate was placed against the outside border of the plot and pounded into the ripped zone with an 8-pound hammer. Loose soil was shoveled from the soil rip adjacent to the steel plug and tightly tamped back in place with the head and handle of the sledge hammer. A handyman jack was used to extract the steelplate without disturbing the plot borders nor the tamped soil.

[3] GARCIA, GEORGE, HICKEY, W. C., JR., and DORTIGNAC, E. J. AN INEXPENSIVE RUNOFF PLOT. U.S. Forest Serv. Res. Note RM-12, 8 pp., illus.

[4] This method was first tested by sealing various 3-foot lengths of ripped soil. After the sealing was completed, 110 gallons of water were poured into each length of rip. Forty-eight hours later the rips were dug out at each end of the 3-foot sealed portions. No leakage was noted in any of these preliminary tests nor in subsequent examinations of soil profiles outside runoff plots after rainstorms.

IGURE 10. — Sealing the soil rips at runoff plot borders.

Four rain gages, two recording and two standard, were installed at the start of this study. Two more gages were added later. Six gages were needed, because precipitation varied appreciably for certain storms (fig. 11). Despite the variation in precipitation measured between gages for individual storms, the seasonal catch did not vary greatly between gages on the same aspect.

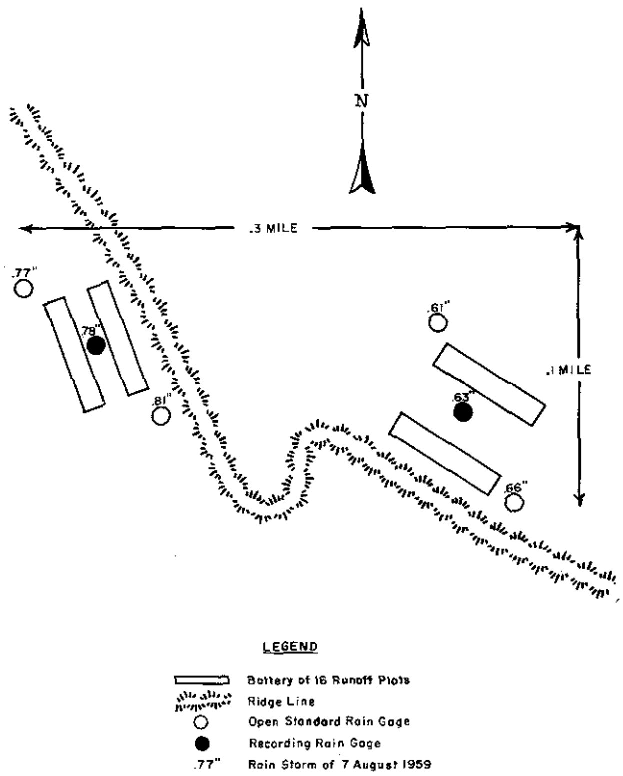


FIGURE 11. — Study layout and location of rain gages. Note the variation in rainfall measured after a single summer rainstorm.

Results

Vegetation

Attempts to establish alkali sacaton and chamiza were mostly unsuccessful. These species were seeded in the spring, summer, and fall of 1959, 1960, and 1961. Seeds germinated when favorable moisture conditions prevailed but died in the subsequent excessive heat, drought, or severe overwinter conditions. On several occasions, the excessive surface runoff during torrential rainstorms washed the surface soil and germinated seedlings into the collection troughs and barrels.

Straw was used for mulching on two soil-ripped plots seeded in the summer of 1961. Alkali sacaton became established on one plot and chamiza on the other. These two plots were covered with snowfence to provide half-shade in late August and September.

Seedlings survived the winter with no protection except the small amount of residual straw that provided a partial cover. By May 1962, the dry soil and strong winds were threatening the survival of these established plants. Soil deposition from wind had already covered some of the new plants.[5] Additional straw mulch was placed over these two plots and on the bare soil to the windward. In August 1962, an excellent stand of alkali sacaton had become established on one plot and chamiza on the other (fig. 12). The study has not progressed long enough to provide an indication of the effect of this newly established vegetation on surface runoff and erosion.

Native vegetation improved slightly over the entire site during the 3 years. No significant

FIGURE 12. — One-year-old alkali sacaton plants appear permanently established.

[5] Soil movement by wind action was most serious during the 1961-62 fall-winter-spring period. By May 1962, windblown soil had filled the 0.3-cubic-foot capacity of runoff collection troughs, necessitating removal of soil before the start of the summer rains.

differences in vegetation were measured between the various conditions sampled at the start and end of the study, except on the two plots successfully seeded.

Surface Runoff

First year after treatment

Overwinter (1958-59) and early-spring precipitation did not produce measurable runoff from the check or untreated plots on the upper slope of either aspect. These were the first plots to be completely installed. The first rainstorm that produced measurable surface runoff occurred on May 26, 1959 (table 2).

TABLE 2.—*Rainfall and surface runoff from upper slope untreated plots, May 26, 1959*

Aspect	Rain	Surface runoff	Portion of rain as runoff
	Inch	*Inch*	*Percent*
Northeast	0.58	0.248	43
Southwest	.26	.150	58

A complete reduction (100 percent) in surface runoff was attributed to soil ripping because no runoff was measured on any of the treated plots. This was an important reduction, as about one-half of the rainfall produced surface runoff.

All plots were operating before the next rain, which fell on June 21. This storm varied between 0.26 inch and 0.30 inch among the four rain gages then installed. About 32 percent of this rain ran off the untreated plots on the northeast exposure, and 8 percent ran off on the southwest aspect. No runoff was yielded from any of the soil-ripped plots.

Nine additional rainstorms produced surface runoff in 1959, the last storm occurring on October 30 and 31. Five of these storms produced appreciable quantities of runoff on untreated plots (table 3).

TABLE 3.—*Total rainfall and total surface runoff from untreated plots for period June 21 through October 31, 1959*

Aspect and slope	Rainfall	Surface runoff	Portion of rain as runoff
	Inches	*Inches*	*Percent*
Northeast; upper	4.35	1.516	35
Northeast; lower	4.35	1.972	45
Southwest; upper	4.45	.311	7
Southwest; lower	4.45	.464	10

Surface runoff varied from 9 to 72 percent of the total measured rainfall, depending on the size of storm and rainfall intensity. To illustrate, the three largest rainstorms (0.94, 0.79, and 0.70 inch) on the northeast aspect produced 59 and 74 percent of the total annual runoff from check plots on the upper and lower slopes, respectively. But measured runoff was very similar to the quantity of rainfall received at rates exceeding 0.25 inch per hour for all but the last storm. Rainfall intensities were much lower during the prolonged October 30-31 storm — only 0.02 inch of rain fell at rates exceeding 0.25 inch per hour. Surface runoff of 0.47 and 0.56 inch for the upper and lower slopes, respectively, approximated the total rainfall exceeding 0.10 inch per hour. Surface runoff amounted to 51 percent of storm rainfall on the northeast exposure.

Surface runoff was much less from plots installed on the southwest aspect, which contains mostly shale parent material. Two explanations are given for this apparently higher infiltration rate on the much poorer soil and more xerophytic site. The shale material develops large cracks in drying due to shrinkage (fig. 13). This network of fissures reacts similarly to the mechanically soil-ripped areas in regard to water intake. Also, soil ripping on the adjacent surrounding area may have facilitated soil cracking on the untreated plots and caused soil piping, a type of subterranean or tunnel erosion (fig. 14). Soil piping was first observed on the southwest aspect.

Regardless of this unanticipated finding, soil ripping caused an appreciable reduction in surface runoff on both aspects during the first year following treatment (table 4).

TABLE 4.—*Surface runoff on soil-ripped and untreated plots, 1959–60 season*

Aspect and slope	Surface runoff		Reduction in surface runoff
	Untreated	Ripped	
	Inches	*Inches*	*Percent*
Northeast; upper	1.764	0.079	96
Northeast; lower[1]	1.944	.029	99
Southwest; upper	.532	.004	99
Southwest; lower[1]	.355	.027	92

[1]Excludes the May 26, 1959, rainstorm—plots not installed.

Second year after treatment

During the second summer after soil treatment there were 13 storms, each with less than 0.2 inch of rain. Surface runoff was not produced. However, the 5-day autumn rainstorm (October 15-19) produced surface runoff. Soils were extremely dry at the start of the rainstorm, and surface runoff from untreated plots was much less at the beginning than during the latter part of the storm when soils were wet (table 5).

TABLE 5.—*Surface runoff on untreated plots during rainstorm October 15 to 19, 1960*

Aspect	October 15-17			October 19		
	Rain	Surface runoff	Portion as runoff	Rain	Surface runoff	Portion as runoff
	Inches	*Inch*	*Percent*	*Inch*	*Inch*	*Percent*
Northeast	2.48	0.124	5	0.90	0.352	39
Southwest	2.54	.056	2	.88	.264	30

Reduction in surface runoff caused by ripping on the southwest aspect was much greater during the latter part of the storm (table 6).

Apparently, after 2.5 inches of rain in 3 days the soil cracks on the untreated plots of the southwest aspect were filled by soil swelling and by deposition of eroded soil.

The portion of rain as surface runoff on the northeast exposure was much less in 1960 than

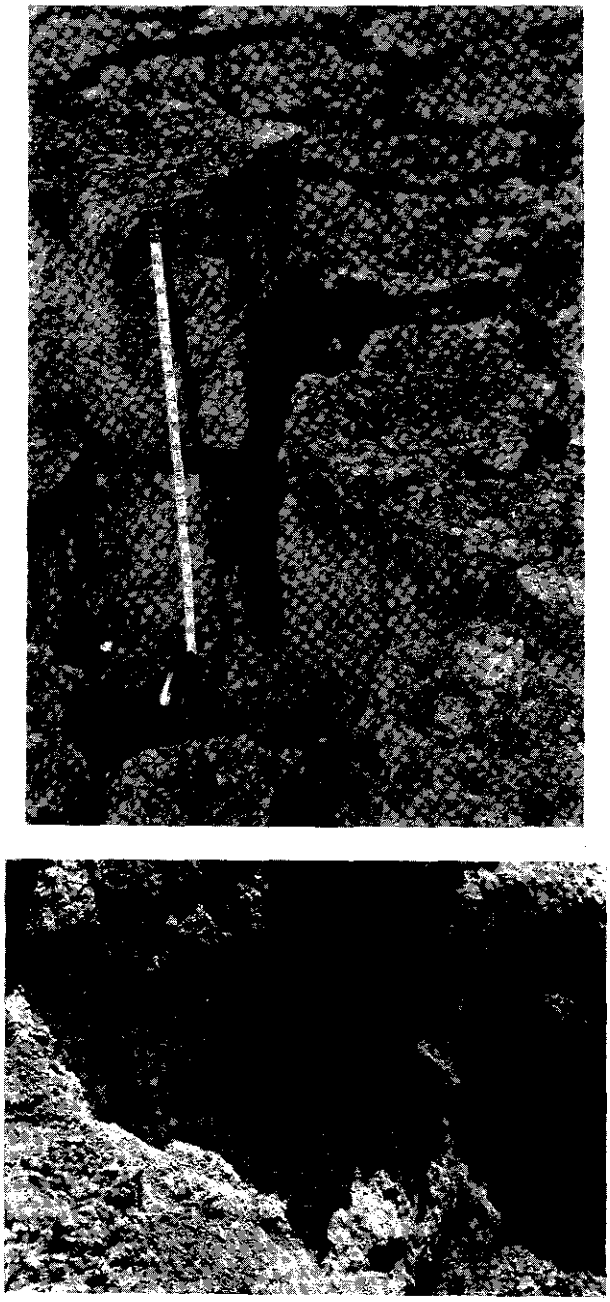


FIGURE 13. — Characteristic vertical cracking of shale material into hexagonal columns.

TABLE 6.—*Reduction in surface runoff on soil-ripped plots during rainstorm October 15 to 19, 1960*

Aspect and slope	Reduction in surface runoff	
	October 15-17, 1960	October 19, 1960
	Percent	*Percent*
Northeast; upper	73	77
Northeast; lower	99	97
Southwest; upper	26	67
Southwest; lower	44	69

in 1959, but it was quite similar on the southwest aspect (table 7).

