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Report of the Water Management Subcommittee

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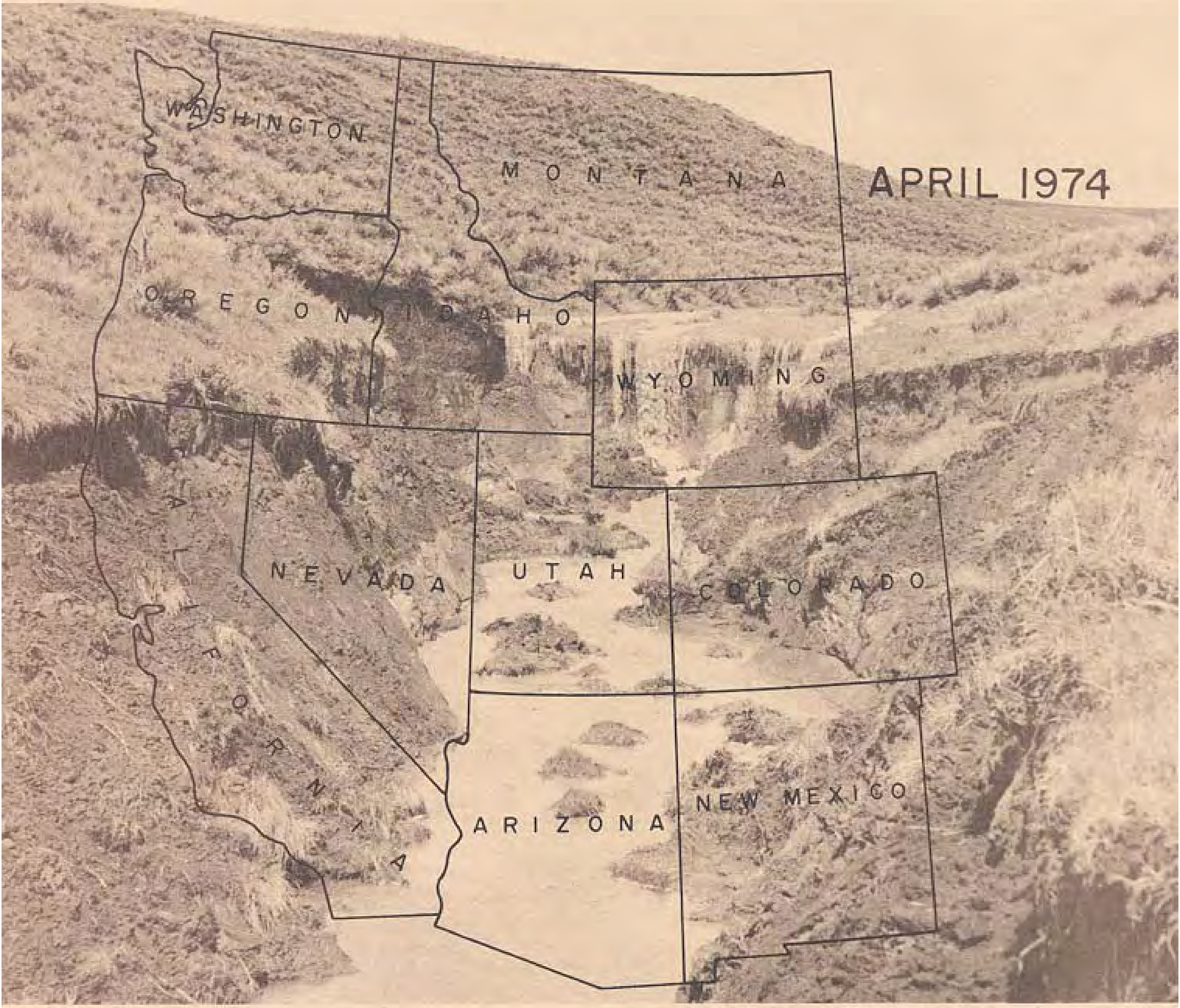

EROSION AND SEDIMENT YIELD METHODS

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PACIFIC SOUTHWEST

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REPORT

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WATER MANAGEMENT SUBCOMMITTEE

on

EROSION AND SEDIMENT YIELD METHODS

May 1974

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Foreword

This report is intended for use by field workers, students, or others not intimately aware of the variety of attempts at developing erosion or sedimentation estimating techniques. The summaries of 12 methods together with the bibliography of related papers should provide sufficient background information to allow an individual to use the method that seems most suited to a particular watershed problem.