Third year after treatment

In 1961, eight rainstorms produced surface runoff; the first occurred on July 3 and the last on October 30. This runoff was markedly reduced by soil-ripping even in the third year after treatment (table 8). Total surface runoff and the reduction caused by soil ripping is given by aspect and slope position.

TABLE 7.—*Total rainfall and surface runoff on untreated plots, 1960*

Aspect and slope	Rainfall	Surface runoff	Portion of rain as runoff
	Inches	*Inch*	*Percent*
Northeast; upper	3.38	0.219	6
Northeast; lower	3.38	.733	22
Southwest; upper	3.42	.386	11
Southwest; lower	3.42	.254	7

Reduction in runoff varied from 61 to 100 percent for individual storms. A somewhat greater percent of reduction in runoff was measured from the smaller storms (table 8).

TABLE 8.—*Surface runoff on treated and untreated plots, July 9–October 30, 1961*

Aspect and slope	Total surface runoff		Reduction in surface runoff	Reduction in runoff for storms of—	
	Untreated	Treated		Less than 0.10 inch	0.10 to 0.52 inch
	Inches	*Inch*	*Percent*	*Percent*	*Percent*
Northeast; upper	1.404	0.339	76	78	76
Northeast; lower	1.707	.266	84	96	84
Southwest; upper	.475	.061	87	90	86
Southwest; lower	.687	.120	83	94	81

The portion of rainfall yielded as runoff from untreated plots in 1962 varied between aspects and positions (table 9).

TABLE 9.—*Total rainfall and surface runoff from untreated plots, 1962*

Aspect and slope	Rainfall	Surface runoff	Portion of rain as runoff
	Inches	*Inches*	*Percent*
Northeast; upper	4.65	1.40	30
Northeast; lower	4.65	1.71	37
Southwest; upper	4.41	.48	11
Southwest; lower	4.41	.69	16

Soil Erosion

In 1959 and 1961, soil losses from untreated plots on the northeast aspect were much greater than from the poorer site on the southwest exposure. In contrast, the late fall rainstorm of October 15-19, 1960, resulted in similar amounts of erosion from both aspects. Table 10 compares the annual measured soil losses from treated and untreated plots. The reduction in erosion averaged 86 percent in 1959, 73 percent in 1960, and 30 percent in 1961. However, erosion from land slopes was relatively small from all conditions sampled. Even the maximum annual soil loss of 4,152 pounds per acre from the upper slope on the northeast aspect is considerably less than might be expected from these deteriorated sites. But plots 31 feet long do not accurately measure erosion losses — probably less than one-third of the actual soil losses occurring above the gully system on this site. On the other hand, surface runoff per unit-area on these plots is much more representative of runoff over the larger site area.

Summary and Conclusions

By 1963, approximately 30,000 acres of public domain in the Rio Puerco has been treated with the Jayhawk Soil Saver, commonly called a soil ripper, and seeded to grass and browse species. The maximum slope treated is about 20 percent, but slopes as great as 30 percent might be so treated.

During the 3-year study, surface runoff did

TABLE 10.—*Comparison of soil losses by topographic positions for soil-ripped and untreated plots, 1959–61*

Year, aspect, and slope	Untreated	Ripped	Reduction
1959	*Pounds/acre*	*Pounds/acre*	*Percent*
Northeast; upper	2,218	110	95
Northeast; lower	1,912	100	95
Southwest; upper	300	74	75
Southwest; lower	614	131	79
1960			
Northeast; upper	76	27	64
Northeast; lower	200	7	96
Southwest; upper	252	90	64
Southwest; lower	81	27	67
1961			
Northeast; upper	4,152	1,877	55
Northeast; lower	2,480	1,350	46
Southwest; upper	1,763	1,634	7
Southwest; lower	1,888	1,691	10

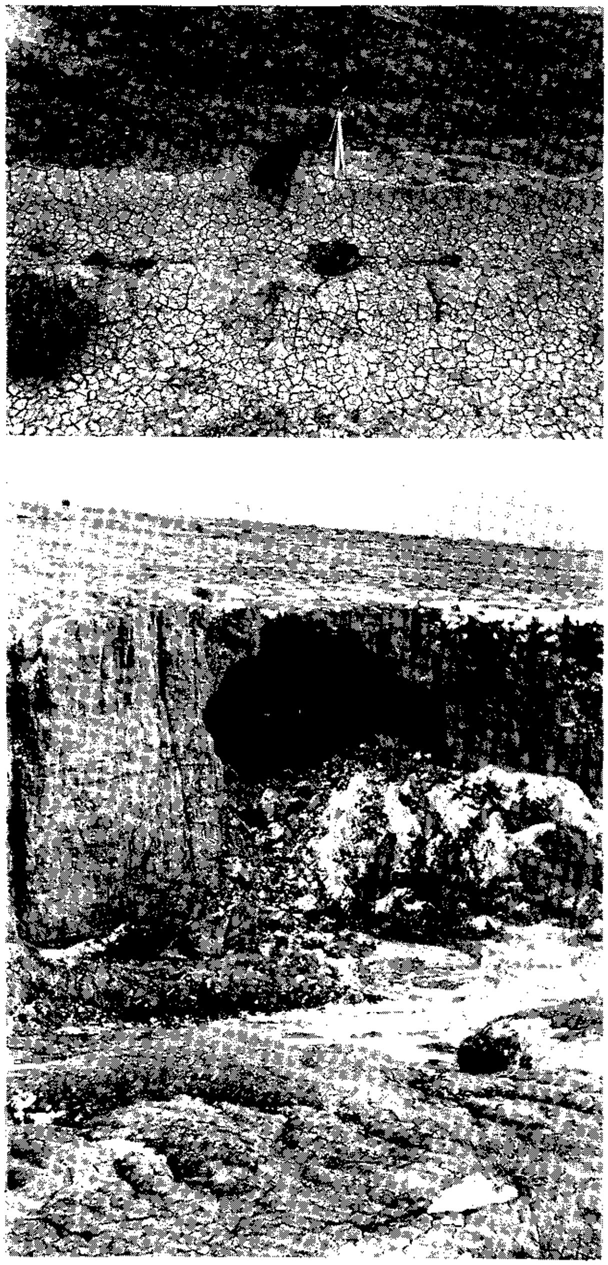


FIGURE 14. — Soil pipe openings on a side slope and in a gully wall representing the pipe inlet and outlet.

not occur before May 26 nor after October 31. During these years measured runoff from untreated or check plots averaged 22 percent of the runoff-producing rain received in the period between May 26 and October 31, 32 percent on the north aspect and 11 percent on the south exposure. But surface runoff from individual storms varied from 0 to 93 percent of the total storm rainfall, depending on quantity of rainfall, rainfall intensity, and antecedent soil moisture conditions. However, annual runoff was only 10 percent of annual precipitation.

Soil ripping with the Jayhawk Soil Saver reduced surface runoff about 97 percent the first year. The effect of this treatment persisted even without vegetation improvement during the 3 years. In the third year following the soil-ripping operation, an 83-percent reduction in surface runoff was experienced. Erosion was likewise reduced, amounting to 86 and 30 percent for the first and third years following the soil-ripping operation.

Soil ripping is effective in reducing surface runoff and erosion from deteriorated rangelands in this area.

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A SUMMARY OF THE WORK OF THE INTER-AGENCY SEDIMENTATION PROJECT

[Paper No. 25]

By FRED S. WITZIGMAN, *hydraulic engineer, U.S. Army Engineer Division, Missouri River*

Abstract

The Inter-Agency Sedimentation Project was initiated in 1939, mainly to develop improved sediment sampling instruments and techniques for measurement and analysis of sediment loads in streams. In 1956, the purpose of the project was expanded to include the solution of sedimentation problems that are of common concern to Federal agencies on the Subcommittee on Sedimentation of the Inter-Agency Committee on Water Resources, with special emphasis on methods of sampling automatically.

Manually operated sediment samplers developed and currently recommended for field use include: (1) three depth-integrating suspended-sediment samplers that collect samples continuously from the stream as they are lowered from the surface to the bed and raised back to the surface; (2) two point-integrating suspended-sediment samplers with electrically operated valves; and (3) three bed-material samplers.

Instruments have been developed, such as the single-stage sampler that is in widespread use and the pumping samplers that are in the field-testing stage, for obtaining samples or sediment information automatically from flashy streams when no observer is present.

Two sediment-size analyzers have been developed. The bottom-withdrawal tube is a sedimentation device for size analysis of sediments finer than 0.7 mm. The visual-accumulation tube is a sedimentation device for the particle-size analysis of sand samples.

Methods for determining concentration and particle size gradation which are being explored are electronic sensing, turbidity, ultrasonic sensing, and nuclear.

History and Program of the Project

Several agencies of the United States Government organized an Interdepartmental Committee in 1939 to study problems in collecting sediment data and to develop, improve, and standardize methods and equipment for determining the quantity and character of sediment carried by streams. The initial project was under the general supervision of E. W. Lane of the Iowa Institute of Hydraulic Research. In April 1946, the activities and functions of the Committee were transferred to the Subcommittee on Sedimentation of the Federal Inter-Agency River Basin Committee. One of the objectives of this Committee is the coordination of the hydrologic activities of the Federal Departments through the assistance of several subcommittees. In June 1948, the project was transferred from the Iowa Institute of Hydraulic Research to the St. Anthony Falls Hydraulic Laboratory of the University of Minnesota in Minneapolis, Minn. In 1955, the name of the parent Committee was changed to the current designation, Inter-Agency Committee on Water Resources.

In 1956, the Subcommittee on Sedimentation adopted a Guidance Memorandum that outlined the program and organization of the present Inter-Agency Sedimentation Project. The basic purpose of the project is to solve sedimentation problems of common concern to agencies that are represented on the Committee. Since 1956, major emphasis has been on development and improvement of equipment for the automatic collection and analysis of sediment samples.

The executive direction of technical phases of the project is the responsibility of a Technical Committee, whose membership is made up of representatives from Federal agencies actively interested in sedimentation problems. The Committee provides technical advice and assistance to the project staff, who carry out the development, testing, and calibration of instruments, preparation of technical reports, and other operational phases of the project. The agencies actively cooperating in the project and currently represented on the Technical Committee are: Army Corps of Engineers, Geological Survey, Bureau of Reclamation, Agricultural Research Service, Public Health Service, Forest Service, Tennessee Valley Authority, and Soil Conservation Service. Results of the cooperative study to date are incorporated in a series of technical reports listed in the appendix. Many sediment sampling devices and analytical methods have been developed by the project.

The following personnel are currently active on the project: Frederick S. Witzigman, who prepared this paper, Russell P. Christensen, and Martin E. Nelson of the U.S. Army Corps of Engineers; and Byrnon C. Colby, project engineer, who reviewed this paper, Thomas F. Beckers, and John V. Skinner of the U.S. Geological Survey.

This paper was prepared to summarize major accomplishments of the project. The work of the project from 1939 to the present time may be divided into four phases. The three that relate to the development of sampling or analyzing devices are discussed in this paper under "manual sediment samplers," "automatic samplers," and "sediment analyzing devices." Work under a fourth title "theories and procedures" is not directly and closely related to the development of specific methods or instruments and is not discussed in this paper but is covered in the reports listed on page 176.

Manual Sediment Samplers

A series of suspended-sediment and bed-material samplers (some are shown in fig. 1) that are operated manually have been developed by the project. These samplers are of three types: depth-integrating, point-integrating, and bed-material.

Depth-Integrating Samplers

Depth-integrating samplers traverse the stream depth at the sampling vertical to within a few inches of the bed, move at a uniform

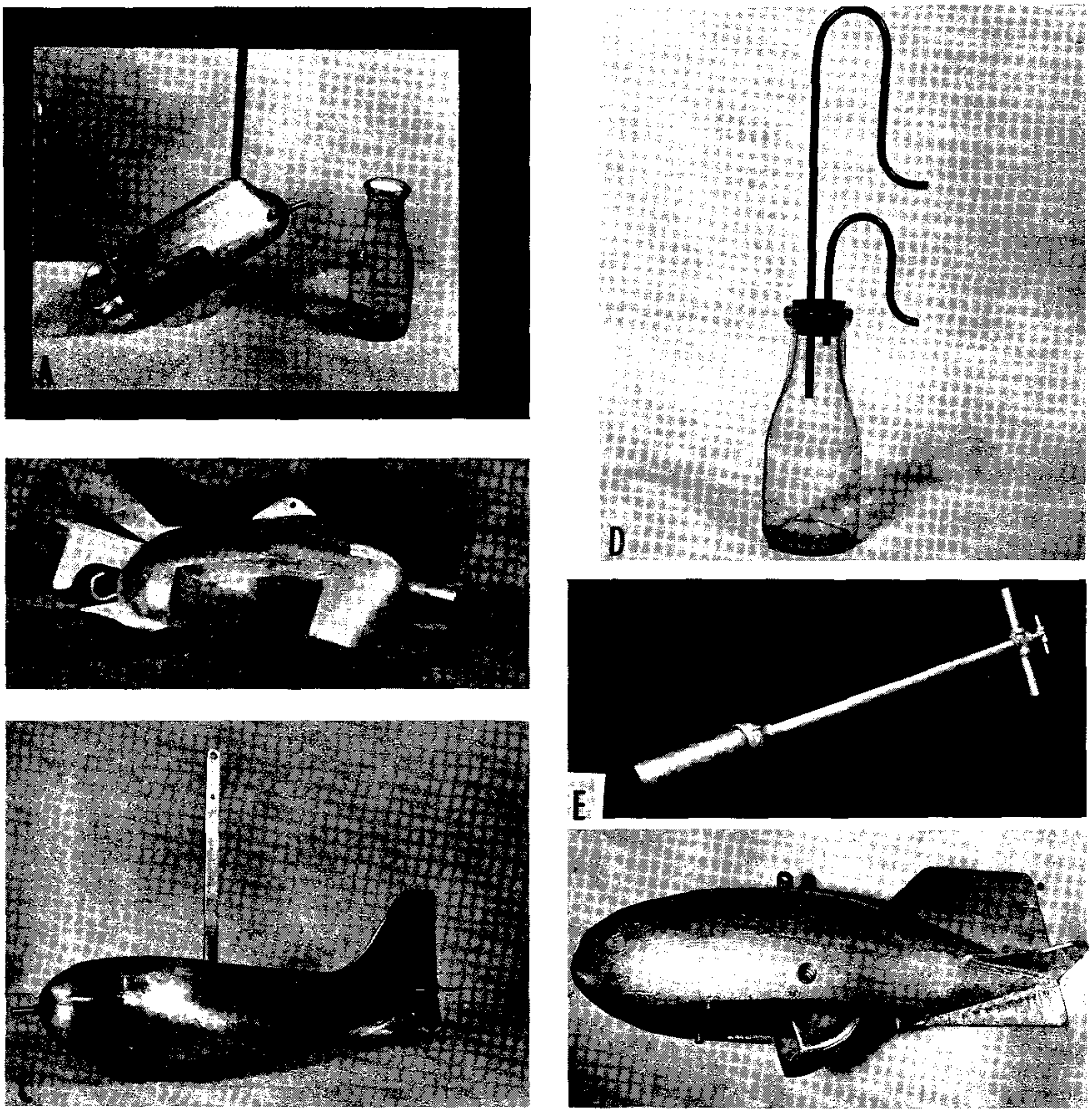

FIGURE 1.—Sediment samplers: *A*, US DH-48; *B*, US DH-59; *C*, US DH-49; *D*, single-stage; *E*, US BMH-53; *F*, US BM-54.

vertical speed, and receive instantaneously at every point a small specimen of the water-sediment mixture, which is later analyzed in the laboratory for sediment concentration and particle size. The nozzle is about 0.3 to 0.4 ft. above the bottom of the sampler. The sample container is a round glass pint milk bottle. An exhaust line allows air to escape from the sample container as the sample enters. The sampler is limited to two-way sampling in depths not greater than 18 ft. One or another of the three types of depth-integrating samplers that have been developed by the project can be used satisfactorily for sampling many streamflows. (The 100-lb. point-integrating sampler is used for depth-integration when depths or velocities are too great for the heaviest depth-integration sampler.)

The US DH–48 hand sampler is used to obtain suspended-sediment samples from streams that can be waded. The sampler is made of cast aluminum and weighs 4½ lb. It partially encloses the sample container. A brass intake nozzle points into the streamflow. A standard ½-inch wading rod is threaded into the top of the sampler body for suspension.

The US DH–59 handline depth-integrating sampler is made of cast bronze and partially encloses the sample container. It weighs about 22 lb. and is equipped with tail vanes to orient the intake nozzle into the approaching flow. This sampler is suspended on a suitable handline.

The US D–49 is a 62-lb. bronze depth-integrating sampler. A hinged head, from which the nozzle projects into the streamflow, permits access to the sample container, which is enclosed in the sampler body. Tail vanes orient the instrument into the streamflow. The sampler is suspended on a steel cable and is lowered and raised by means of a reel mounted on a crane.

Point-Integrating Samplers

Point-integrating samplers collect a water-sediment mixture at one point in the cross-section of a stream. The sample is integrated over the duration of the sampling time. The point-integrating samplers are shaped like the 62-lb. depth-integrating sampler (US D–49, fig. 1) and are equipped with a valve that can be operated electrically after the instrument has been lowered to the sampling point. The valve has either two or three positions: (1) a position for equalizing the air pressure in the bottle with the hydrostatic pressure at the sampling point; (2) the sampling position; and (3) a closed position (in some samplers position 1 is used as a closed position). The samplers are made of cast bronze, and are equipped with tail vanes, a pressure-equalizing chamber, and a hinged head that contains the nozzle, valve, and valve operating mechanism. The hinged head provides access to the sample container, which is a round glass pint milk bottle enclosed in the sampler body. An exhaust port on the side of each sampler head allows air to escape as the sample container fills. The samplers are suspended on a two-conductor steel cable, reel, and crane.

The US P–46–R sampler weighs 100 lb. It can be used for point-integration or to depth integrate on a round trip basis to a depth of 18 ft. or in one direction to a depth of 30 ft. Greater depths can be integrated by dividing the total depth into two or more sections of not more than 30 ft. each. The sampler has a rotary valve that is operated electrically by a rotary solenoid that has the three positions mentioned above. A signal indicates when the valve is in the sampling position. The valve is operated by a telephone dial switch at the observer's station.

A new 100-lb. US P–61 point-integrating sampler is being developed. Two different valve mechanisms have been tested. In the first mechanism a rotary solenoid, when energized, turns a rotary valve from the normally closed and pressure-equalizing position to the sampling position and holds the valve open in the sampling position as long as the solenoid is energized. In the other mechanism, the rotary valve has three positions and the valve is turned by a spring and ratchet. A lever on the side of the head is used to cock the mechanism to the first or pressure-equalizing position, and a solenoid trips the ratchet to let the spring turn the valve to the second and third positions, successively.

The US P–50 sampler is 3 ft. 8 in. long and weighs 300 lb. Either a 1-quart or a 1-pint round glass milk bottle is used as a sample container. An electrically operated slide valve has two positions. The valve is held in the equalizing position by a spring. Solenoids, when electrically energized, hold the valve in the sampling position. This sampler may be used in high velocities and in depths to 200 ft.

Bed-Material Samplers

A bed-material sampler collects a sample of the sediment mixture of which the streambed is composed. It should not be confused with a bedload discharge sampler which samples the rate of discharge of sediment moving as bedload. Only bed-material samplers are described here.

The US BMH–53 is a piston-type hand sampler that is used to collect a sample of sediment from the bed of a stream which can be waded. The sampler consists of a cylinder that is 2 in. in diameter and 8 in. long which can be pressed into the streambed manually. A piston inside the cylinder retracts as the cylinder is pressed into the bed. It helps retain the sample when the sampler is withdrawn and then is used to push the sample from the cylinder. The overall length of the sampler is 46 in.

The US BMH–60 is a 30-lb. sampler, 22 in. long, made of cast aluminum, and used from a handline to collect a sample from the bed of a stream, lake, or reservoir. A cross-curved constant-torque (Negator) spring drives a single bucket that swings out of the sampler body to scoop up and completely surround a sample of about 160 cc. from the top 2 in. of the streambed. When the sampler is supported by the handline and the safety yoke is in place, the bucket can be cocked to the open position in which the bucket is completely retracted into the sampler body. As long as the safety yoke is in place on the hanger, the bucket mechanism cannot be released. When the sampler is supported by the handline and the yoke is removed, a sample can be taken by lowering the sampler onto the streambed until the suspension line is slack. When the sampler rests on the streambed, the mechanism trips and a sample is taken from the bed.

The US BM–54 is a 100-lb. cast iron, bed-material sampler, 22 in. long. When supported by a steel cable, the bucket can be cocked to the open or sampling position. When tension on the cable is released by resting the sampler on the streambed, the mechanism is tripped and the single bucket, powered by a spiral spring, swings out of the bottom of the sampler body and scoops a sample from the top 2 in. of the streambed. The bucket surrounds and encloses the sample in such a way that none of the sediment is washed out.

Automatic Samplers

Two types of so-called automatic suspended-sediment samplers have been designed and tested by the project. One is called the single-stage sampler, and the other is the pumping sampler, which has three methods for handling the sediment samples. These samplers are automatic in that they may be installed at the sampling station and set to collect samples even when unattended.

Single-Stage Sampler

A single-stage sampler is a simple device, which was developed for use on flashy and intermittent streams, at remote or not easily accessible sites where adequate samples cannot be obtained manually.[1] The sampler (fig. 1) consists of a container equipped with intake and exhaust tubes designed to obtain a single suspended-sediment sample automatically when the water surface first rises to a selected stage that submerges the sampler. The sample is collected with respect to gage height and not time.

Samples taken with single-stage samplers are not as representative of the sediment concentration in the stream cross section as are samples taken with manual samplers; therefore, the latter samplers should be given primary consideration at every station. However, the single-stage sampler provides a means of obtaining some suspended-sediment data for streams or storms that would not be sampled otherwise.

A single-stage sampler installation consists of five basic parts:

(1) A sample container such as a 1-pint glass milk bottle;

(2) A siphon-shaped copper air-exhaust tube, with an inside diameter of about $\frac{3}{16}$ in.;

(3) A siphon-shaped copper intake tube and nozzle, with an inside diameter of about $\frac{3}{16}$ in.;

(4) A tight-fitting stopper that seals the bottle and has two holes which hold the tubes tightly in place;

(5) A rack for supporting and protecting one or more samplers one above the other, to sample at different stages.

Single-stage samplers have the following desirable qualities:

(1) Samplers may be installed at the station well in advance of a flood or rising stage;

(2) No one need be present at the time of sampling;

(3) Samples may be obtained at predetermined stages of the stream;

(4) Sampling apparatus is inexpensive.

Limitations of the sampler that may cause errors are:

(1) Samples are collected at or near the stream surface and usually near the edge of the stream or near a pier or abutment;

(2) Size, shape, and orientation of intake and air exhaust elements may fail to provide intake ratios (average velocity in nozzle to stream velocity approaching nozzle) sufficiently close to unity to sample sands accurately;

(3) Obstructions due to the presence of trash and drift during sampling may create unnatural flow lines at the sampler nozzle and cause inaccurate sampling, which may not be detectable later;

(4) Flow may circulate through the sampler after the original sample has been collected.

Four types of single-stage samplers have been designed for different sampling conditions. The vertical-intake type is accurate only for sediments finer than 0.062 mm., for water-surface surges less than 4 in., and for velocities that are reasonably low at the sampling point. Its sampling efficiency usually is little affected by drift and debris, by circulation through the sampler, or by a reasonable amount of shielding if the sediments are fine.

Any one of three horizontal intake nozzles may be used to sample sands as well as fine sediments. The intake nozzles are inclined downward at 20°,

[1] Reference report 13; see p. 177.

15°, or 10° to prevent deposition of sediment in the intake prior to sampling. The smaller angles are used with higher velocities, because at high velocities sediment is less likely to deposit in the nozzle. The height of the siphon-shaped intake and exhaust tubes is selected to accommodate the velocity and surge conditions at the sampling site.

Pumping Samplers

Pumping samplers with three different sample handling systems have been developed and tested.[2] These samplers automatically obtain frequent samples of suspended-sediment concentration of a stream that may not be readily accessible to an observer. Samples are taken from one point in the stream, the point at which the pumping intake is located. Each sampler consists of an intake, pumping system, and sediment handling system.