EROSION AND SEDIMENT YIELD METHODS
REPORT OF THE WATER MANAGEMENT TECHNICAL SUBCOMMITTEE

Erosion and Sediment Yield Methodology Task Force, PSIAC

May 1974

INTRODUCTION

At the 71-3 meeting, the Pacific Southwest Interagency Committee gave approval to the request of the Water Management Technical Subcommittee to form a task force to work on erosion and sediment yield methodology as it applies to conditions in the Pacific Southwest. Subsequently, an interagency task force was organized comprised of the following members: Marvin C. Meier, Chairman, U.S. Forest Service; Perry Y. Amimoto, California Division of Soil Conservation; Dale Burnett, U.S. Army Corps of Engineers; Elliott M. Flaxman, Soil Conservation Service; Richard F. Hadley, U.S. Geological Survey; Kenneth G. Renard, Agricultural Research Service. Mr. Hadley became chairman in December 1972, following the transfer of Mr. Meier out of the region.

The objectives of the task force are to review the literature and evaluate and discuss methods of estimating on-site erosion and downstream sediment yield as to the data requirements, applicability to field project situations, reliability, and physical situations under which they are valid.

The 1968 report of the Water Management Subcommittee entitled, "Factors affecting sediment yield and measures for the reduction of erosion and sediment yield," outlined a procedure for estimating sediment yield. That report was directed toward broad planning needs. This report is directed toward detailed project planning and design in the Pacific Southwest area.

Climatic and physiographic variability within the Pacific Southwest make problems of estimating sediment yield or on-site erosion difficult. Although actual field measurements are most desirable, they are not available in most areas, and time does not permit undertaking a detailed data-collection program to obtain such information. Several prediction methods have been developed from research generally with limited climatic and physiographic variability. One of the objectives of this report is to examine several of these methods and to provide guidelines for their usefulness in the Pacific Southwest.

PROCESSES OF EROSION, TRANSPORT, AND DEPOSITION

The processes of erosion, transport, and deposition of particles, either disintegrated rock or soil, represents sedimentation. These processes are part of the normal cycle of geologic events that shape the landforms of the Earth, and the rates at which the processes act are dependent on such variables as rock or soil type, climate, relief, plant cover, and land use. Interference by man in altering the land by mechanical treatment, cultivation, vegetation manipulation, or structural regulation of streamflow has a marked influence on the sedimentation cycle. The processes and products of sedimentation are represented in the entire geologic column but the part of the cycle of primary interest here is modern sedimentation influenced to a large degree by man's activities.

Erosion by water begins with the intial detachment of soil or weathered rock material on upland areas. This kind of erosion may be divided into sheet and rill erosion and channel erosion, which includes gullying. These basic processes are the first step in the movement of sediment from upstream source areas to downstream locales of deposition.

Sheet erosion may be defined as the removal of soil and weathered rock material as a thin sheet by overland flow that is not concentrated in well-defined channels. The eroded material being transported results from impact energy as individual raindrops intersecting the land dislodge sediment and form the shear force produced by the water moving over the land surface. It is difficult to differentiate between sheet and rill erosion in the field because runoff will tend to concentrate quickly in small rills on irregular surfaces. Therefore, in less advanced stages, sheet erosion is an intangible factor in the evaluation of soil loss or sediment yield from any watershed. Without continued accurate quantitative measurements along established ranges, the amount of sheet erosion is generally too small to be observed. Criteria that have been used to estimate the approximate rate of sheet erosion are such features as pedestaled vegetation, shallow rills, and soil characteristics. Such evidence may indicate serious erosion, but the extent and rate cannot always be determined precisely.

The relation between sheet erosion and rock type is variable. Where bedrock is covered by a thick mantle of weathered rock and residual soil, sheet erosion is generally more severe than in areas where the bedrock is at or near the surface. However, sheet erosion can be severe on exposed bedrock, such as shale, which has a low inherent resistance to erosion. Also, the severity of sheet erosion is governed, to a large degree, by the type and density of the plant cover and, to a lesser extent, by the characteristics of the weathered mantle such as grain size and infiltration capacity.

Runoff from hillslopes in upland areas concentrates in rills and small channels. These channels increase in size in a downstream direction as the drainage network enlarges. Channel erosion is the detachment of sediment from the bed and banks of stream channels by fluvial processes. Channel erosion is controlled by many factors such as the bed slope, velocity of flow, suspended-sediment load being carried by the stream, cohesiveness of bed and bank material, plant cover on banks, and particle size of sediment available for transport in the stream. Therefore, channel erosion generally is quite variable from place to place in any channel reach. Adjustments are made by the stream when the ability to transport sediment is decreased or part of the sediment load is deposited because of reduction in slope or absorption of flow into a permeable channel bed.

Because of the complexities of the system involved in erosion on hillslopes and channels in upland areas and the entrainment and transport of the eroded material, accurate sediment routing and definition of sediment source areas is difficult. In arid areas particularly, where storms generally are widely scattered and of small areal extent, the eroded sediment is often transported only a short distance and redeposited in a single event. Therefore, the relation of sediment yield rates from small upland areas to larger areas downstream is too complex to evaluate in most cases.

The transportation of sediment by streamflow is complex because of the many variables involved. Fine particles are transported in suspension and may be moved far downstream. Coarse particles may be transported momentarily in suspension but are usually rolled along the streambed. Other important factors in sediment transport are the supply that is available for movement, the sizes and density of particles, channel geometry, characteristics of the flow, and quality of water.

Most of the sediment that is eroded from upland areas eventually makes its way to the valley floors and channel flood plains before it is deposited. Some of the sediment is deposited enroute to these downstream points in reservoirs and other water regulating structures or on alluvial fans where stabilization by vegetation occurs. It is important to recognize, however, that any deposit of unconsolidated sediment probably will be transitory. A change in climate, land use or vegetational cover may regenerate the sedimentation cycle and transport the sediment farther downstream.

METHODS INVESTIGATED

The methods available to estimate on-site erosion and sediment yield from small watersheds were determined from an extensive literature search and by contacting agencies with water resources and sedimentation research programs in the Pacific Southwest area to ascertain the procedures they use. In spite of a large bibliography of published material on erosion and sedimentation, the number of methods that are germane to this report was narrowed to 12. Six of the methods provide estimates of on-site erosion and six provide estimates of sediment yield in a stream draining a small natural watershed.

A plan of evaluation of the selected methods was developed in order to accomplish the objectives of the task force. The work plan consisted of the following steps: (1) summarize the pertinent characteristics of each method, (2) describe the origin and development of each method, including the geographic location of research sites, and (3) test the methods with actual field data where suitable data are available.

EVALUATION OF METHODS

Table 1 was prepared to provide the field investigator with a rapid means of selecting a method for estimating erosion and sediment yield rates. The table compares each method relative to the factors formulating all methods considered so that during the planning process all the methods can be considered for applicability to a particular problem. By use of the table, the investigator can determine the data necessary to solve the selected method within the constraints of accuracy needed, time available, and financial resources. Although Table 1 provides a convenient guide in selecting an appropriate method for field use, it should be pointed out that the listed factors are quite general, and should not be used as a substitute for a detailed study of the specific characteristics of each factor.

The task force prepared summaries of the 12 methods selected. The objective of the summaries is to present a brief description of each method in a format that will allow comparison among the methods. The summaries in Appendix I show the essential elements of each method including the location of study, physical characteristics of the research area, methods of analysis, predictive equations, and tests and limitations of the method. The summaries are divided into two groups: (1) methods for estimating erosion, and (2) methods of sediment yield prediction.

SOME APPLICATIONS OF ON-SITE EROSION AND SEDIMENT YIELD METHODS USING FIELD DATA

As stated in the Introduction of the report, the Task Force intended to test many of the selected methods in areas of the Pacific Southwest region where adequate field data were available. This has not been possible to complete but some applications are presented here for one on-site erosion method--the universal soil loss equation (Wischmeier and Smith, 1965), and one sediment yield method--the predictive equation of Flaxman (1972), as revised (1974).