The intake can be a 1-in. opening in a plate mounted flush on the face of a guide wall that is parallel to the streamflow. The inflow is through a hose to a pump that delivers the sample to a collecting and recording system. A trap in the intake line prevents small fish from reaching and jamming the pump. Any obstruction lodged in the trap is flushed back to the stream just before sampling. The pumping system is operated by a timing device that can be adjusted to take samples at any desired frequency. A safety system shuts off the sampler for 12 hours if the water level falls below the intake or the intake is obstructed.

In the accumulated weight-recording system, samples enter a settling tank where the sediment settles onto a tray. The accumulated weight of sediment is measured by a spring-transformer scale and recorded on a strip chart. The pumping, collection, and recording equipment are housed in an 8- by 10-ft. shelter. The system has a total capacity of 1,300 lb. of sediment and records accumulated weight to the nearest 2 or 3 lb. throughout each of thirteen 100-lb. increments. The average concentration of suspended sediment is computed from the weight of sediment accumulated on the tray and the volume of pumped sample for the measurement period. This sampler obtains a time-weighted concentration that is accurate for fine sands and coarse silts during periods of steady flow; but sudden, or short time, changes in concentration may not be defined.

The sediment volume recording system (fig. 2) consists of a rack that supports 12 sedimentation tubes, each having a constricted section at the bottom for measuring sediment volume; a 16-mm. movie camera for recording the column of sediment and the water level in the sedimentation tube; and a concentric bottle rack that carries 72 pint milk bottles for collecting check samples for analyses in the laboratory. A sample is pumped into one of the sedimentation tubes each half hour. About 5½ hours later, the camera takes a picture of the accumulation of sediment in the constricted section of the tube and also of the height of water in the tube. Then the tube drains in preparation for taking another sample 6 hours after the previous sample was taken. The volume of each sedimentation tube has been calibrated against height of filling so that the volume of the sample and the volume of accumulated sediment can be determined from the picture. The relation of volume ratio to weight concentration is determined for various particle size ranges of sediment encountered at a sampling station. A splitter on top of one of the 12 sedimentation tubes diverts a part of the sample to a pint milk bottle every 6 hours. The milk bottle sample may be analyzed later in the laboratory as a check on the concentration obtained from the pictorial record. This method is not always satisfactory where

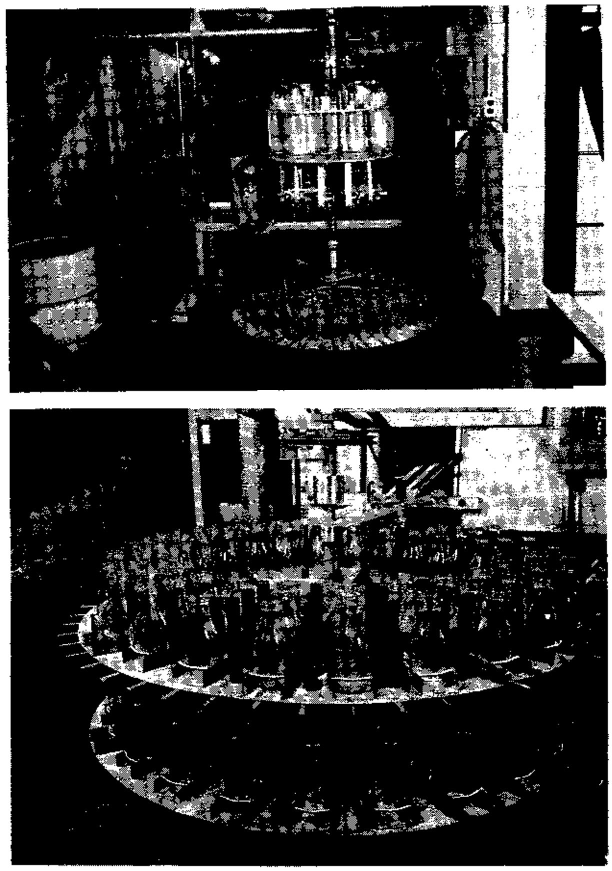

FIGURE 2. — Sample handling systems for pumping sampler: Top, Sediment volume recording system; bottom, individual-sample bottling system.

[2] Reference report Q; see p. 177.

the percentage of clay and silt is high, because the water may be too turbid for a good picture of the water-sediment interface.

The individual-sample bottling system (fig. 2), collects samples in pint milk bottles for analysis in the laboratory. The sample handling system consists of two concentric bottle racks, one above the other, which carry a total of 145 pint milk bottles. Tubes through the upper rack guide the sample to bottles on the lower rack. A special pen records sampling cycles on a river stage recorder. The bottling system can be adjusted to operate for any desired sampling frequency and for any range of river stage by means of a cycling switch and float switch, respectively. This device can collect samples for as long as 72 days without servicing. It is relatively simple and can be made portable.

Sediment Analyzing Devices

Two sediment size analyzers, the bottom-withdrawal tube and visual-accumulation tube, have been developed and four other devices for determining suspended-sediment concentration, or concentration and particle size distribution, are being investigated. The devices include electronic sensing, turbidity, ultrasonic, and nuclear equipment.

Bottom-Withdrawal Tube for Size Analysis of Sediments

The bottom-withdrawal tube was developed to determine size distribution of particles up to 0.7 mm. in samples of suspended sediment.[3] This device is a glass tube 100 cm. long and 1 in. in diameter, with a volumetric scale along its length. The tube is open at the upper end and contracts to 1/4 in. at the lower end, which is equipped with a quick-acting outlet valve. The sample is uniformly dispersed in the tube. Then the tube is placed in an upright position and samples of known volume are drawn from the bottom at known time-intervals. The sediment weight in each fraction is determined by drying and weighing. Then the particle size distribution can be computed by use of an Oden curve. The cumulative size-frequency distribution is determined graphically by the intercepts, on the ordinate axis, of tangents to the Oden curve.

Visual-Accumulation Tube for Size Analysis of Sands

The visual-accumulation tube method is a rapid and accurate means for determining the sedimentation-size distribution of the sand in suspended-sediment samples and in streambed and beach material samples.[4] The size analysis is based on a stratified sedimentation system in which the sample is introduced at the top of a transparent settling tube containing distilled water (fig. 3). The sediment accumulates in a contracted section at the bottom of the tube. A manually operated pen is used to trace the height of sediment accumulation on a chart (fig. 4), which moves at a uniform speed.

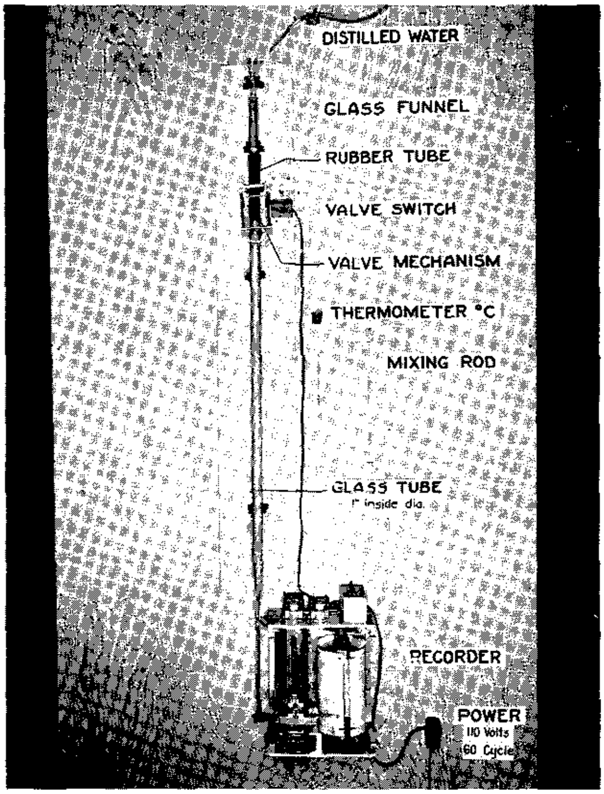

FIGURE 3.—Visual-accumulation-tube sand size analyzer.

The equipment consists of a sedimentation tube and a special recorder. Five sizes of tubes are available. Four tubes have lengths of 120 cm. and inside diameters of 1 in., except for the lower ends that have a constricted sand accumulation section with a diameter of 2.1, 3.4, 5.0, or 7.0 mm. Tubes of these sizes can be used for analysis of samples having a small quantity of sand mostly less than 1 mm. in diameter. A fifth size tube is 180 cm. long and 2 in. inside diameter and has an accumulation section of 10 mm. inside diameter. It is used for analysis of bed and beach or other sands of coarse sizes when sufficient quantities of material are available.

For the visual-accumulation tube method of particle-size analysis the sand portion of a suspended-sediment sample is separated from the silt and clay by sieving or by sedimentation. The 180-cm. tube is satisfactory for analyzing

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[3] Reference reports 7 and 10; see p. 176.

[4] Reference report 11; see p. 176.

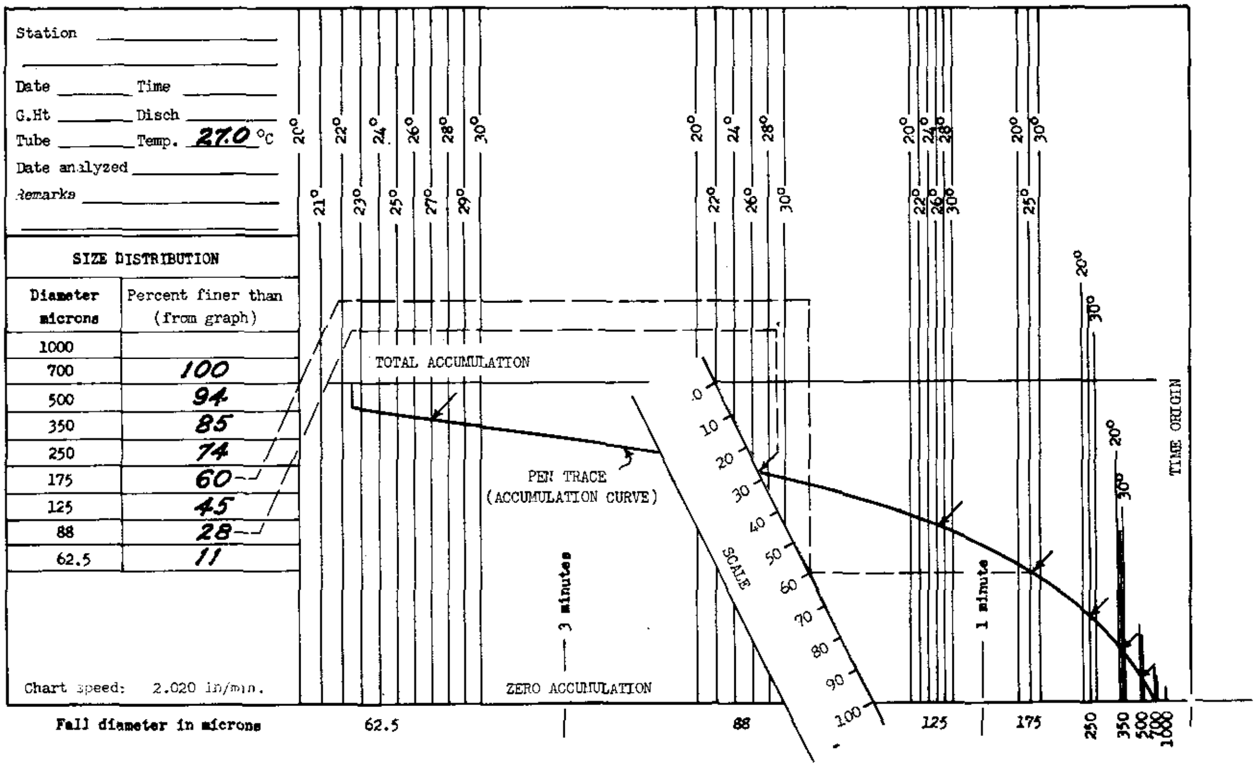


FIGURE 4. — Visual-accumulation-tube sand size analyzer recorder chart for 120 CM tube, showing method of reading size distribution.

samples containing sand up to 2 mm. in diameter. Analyses are in terms of fall velocity of individual particles of which the sample is composed. A sample can be analyzed in less than 10 minutes, which is faster than a sieve analysis. Experience has shown that this sand-size analyzer is a very satisfactory device for determining particle-size distribution for sands in the size range from 0.062 to 2 mm.