As a test of the possible utility of the Universal Soil Loss Equation for rangeland applications, limited data were used from the Walnut Gulch Experimental Watershed operated by the Agricultural Research Service in southeastern Arizona (Renard and Simanton, 1973). The utility of the soil loss method for prediction purposes is predicated by the need to evaluate the soil, cover and land treatment factors from some known locations for arid and semiarid rangeland conditions.

The Universal Soil Loss Equation as presented by Wischmeier and Smith (1965) is

$$A = RKLSCP$$

where A is the computed soil loss per unit area.

R, the rainfall factor, is the number of erosion-index units in a normal year's rain. The erosion index is a measure of the erosive force of specific rainfall.

	METHOD	FACTOR	GEOLOGY AND SOILS					CLIMATE				RUN-OFF		TOPOGRAPHY							GROUND COVER			LAND USE				UP-LAND ERO-SION		CHANNEL 1/ EROSION AND SEDIMENT TRANSPORT			COST OF FIELD DATA			METHOD OF SOLUTION			LIMITATIONS AND APPLICABILITY
		PROPORTION NONERODIBLE	SOIL SIZE DISTRIBUTION	SOIL DENSITY	% ORGANIC	SOIL STRUCTURE	PERMEABILITY	ANNUAL PRECIP.	PRECIP. INTENSITY	RELATIVE RAIN AREA	ANNUAL TEMP.	RUNOFF	STREAM HYDROGRAPH	SLOPE	SLOPE LENGTH	AREA	DRAINAGE DENSITY	RELIEF RATIO	SHAPE OF BASIN	ANGLE OF JUNCTION	% BARE GROUND	EFFECT OF FIRE	VEGETATIVE COVER	ROADS, URBAN	PRACTICE FACTOR	GRAZING	LOGGING	TEST PLOTS	FARM PONDS	CHANNEL X-SECTION AND SLOPE	SUSPENDED LOAD	RESERVOIR SEDIMENTATION	LOW	MEDIUM	HIGH	ANALYTICAL	NOMOGRAPH-CHARTS	COMPUTER	
ON-SITE EROSION	BRYAN		X O		X O				X O					X O														X											NO PREDICTIVE EQUATION. DATA RELATES SOIL ERODIBILITY TO WATER SOLUBLE AGGREGATES > 3mm
ON-SITE EROSION	FOSTER AND MEYER		X O						X O					X O	X O													X						*		*			EQUATION UNIVERSALLY APPLICABLE IF COEFFICIENTS ARE DETERMINED.
ON-SITE EROSION	MEEUWIG	X O	X O	X	X O				X O					X O									X O					X						*		*	*		EQUATIONS DETERMINE RELATIVE ERODIBILITY BUT AT A CONSTANT RATE OF PRECIPITATION.
ON-SITE EROSION	MEYER AND WISCHMEIR		X O	X O					X O			X O		X O	X O	X O												X					*			*			EQUATION UNIVERSALLY APPLICABLE BUT COEFFICIENTS DIFFICULT TO DETERMINE.
ON-SITE EROSION	MUSGRAVE		X O			X O	X O		X O					X O	X O										X O			X					*			*			EQUATION UNIVERSALLY APPLICABLE BUT LIMITED TO SLOPES LESS THAN 20 PERCENT.
ON-SITE EROSION	WISCHMEIR AND SMITH		X O			X O	X O	X	X O					X O	X O										X O			X						*		*	*		EQUATION UNIVERSALLY APPLICABLE BUT LIMITED TO SLOPES LESS THAN 20 PERCENT.
SEDIMENT YIELD	ANDERSON	X	X					X	X O	X O		X O	X	X O		X O			X			X O	X O	X O		X	X			X	X	X O			*	*		*	EQUATION APPLICABLE MAINLY IN LARGE WATERSHEDS BUT NEEDS SEDIMENT TRANSPORT DATA.
SEDIMENT YIELD	BRANSON AND OWEN		X									X		X			X O	X O		X	X O											X	*			*			EQUATION UNIVERSALLY APPLICABLE BUT CORRELATION COEFFICIENTS FOR EACH AREA MUST BE DETERMINED.
SEDIMENT YIELD	FLAXMAN		X O					X O			X O	X O		X O															X			X	*			*			EQUATION UNIVERSALLY APPLICABLE ESPECIALLY IN WESTERN UNITED STATES.
SEDIMENT YIELD	NEGEV		X						X				X																		X								EQUATION UNIVERSALLY APPLICABLE BUT NEEDS PRECIPITATION AND RUNOFF DATA.
SEDIMENT YIELD	RENARD											X O	X O	X O		X O														X O	X	X		*				*	EQUATION APPLICABLE UNIVERSALLY IF RUNOFF GENERATION METHOD AVAILABLE. 2/
SEDIMENT YIELD	TATUM								X O					X O			X O		X O			X O										X	*				*		EQUATION APPLICABLE TO SOUTHWESTERN UNITED STATES. NEEDS PRECIPITATION & BURN EFFECT DATA.