Electronic Sensing Device

A commercial electronic sensing device (fig. 5) is being studied to determine its capacity to analyze fluvial suspended sediments for particle-size distribution and sediment concentration.

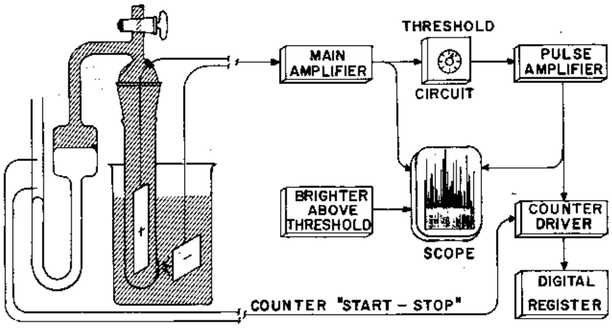
The counter measures and counts individual particles as they pass through a small aperture. A known volume of an electrolyte (aqueous salt solution) that contains the particles in dilute suspension is drawn through the aperture. The resistance between electrodes on each side of the aperture changes whenever a particle displaces part of the liquid in the aperture. A constant voltage is imposed on the electrodes so that the change in resistance produces an electrical pulse that is proportional to particle volume. The electrical pulses are amplified so that they can be screened as to size and counted.

The counter has an adjustable threshold level below which electrical pulses are not counted. The threshold can be set so high that none or only a few of the largest particles are counted. Then it can be lowered in successive steps and a count of pulses larger than each step can be taken. The relation of pulse height to particle volume can be established by calibration with particles of a known size. Thus, the number of particles in each size range can be determined.

Tests indicate that composition or density of the particles has little or no effect on results of the analysis. The analyzer seems to be an accurate method for determining the number and size of particles in the silt size range.

Turbidity Method

The turbidity method of analyzing sediment is being studied. The equipment (fig. 6) consists of a pump and recirculating system, sedimentation chamber, and the General Electric recording turbidimeter, which contains a turbidity detector and a recorder. Turbidity, which is the cloudiness in a liquid, is measured by a photovoltaic cell in the detector and interpreted in the recorder as the ratio of the light scattered by the particles in the liquid to the light transmitted through the liquid. The transmitted light is measured for 15 sec., the scattered light



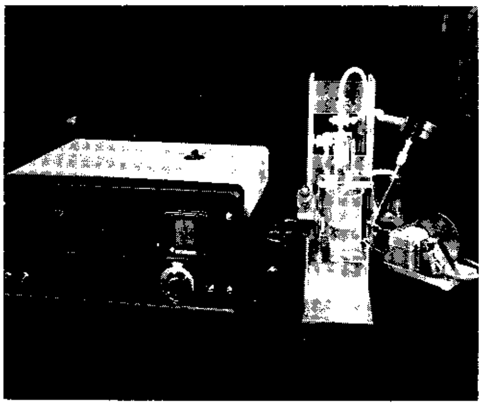
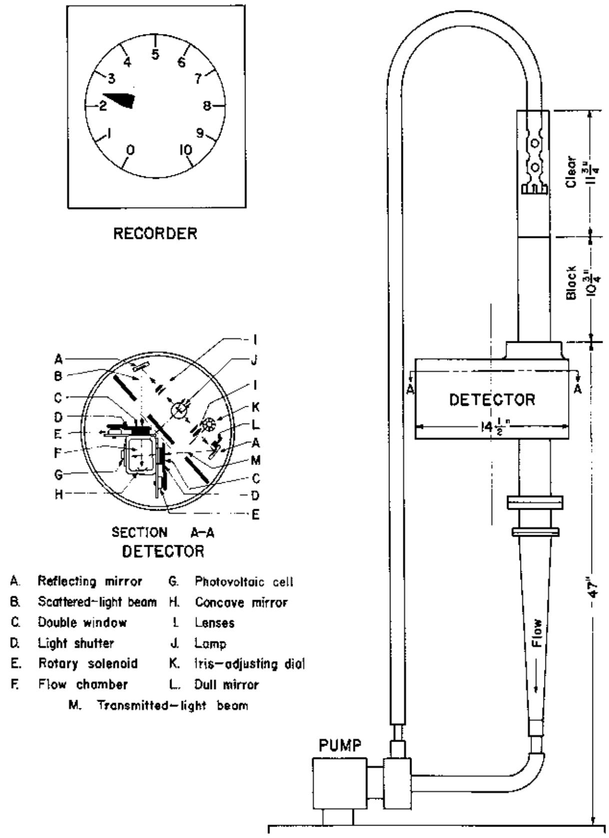


FIGURE 5. — Electronic sensing device for sediment.



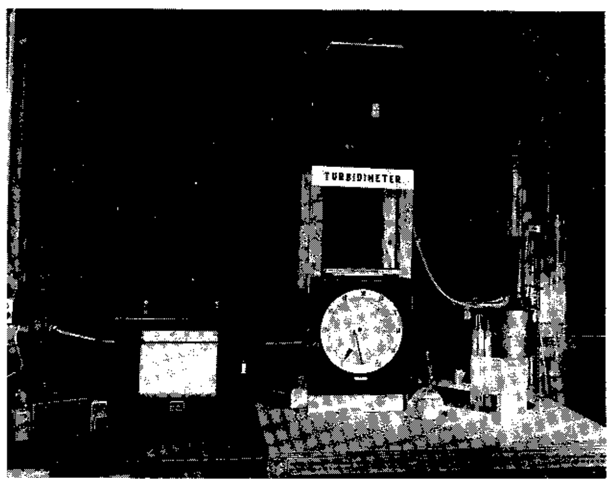


FIGURE 6. — Turbidimeter to analyze sediment.

for 45 sec., and the ratio is computed and recorded during the latter period. This cycle is repeated continuously. Stability of the ratio measurement is achieved by using a single light source and a single photovoltaic cell.

The turbidity method for determining particle-size distribution and concentration in a suspended-sediment sample consists of two steps: (1) Turbidity of a sample being pumped through the detector is recorded continuously for determination of concentration; (2) for particle-size determination, the flow is suddenly stopped and turbidity is recorded against time as particles settle out of suspension. Particles of uniform density and shape fall at rates proportional to their size, and light is obscured in proportion to particle size and concentration. The relative weight of each particle-size group required to obscure light to a given degree is represented by a hiding factor. The weight of sediment in each size group is computed in percentage of the total for each incremental change in turbidity by using the equivalent hiding factor and making adjustment for concentration.

Calibration tests of this method were made to determine the relation of turbidity to the characteristics of various types of sediment. Observed turbidity and settling time were related graphically for each tested concentration. Particle size was computed by Stokes' Law for settling time and temperature observed in the tests.

Then particle size was related to turbidity graphically through common values of settling time. Size distribution was computed as cumulative percentage of each size fraction and was presented by a log-probability plot on which cumulative percentage finer is plotted against size. Particle-size distribution is defined by computing, from the log-probability graph, the geometric mean diameter and the geometric standard deviation.

After particle size has been determined, concentration is found from a calibration graph (fig. 7) in which turbidity is plotted with respect to concentration and the geometric mean diameter and the geometric standard deviation are used as additional parameters. A graph such as that of figure 7 is prepared from tests on known samples of the particular type of sediment that is to be analyzed.

The turbidimeter can be adjusted to measure fairly accurately a wide range of concentrations, from as small as 0 to 10 p.p.m. to as large as 0 to 100,000 p.p.m. Also, it can measure the sizes of particles within the approximate range from 0.020 to 0.120 mm. Finer particles settle so slowly that a test may take an excessively long time, whereas coarser particles settle so rapidly that an unreasonably tall sedimentation chamber may be required.

The principle of the turbidimeter appears to be adaptable to a field instrument for monitoring concentrations and particle-size distributions of suspended sediment pumped continuously from a stream.

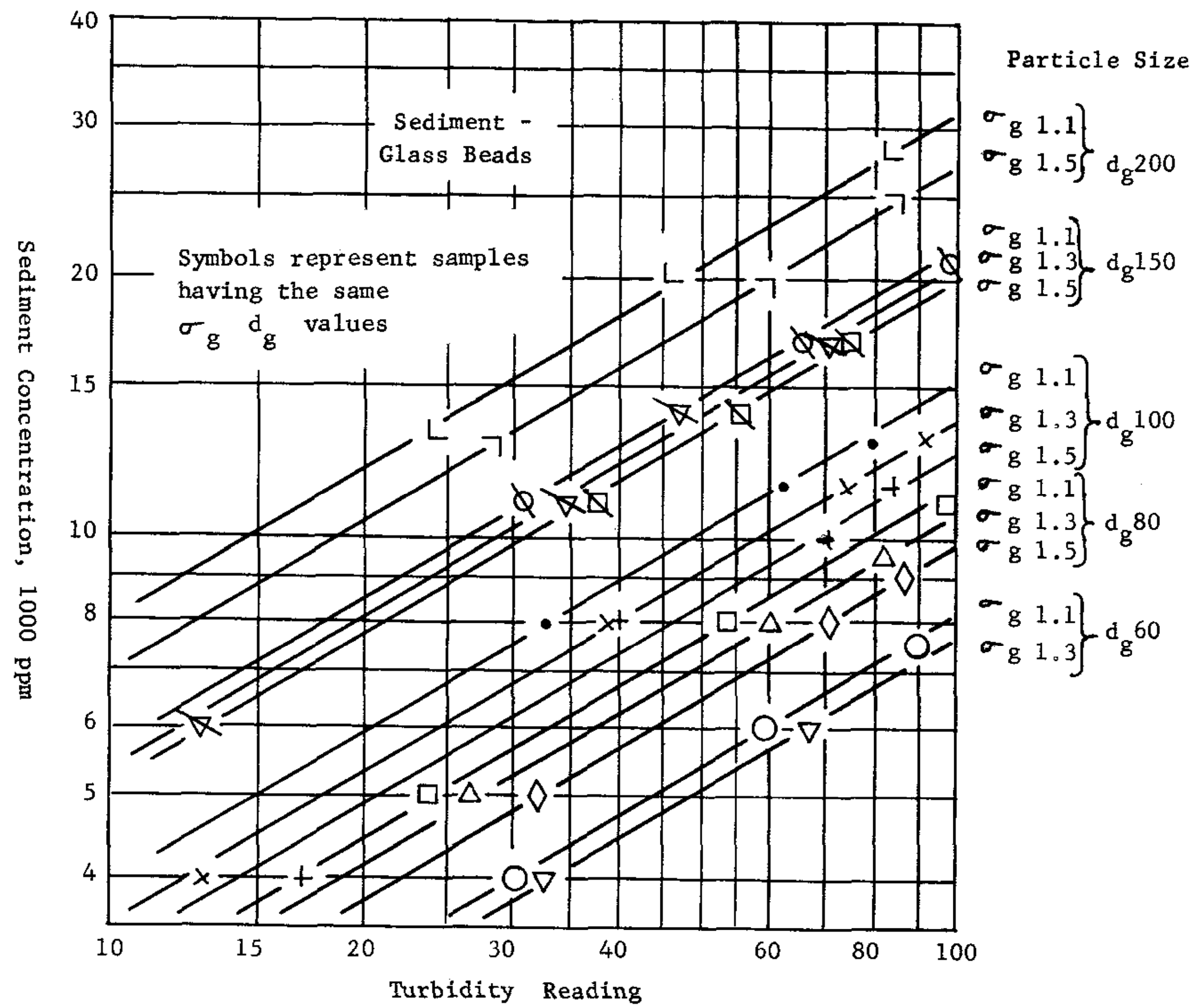


FIGURE 7. — Concentration-turbidity calibration graph.

The results of a particle-size analysis (fig. 8) of a prepared sample of glass beads were about the same whether made with the electronic sensing device, the turbidimeter, or the visual-accumulation tube.

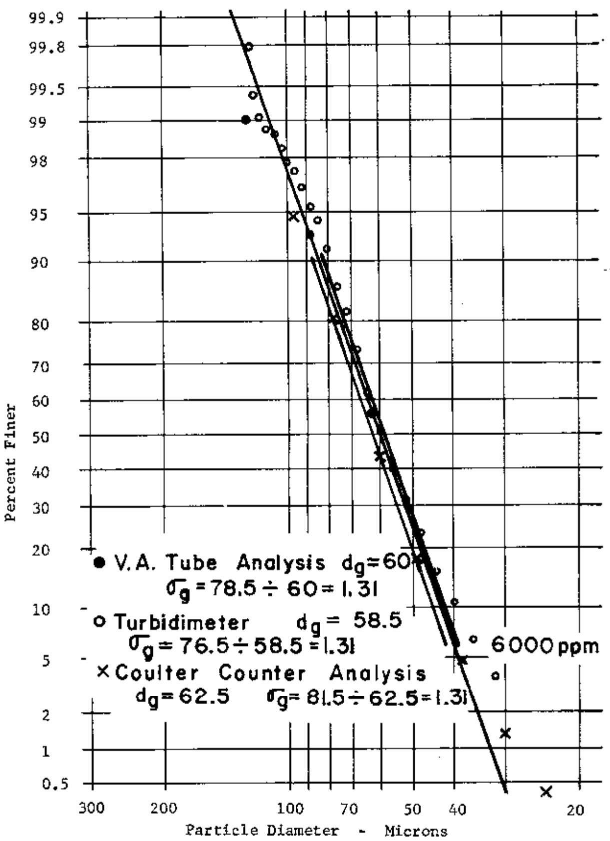


Figure 8. — Results of visual-accumulation-tube, turbidimeter, and electronic sensing device.

Ultrasonic Method

Ultrasonic equipment is being developed to determine size distribution and concentration of sediments in sizes from 0.040 to 1.0 mm.

In this equipment (fig. 9) a high frequency electrical current is imposed on a quartz crystal for about 6 micro-seconds at a repetitious rate of 200 times a second. The quartz crystal, which is mounted in the wall of a sedimentation tube, converts the electrical pulses into displacement pulses or sound waves. The wave passes through the fluid in the sediment chamber and strikes a second crystal in the wall on the other side. The two crystals are of matched frequencies. The second crystal acts as a transducer and converts the sound wave to a secondary electrical current. The electrical current is fed back through an attenuator and displayed on an oscilloscope.

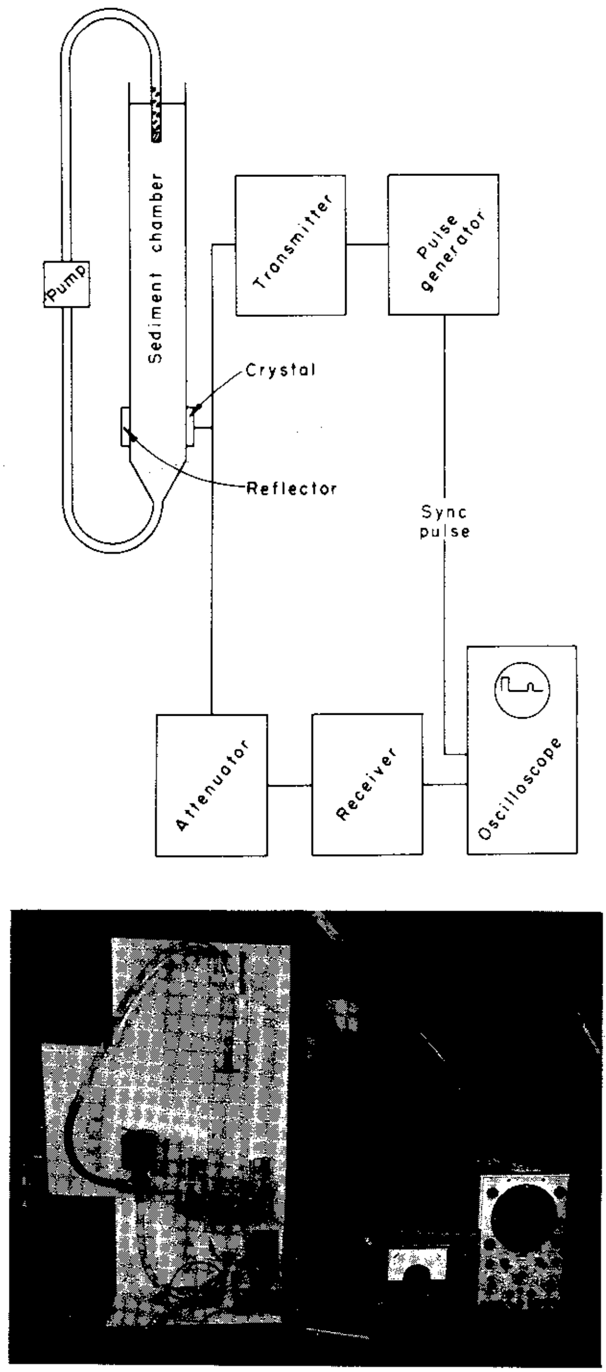


Figure 9. — Ultrasonic equipment to measure sediment.

The effect of sediment on attenuation of the sound wave is determined as follows: With water in the sediment chamber, the top of the oscilloscope trace is adjusted to a reference line on the oscilloscope screen. Then sediment is introduced into, and circulated through, the sedimentation chamber. The presence of the sediment reduces the height of the trace. Electrical resistance is removed from the attenuator in the secondary electrical circuit until the trace is restored to the original height on the oscilloscope. The electrical resistance that was removed is a direct measure of the energy loss caused by the addition of the sediment. The energy loss varies directly as the concentration of sediment.

Unfortunately, attenuation of ultrasonic energy depends as much on particle size as on concentration. Although the ultrasonic equipment can be calibrated to determine quickly and accurately the concentration of sediment of a known single size, or a single size distribution, the determination of the concentration of sediment of an unknown size distribution is difficult. For sediments that have a size distribution that can be expressed by two parameters such as the geometric mean diameter and the standard deviation, it is possible to determine the size distribution in an unknown sample. Calibration and analysis must cover a range of about 10 frequencies. After the size distribution is determined, the concentration can be found.

The ultrasonic equipment operates reasonably well in the laboratory, although further development will be needed before it will be competitive with more common laboratory methods of analysis. The potential for field use has not been evaluated.

Nuclear Approach to Analysis of Sediment

The possibility of using radioisotopes for determining the concentration of suspended sediments is being investigated. The Atomic Energy Commission and Parametrics, Incorporated, are cooperating with the Inter-Agency Sedimentation Project on a study of nuclear possibilities.

The first phase of the investigation is a study by Parametrics, Incorporated, of the feasibility of using X-ray emitting radioisotopes for the measurement of the solid-liquid ratio in natural waters. The investigation is both theoretical and experimental with emphasis on the following items:

(1) Chemical constituency and variation of sediment and flow.

(2) Investigation to determine whether X-ray, gamma, or beta emitters are best.

(3) After selection of a general type of emitter, determination of availability, cost, and licensing potential.

(4) If a single isotope is strongly suggested from item 3, further study of this isotope only. Otherwise, the best two isotopes will be considered for the remaining parts of the investigation. If the multisource method seems best, several isotopes will be considered.

(5) Prediction of detector response, accuracy in determining percentage of solids, and source strength requirements as a function of liquid density and concentration of solids.

(6) Basic confirmation of predictions with limited laboratory experimentation. Modification or sophistication of response theory will be made as indicated.

(7) A preliminary study of the suitability of various detectors as a basis for recommendations.

(8) A preliminary investigation of circuitry techniques suitable for data processing to obtain solids concentration automatically.

Future Program

Project efforts in the near future will emphasize (1) preparation of an up-to-date report on the measurement of fluvial sediment discharge, (2) field tests of the pumping samplers, and (3) development work on the electronic sensing, turbidity, ultrasonic, and nuclear devices for analysis of suspended sediment samples in the laboratory and for automatic collection and analysis of suspended sediments in flowing streams.

List of Project Reports

Reports on the cooperative study of methods used in measurement and analysis of sediment loads in streams covers phases indicated by the following titles prepared by the Inter-Agency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, Minneapolis:

Report No. 1. — Field practice and equipment used in sampling suspended sediment, August 1940.

Report No. 2. — Equipment used for sampling bed load and bed material, September 1940.

Report No. 3. — Analytical study of methods of sampling suspended sediment, November 1941.

Report No. 4. — Methods of analyzing sediment samples, November 1941.

Report No. 5. — Laboratory investigations of suspended-sediment samplers, December 1941.

Report No. 6. — The design of improved types of suspended-sediment samplers, May 1952.

Report No. 7. — A study of new methods for size analysis of suspended-sediment samples, June 1943.

Report No. 8. — Measurement of the sediment discharge of streams, March 1940.

Report No. 9. — Density of sediments deposited in reservoirs, November 1943.

Report No. 10. — Accuracy of sediment size analyses made by the bottom-withdrawal-tube method, April 1953.

Report No. 11. — The development and calibration of the visual-accumulation tube, 1957.

Report No. 12. — Some fundamentals of particle-size analysis, December 1957.

Report No. 13. — Single-stage sampler for suspended sediment, 1961.

Report AA. — Federal Inter-Agency Sedimentation instruments and reports, May 1959.

Report Q. — Investigation of a pumping sampler with alternate suspended-sediment handling systems, progress report, June 1962.

Note. Other lettered reports, A to P, are manuals on sediment sampler operation or studies of sampler and equipment operation.

DISCUSSION — SYMPOSIUM 1
Land Erosion and Control

Moderator: John B. Stall, Illinois Water Survey

Panel: Russell Woodburn, ARS
Sam Maner, SCS
Stan Ursic, FS

MR. STALL:

Gentlemen, we have been treated today to 25 papers on Land Erosion and Control. I like to think of these as being building blocks or bricks as mentioned yesterday by Dr. Vanoni. Underlying them all is a structure that governs sediment movement and which we are all seeking. After hearing these papers, we should reflect to some degree as to how these may fit together; as an attempt to do that in panel form, we have asked three persons to do this who are willing to make public for you their reflections as to today's activities. These people are Sam Maner of the Soil Conservation Service, Stan Ursic of the Forest Service, and Russell Woodburn of the Agriculture Research Service.

We have a number of questions from the question box for the individual speakers. We will ask them to answer these. We hope, however, that the three brief summaries that these men are going to give now may stimulate your own thinking somewhat, either by agreement or disagreement, and move you to participate in the discussion which will follow. To begin with, I want to call on Mr. Maner. I have told all these men they can be as brief or as long as they like up to a couple of minutes.

MR. MANER:

Since Mr. Bryant introduced those statisticians to the conference yesterday, I would like to place our kind of work — which is more or less a very small flood control or flood prevention type of structural program — in the same light as compared to some of the things that you people can do in the Bureau of Reclamation and the Corps of Engineers. When those two people missed the target in that joke yesterday, 3 feet on one side and 3 feet on the other and concluded that between them they got a dead center deal, we have to get that dead center more or less on our little structures because we do not have the leeway that you people may have. (sic) In other words, in some of your large structures out here you might be able to get by with an area of a foot of sediment, whereas a foot or 6 inches is all we have to work with. So we are the dead center group when it comes to that. My general impression is that this whole deal, so far, has been very good and that is what you would expect a guy to say when there are 270 people out there who might disagree with you if you said it was bad. Seriously, it is real good.

One of the things that was most gratifying yesterday was something Dr. Wolman said. I, myself, feel like when you classify these people, most of those in the Soil Conservation Service doing sedimentation work are supposed to be geologists. I think in the other agencies a big portion of these people might be hydraulic engineers. Being classified as a soil conservationist, I am somewhere between the geologist and the engineer. Dr. Wolman said that, strictly speaking, there is some place where the geologist quits and a point where the engineer begins, and I hope I am somewhere in between those two guys. I don't believe I will take any more of your time. If you have a question as far as my paper is concerned or on the type of work I have been doing, which is primarily sediment delivery ratio studies as they relate to the physical characteristics of watersheds, I will be glad to answer those either now or after the discussion.

MR. STALL:

Next, I want to call on Stan Ursic of the Forest Service.

MR. URSIC:

John, this assignment reminds me of Otis Copeland's story of the sailor shipwrecked with 12 beautiful girls. Perhaps it's more like the sailor on a weekend pass who has a larger array of material to sample but who is handicapped by the time factor and certainly by other considerations.

Vegetative cover prevents accelerated erosion and sedimentation. This salient fact was stressed by a great majority of the papers presented here today. The problem is one of economic use of the land to produce the food, the fiber, and the wood products we need.

One solution has been suggested — move all the people off the land and let nature take over again. Perhaps in view of recent world events, this possibility is becoming a little less remote.

Forests — The major problem on forest lands is caused by disturbances. Other than the catastrophic effects of wildfire, the principal disturbances are those associated with logging activities. However, with proper management practices, as brought out by the papers of Howard Lull and Dick Fredericksen, sedimentation as measured by stream turbidity can be reduced to prelogging levels within a period of 2 or 3 years. Perhaps some of you may have questions as to whether or not this applies to areas with less rainfall.

Range — The problem is one of proper utilization, and here two papers have significantly pointed out that very small changes in vegetative cover are important. These are the papers of Mr. Lusby and Mr. Otis Copeland.

Open Land — Here, I believe, the problem is one of minimizing the time when the soil is left exposed to rainfall energy and the application of measures designed to reduce movement to channels.

Of the 25 papers presented, 14 dealt with sedimentation sources, 6 with erosion control, and 5 with miscellaneous topics.

The sources are not so much a problem for research as they are a problem in management. As Mr. Bullard pointed out, we have the know-how; it boils down to the question of how much we are willing to pay to take care of them.

Control — None of the papers have given any indication that erosion problems cannot be solved. On the contrary, there is an undercurrent of optimism, and I believe rightly so. As noted yesterday, none of the papers have dealt with the present extent of erosion. How much work has been done in assessing the erosion problems in this country? Are these data available? How much more work is needed? Are these data available? Lastly, in the papers presented, there has been no suggestion of new or drastic or imaginative methods to control erosion, except perhaps that of leveling the hills to reduce slopes. Thank you.

MR. STALL:

Thank you, Stan. Next, I want to call on Russell Woodburn of Agricultural Research Service.

MR. WOODBURN:

Gentlemen, I would say this is a fairly easy assignment. It is about like giving a man the job of summarizing the Sears, Roebuck catalog in 5 minutes. I have been impressed with the way that the program began this morning with Mr. Roehl's discussion of soil erosion and its control. He started his discussion of sedimentation with erosion which, it is very likely, is the beginning of the whole process. He followed that through the various aspects of erosion — upland erosion, sheet erosion, small channel, then the extreme case of gully erosion. That theme has been carried on further by other speakers throughout the day. Then we moved on down into flood plains. Mr. Parsons and some of the other speakers mentioned channel problems, another special case of erosion, channel instability, and the protection of channels. Then we moved on into some of the areas covered by other speakers — watershed characteristics and the relation of these various characteristics to erosion and to sediment production.

The general difference was touched upon, at least to some extent, of erosion and sediment production as such. We have covered then a very broad spectrum of the problem of erosion and some of the remedial measures for erosion and the relationship to sedimentation. I was impressed with the fact mentioned by several speakers that a little bit of grass goes a long way in solving this problem and by that, Mr. Ursic, I would not leave out the trees. To me, one of the most impressive parts of this whole discussion has been the common denominator of the erosion problem and the sedimentation problem faced by all of our Federal agencies dealing with water in its broad aspect. We all have to face the problem of erosion and the problem of sedimentation. It is gratifying to know that progress is being made as reported by a number of the speakers and the progress in general has consisted of the application of a lot of hard work and the application of many of the old well known and well established principles, and, thus far, I have not seen nor have I heard reported any amazing break-throughs or any miracle drugs to solve the disease. Thank you.

MR. STALL:

Thank you, Russell. In my own case, my principal reaction here today has been — what a sheltered life we lead up in Illinois in the Cornbelt! A reasonable rate of sheet erosion from our watersheds might be 4 tons per acre per year and a reasonable rate of sediment in the reservoirs may be equivalent to 1 ton per acre per year and some of the figures we have seen here today just astound me. Now, we have 10 or 12 questions which I am going to take in order. I hope the authors in question are still here. We will allow a limited contribution from the floor or question from the floor if it is associated with the question or point we have under discussion at the moment.

The first is a question of Mr. Beer who talked about gullies in Iowa and the question is this: "In explaining gully growth, Mr. Beer, the equation contained a factor linked from the end of the gully to the watershed divide. Would you explain the coefficient and the exponent of this factor? What is the reason for the importance of this factor? And does the gully area increase at a geometrical rate as the gully progresses upstream?"

MR. BEER:

First of all, to give some thinking on the inclusion of the X_{14} which is the variable in question. You noted from Mr. Jacobson's first slide and the first slide that I had that you must, I believe, include some factor that measures the potential for widening along the existing gully. That was the reason for X_8 for the length of the present gully. In other words, any time you get a little bit of concentration of water along the edge of the gully, you are going to get widening. Now, with that, the idea was that you must then provide some measurement for the amount of runoff contributing to the overall or lengthening of the gully. That was the reason for the inclusion of the X_{14}. You might ask why do you use length instead of areas. Well, it is a simple fact — we were not thinking far enough ahead to have those areas delineated whereby it could be measured, but I am not too much concerned, because the analysis showed approximately 0.85 correlation between the watershed length and the watershed areas, so I think it is at least an index. As to the coefficient, I do not think I am in a position at this stage to say whether it is right or wrong.

Surely, the validity will have to be established with further sampling, and that, of course, is what we plan to do. We will fly Steer Creek again this year. We plan to add a second watershed adjacent to Steer Creek. What I will do is take these data, feed it back into the equation in hand, and then compare the predicted values and see how we are coming along on that. As for the last part of the equation — does it increase in geometric ratio — I don't think I am in a position to answer that yes or no, as I made no correlations between area change and headward growth.

MR. STALL:

Thank you. Does anyone have any comment? The next question is to Mr. Striffler. "The implication of the paper is that land use has affected trout streams. The conclusions indicate that bank erosion is a primary determinant of sediment load. How has land use influenced bank erosion and also how was the bank erosion measured?" Mr. Striffler?

MR. STRIFFLER:

Well, let me answer the first part of that. How did land use affect bank erosion — is that the question?

MR. STALL:

Yes.

MR. STRIFFLER:

It is difficult to point to any specific relationship between land use and the amount of bank erosion within any one watershed. However, we can say several things about bank erosion. In this study a large proportion of our eroding banks occurred where stream bottom lands are pastured. I think this was brought out in the paper. In Michigan we also have another situation where we have very high eroding banks. These may occur in our forested areas as well as in our agricultural or pastured areas. These high banks have been attributed to several causes. First of all, some people say that these banks were originally started during logging days when large numbers of Michigan white pine logs were rolled down these banks into our streams. I cannot accept this as being the primary cause of these high banks. I think that several other things are more important; for instance, reservoir construction downstream which has influenced the grading of the stream, has started a cycle of erosion, which has progressed up these streams. I don't know if that answers that question satisfactorily or not.

MR. STALL:

How did you measure bank erosion?

MR. STRIFFLER:

The bank erosion variable used in the analysis was the total length of eroding banks within each sample watershed. These were measured by the Fish Division of the Michigan Conservation Department, and this information is available in their survey and plan reports.

They actually conducted a field survey where they had a team walk the stream bank and measure the length of each eroding bank. Where their survey did not cover the part of the area I was working with, we did our own survey.

MR. STALL:

Thank you. Any further comment or question? I next have a double-barreled question. I believe I will ask Mr. Betson to answer the first one. "Several of today's papers have reported on complex curve fittings and multiple correlation analyses, with many variable and constraints, using computers. Although the computer may correctly solve the mathematical problem given to it, what assurance is there that the formulation of the problem and interpretation of the mathematical results are correct?" Mr. Betson?

MR. BETSON:

The reticence to use the computer kind of reminds me of a quotation which is not original with me but goes like this: "Even though I don't understand the digestive system, I continue to eat." Proof must lie with the user. Mathematical models are set up usually based on the mass of knowledge we are able to accumulate at the time. If this is fitted to data, the answers will either verify the theory or they will not. If they verify the theory, we are in good shape. What we thought all along is true. If this is not the case, one of two things can be wrong. Either the theory is wrong or the data are wrong. Let's assume the theory is wrong and this has happened. In this program I talked about, we have used it to fit data and found that our theory was a little bit shoddy. We have had to revise our thinking and in light of the revised thinking, we have found out a lot more about watershed characteristics than we knew beforehand.

The other possibility is that the data are in error. Again, we are getting back to the point where the hydrologist or user has to have enough understanding of what he is doing to be able to detect when this happens. The computer techniques are, in a sense, not much different than any other techniques. We can analyze data to death but in the end result, it either gives us the answer we are looking for or it doesn't. It is up to the user himself, I think, to prove whether the answers are consistent with the thinking or not. Does this answer the question?

MR. STALL:

In further answer to this question, I would like to comment myself that it is my feeling that the use of the computer or mathematical model can never relieve us of our own responsibility for understanding of the phenomena involved. The researcher must develop a pattern of understanding into which he can fit his observations somewhere. Then if the result is a complex model to solve, you can take advantage of some of the nice things that have been done in the way of curve fitting as described by Mr. Betson. I feel that the use of mathematical models in an attempt to bare this structure of understanding that Dr. Vanoni talked about is very promising. We should make attempts to reveal this basic structure; but in doing so, usually we cannot ask our own set of observation to give us all the answers. We are required to construct this model in accord with known physical laws and well-substantiated theories inferred from other observations. We then ask the computer to solve this model as we set it up. These complex models are a great help when your own thinking leads you to believe that certain factors should be included in a complex manner. You can often solve it by a mathematical model, but you are still called upon to formulate the problem yourself.

Now, the second question has to do with somewhat the same subject. "What is the effect of errors in the data on the result of multiple correlation analysis. Can small errors lead to large changes in fitted formulas when all the correlations are relatively weak?"

MR. BETSON:

Yes. I think that this is true, and I believe the person asking the question has a good point. This is, of course, one of the many limitations of the multiple regression. It is inherent. Again we have to recognize it, and this regression can give us no better answers than the data we feed into it.

MR. STALL:

I know there are a lot of people here who have experience using multiple regression and some of the more refined probability methods, and I am wondering if anyone would like to comment further on it? Al Sharp? Mr. Sharp has studied this quite considerably — the multiple regression and its uses in studying water yields in the Great Plains.

MR. SHARP:

Thanks, John. I would just like to raise a red flag or two, in use of multiple regression and other statistical treatments of hydrologic and other similar data. First of all, if one has a great many variables and comes out with a great many equations and a great many correlation coefficients, etc., one is very likely to get spurious results because, just by pure chance, one out of every hundred equations may show up highly significant, or five out of every hundred may show up significant, when actually there is no real significance. So, I think all our analyses should bear up under very, very rigid logical examination.

Another remark I would like to make is that I question very much the application of much of our data to the multiple regression technique, because it (the multiple regression technique) was derived from one kind of data and we are applying it to another, and our data just don't fit the premises upon which the multiple regression method is based. I won't go into this; any of you can do that.

Third, I have been trying for years and years to promote a study or project and I want to make an appeal for some support. We do not have statistical procedures now available that properly fit our hydrologic and sedimentation data in many cases. I think it would be highly desirable if, among us, we could derive some support or build up some pressure for such a study. I don't know whether anything could come of it or not, but we certainly ought to know. Every one of us uses a double mass diagram. Nobody knows how much of a break in such curves is necessary for the change in slope to be significant or due to chance. There are many other similar problems involved, so I think that we as sedimentationists and we as hydrologists ought to develop our own statistical procedures through, perhaps, some joint effort.

MR. STALL:

I know there are number of others who have talked about this subject and would like to comment, but let us go ahead. The next question is to Henry Anderson. "Would you please comment on the effect of water temperatures on sediment yield?"

MR. ANDERSON:

I suppose the answer to that is that we had no measures of water temperature associated with our sediment samples. Some of these people have made the correlation on the effect of temperature on sediment yields, which seemed quite startling. We have made none directly on that. We have made evaluation of the relationship of temperature of the area to soil development, and some of the equations in the paper bear on this problem. We have been using the dissociation constant of water as an expression of the temperature of the climate of the region in developing soils. Very highly significant developments have come from this. Is this what this person had in mind?

MR. STALL:

I believe that the implication is just what you have commented — that the effect of temperature can be very enormous, if evaluated, and that if you had information on temperature in your study, we would like to know about it. Apparently you do not.

MR. ANDERSON:

We have measured no measures of temperature of the water associated with sediment measurements. However, in some analyses you do this on a month by month basis and then, of course, this is dealt into the thing in effect.

MR. STALL:

The monthly variation of temperature is inherent in your study. Next, we have a question to Mr. Chepil. "Have you found any significant evidence that saltation and/or avalanching has contributed significantly to bedloads in streams?" While we are waiting for Mr. Chepil, I guess all of you here could not help but notice the similarity between the movies Dr. Chepil showed and those I have seen of Dr. Einstein's — similar movement of bed particles along the bed of the stream. When the wind picks these particles up, they tend to rise vertically and carry farther and tend to be far more violent movement. There is a very striking similarity, and that is the area of this question.

DR. CHEPIL:

We have no measurements of the relation of saltation to bedload movement in streams, and I can't answer that question.

MR. STALL:

Don Parsons has a question.

DR. CHEPIL:

The question is, "What were the approach conditions for the transport of grains as shown in the movies?" I construe this to mean under what conditions the photographs were taken. The length was 4 inches, and the height was 2½ inches. The area was illuminated by a beam of light, which was shot from the top about 1 cm. wide. Concentrated sunlight was used about three times the intensity of sunlight. So what you saw was only the particles within that vertical beam of light, which was parallel with the direction of the wind. Does that answer the question?

MR. STALL:

We have a question from the floor.

MR. NORMAN BROOKS:

How much channel is there upstream?

DR. CHEPIL:

About 5 feet of erodible soil surface. That was sufficient to cause particles to jump at least a foot in height. Many particles jumped much higher than that; about 90 percent of the particles jumped within the height of 1 foot. The rest jumped above 1 foot, or higher. These particles were in saltation up to about ½ mm. in diameter. The length of the upstream air channel was about 50 feet. The length was sufficient for development of an air boundary surface at least 1 foot deep.

MR. STALL:

What was the wind velocity?

DR. CHEPIL:

The wind velocity was about 25 to 30 miles per hour at about 1 foot height. That is equivalent to about 40 to 45 miles per hour at 50 foot height.

MR. STALL:

Thank you very much, Dr. Chepil. We have a question now to Mr. Piest. "Did you take into account the effect of very high floods in permanently changing the watershed, such as by starting gully systems, by changing river channels permanently?"

MR. PIEST:

I don't know whether I understand that question correctly or not. Did I take into account very high floods?

MR. STALL:

Yes — which, by their extreme nature, might originate an entire gully system or channel system?

MR. PIEST:

Let me say that most of the records that I was dealing with were 3 to 7 years in length; few of them were a little bit longer than that. Most of the time you won't have an extreme event (like a 50-year storm) in that short-length period, although with the extrapolation procedure you are supposed to take account of that. However, in several instances there did occur, in the short-term periods, storms that had return periods of 50 years or more. One of these was in Ralph Baird's watersheds at Riesel, Tex. These were 176-acre and 132-acre watersheds, and there was no channel alteration that I know of. One of the drawbacks in my analysis of the data is that, in a lot of cases, I was unacquainted with the particular area. The extrapolation procedures on the water-sediment relationship were, I think, pretty good. However, because there was no long-term stream gaging data in the immediate vicinity of the subject station, we would have to go, sometimes, 25 to 50 miles away for our extrapolation base.

MR. STALL:

Thank you very much. It is possible that large storms could change the nature of the gully system such as to set up an entire new system or pattern of gullies. Apparently your data might have included such an event, but you apparently have not evaluated it to that degree.

MR. PIEST:

You are mostly concerned with channel erosion — the additional erosion that would be contributed by new channels — is that right? Generally speaking, on these small watersheds, many channels are well developed. Except in the more arid regions, I would really minimize the total influence of newly developed channels from extreme storms on the sediment yields (that is, for the watersheds I dealt with). On some of the watersheds in western Nebraska that I know of, channel erosion is significant. The channel erosion for the 20-sq. mi. area of Dry Creek near Curtis, Nebr., for example, is very high, but few of the watersheds in the eastern part of the country had much channel erosion as compared with sheet erosion and rill erosion.

MR. STALL:

Thank you. The next question is to Mr. Bullard, who told us about the release of a large sediment load into a trout hatchery pond. "What is the quantitative evidence of the effect of sediment on the trout in this fish hatchery?" This is a subject that many are interested in, and perhaps you can tell us what happened there.

MR. BULLARD:

I don't know about the effect on the trout. The only effect I saw was on the hatchery superintendent, and he was madder than hell! Seriously, though, I very much wish that in connection with some of these studies, which are being made by various agencies on the effects of this land use and that land use on sediment in the streams, that we could get together with the wildlife people in running studies on the effect of sediment on the aquatic habitat and the organisms therein. I know of a couple of such studies.[1] I was talking with one of the registrants here earlier about this. An aquatic biologist by the name of John Peters, who is in the research end of the Montana Fish and Game Department, has done some work that involves the effect of sediment both from range land and from irrigated croplands on a couple of trout streams (I think in the Missouri Basin — some headwater streams). This very interesting piece of work, which I think is just coming to a conclusion, will probably be reported in one of the wild life journals soon. Some similar work is being done in the Water Research Institute at Oregon State University, Corvallis, by Charles Warren who is also an aquatic biologist. I think at the moment Dr. Warren is more concerned with nutrient loading than sediment loading, but the sediment angles are coming in for study also. This study that was mentioned up in Michigan — maybe there was a cooperative study with the wild life people — but I think that would have afforded an excellent opportunity to learn the other side of this story and it is one that is badly needed.

MR. STALL:

Thank you. We have a couple of questions here that we may have to skip, but I would like to ask Emmet Laursen to come up at this time. He doesn't have exactly questions, but he asked for a little time to comment on a different approach to sediment yield. You have about one minute, Emmett.

[1] CORDONE, A. J., and KELLEY, D. W. THE INFLUENCES OF INORGANIC SEDIMENT ON THE AQUATIC LIFE OF STREAMS. Calif. Fish and Game 47. 1961.

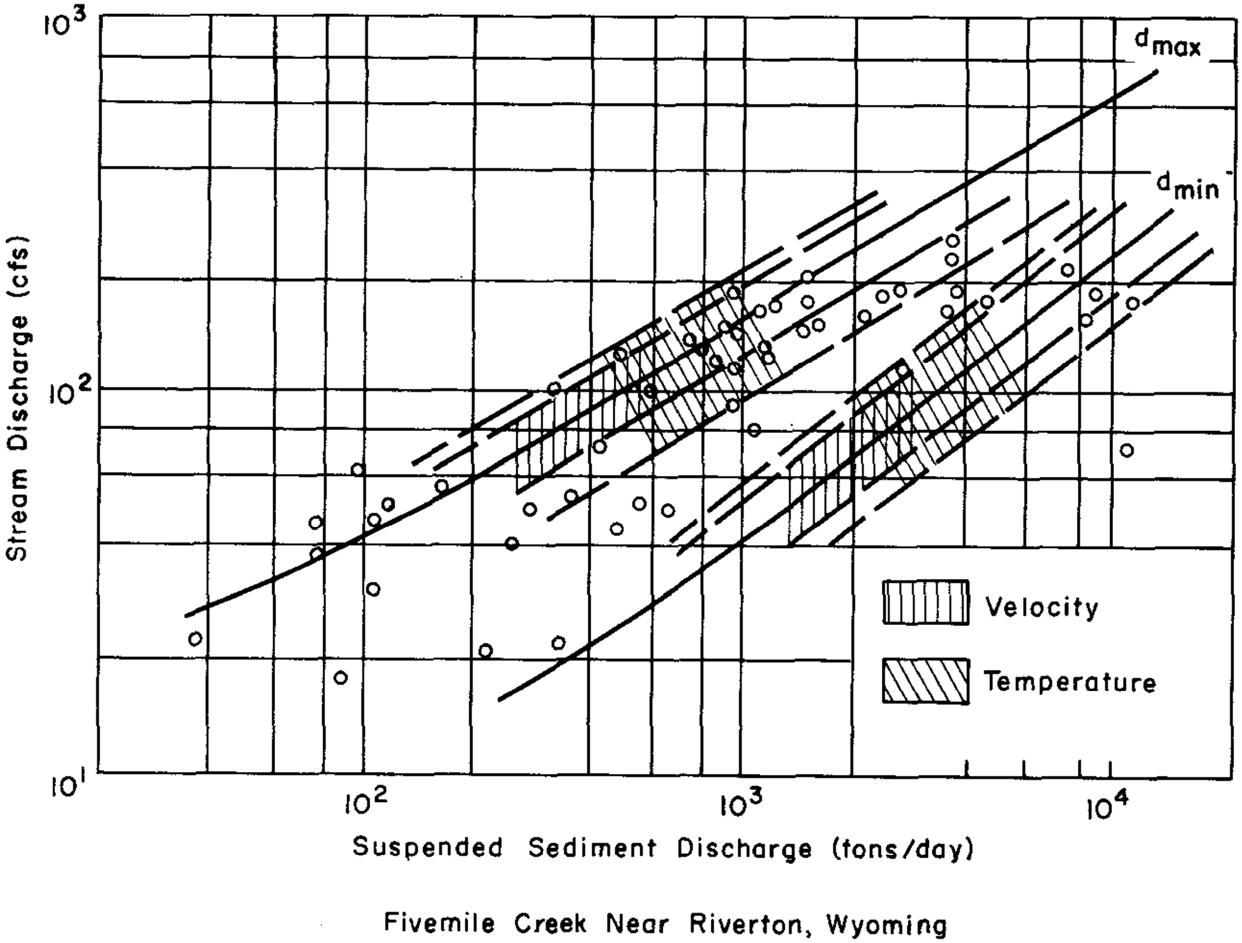


FIGURE 1. — Relation between sediment load and stream discharge at Five Mile Creek near Riverton, Wyo.

MR. LAURSEN:

The accompanying figure is from a Master's study, which attempted to explain the scatter in the relation between sediment load and stream discharge commonly found with natural streams. The example is from Five Mile Creek in Wyoming. (A complete account of the study can be found in the January 1963 issue of the ASCE Journal of the Hydraulics Division in the paper "Sediment-Transporting Characteristics of Streams," by G. A. Zernial and E. M. Laursen.) Data collected by the U.S. Geological Survey on streamflow, bed material, temperature, and sediment load were used. The two heavy curves are the prediction of sediment load if maximum and minimum probable size of bed material and average streamflow and temperature conditions are assumed. Approximately a 10:1 ratio in sediment load can be expected from this change in bed material. The other curves show variable, rather than the sediment yield itself, and come up with a usable relationship. Certainly, the material added should be related to the soil type, the cover, the topography, and the storm. By breaking the total problem of sediment yield up into relatively independent parts, it may be possible to apply more of what is known about rainfall, runoff, and stream behavior and thus, understand sediment yield better.

MR. STALL:

Thank you very much. Gentlemen, I hate to stop but I feel that we should. There are a few of you with unanswered questions. I will refer you to the authors of these papers who are by now pretty well identified and will be here for the next couple of days. We can assure you that all 91 papers of this conference will be published and will be available to you. So, in conclusion of this recap of today's symposium, I would like to comment that I am impressed by the things we do know about sediment movement. We urge that all these things which we have talked about be considered as the building bricks, which Dr. Vanoni mentioned yesterday, and which can ultimately reveal to us the basic structure of understanding of sediment movement which we all desire. With that, I will turn the meeting back to our chairman.

MR. MURPHY:

Thank you, Mr. Stall, and thanks to all the people who had questions. We were concerned with whether our effort to get questions would be productive, but you set our concern to rest. In fact, we had to run 15 minutes overtime to take care of the questions. I do want to thank the speakers on the program this afternoon for their cooperation in sticking to the schedule, in being brief, and in making very fine presentations. I also feel that the audience deserves commendation, too. You have been very patient in sitting here all day from 8 a.m., including this 15 minutes of overtime, and for maintaining a high level of interest. I believe you are to be congratulated. I haven't seen many people leaving. This was a test to your interest in this subject. I appreciate your attention and your interest and with that I am going to turn this over to the man from the Sedimentation Subcommittee, Mr. Berk.

MR. BERK:

Thank you, Mr. Murphy. I have just one announcement I am going to make. Five of the papers scheduled for distribution are now available — Papers Nos. 8, 29, 37, 95, and 96. They are now available with the other papers. I apologize to Mr. Thatcher of the AEC and to Professor Anderson of Mississippi State College, but we just can't have any more announcements because we are overtime. The Sedimentation Subcommittee declares this session adjourned.