X DATA NEEDED TO FORMULATE METHOD
O DATA USED TO SOLVE DERIVED METHOD
* MISCELLANEOUS INFORMATION ON COST AND DATA OUTPUT
1/ CHANNEL SLOPES ARE NEEDED FOR RENARD'S METHOD
2/ USED WITH EPHEMERAL STREAM MODEL IN SOUTHWESTERN UNITED STATES

Table 1.--Summary table of on-site erosion and sediment yield methods

K, the soil-erodibility factor, is the erosion rate per unit of erosion index for a specific soil in cultivated continuous fallow, on a 9-percent slope 72.6 feet long. The reasons for selection of these conditions as unit values is explained in the detailed discussion of this factor.

L, the slope-length factor, is the ratio of soil loss from the field slope length to that from a 72.6-foot length on the same soil type and gradient.

S, the slope-gradient factor, is the ratio of soil loss from the field gradient to that from a 9-percent slope.

C, the cropping-management factor, is the ratio of soil loss from a field with specified cropping and management to that from the fallow condition on which the factor K is evaluated.

P, the erosion-control practice factor, is the ratio of soil loss with contouring, stripcropping, or terracing to that with straight-row farming, up-and-down slope.

Numerical values of each of the six factors have been extensively determined from research data in areas east of the Rocky Mountains. Scarce data has limited the usefulness of the method in the West. The discussion which follows details the use of the relationship in a semiarid rangeland with sparse vegetative cover receiving intense convective summer thunderstorms producing the annual runoff.

Rainfall Factor (R)

Iso-erodent maps are available only for portions of the United States east of the 104th meridian. Therefore, it was necessary to use precipitation data from the Walnut Gulch Watershed to compute storm EI (total kinetic energy of the storm times its maximum 30-minute intensity). The sum of the computed storm EI values for a given time period is a numerical measure of the erosivity of all the rainfall within that period. The rainfall erosion index (R) at a particular location is the longtime-average yearly total of the storm EI values.

The highly variable nature of the air-mass, convective thunderstorms has been well documented. Accordingly, the rainfall factor associated with such precipitation would also be expected to be highly variable.

Table 2.--Annual EI values on Walnut Gulch.

	Index values normally exceeded once in			
Gage No.	1 year	2 years	5 years	10 years
22	35	52	67	76
60	23	67	140	210

Table 2 illustrates the variability of the EI values from two gages selected from the precipitation network on Walnut Gulch. Interestingly a single storm event produced approximately one-fourth of the annual values presented in this table varying from a low of 23 percent to a maximum of 33 percent.

Soil-Erodibility Factor (K)

Soils developed under semi-arid environments such as on Walnut Gulch are undoubtedly quite different from the soils listed in Agricultural Handbook 282. The soil properties listed as influencing erodibility by water are: "(1) those that affect the infiltration rate, permeability, and total water capacity, and (2) those that resist the dispersion, splashing, abrasion, and transporting forces of the rainfall and runoff." Both elements are quite important in the soils encountered in this test evaluation where the surface contains an erosion pavement covering 30 percent of the area unprotected by vegetation.

The soils of the watersheds used in this test evaluation are Rillito-Laveen gravelly loams. These soils are found on gently and moderately sloping ridges formed by the deep dissection of old alluvial fans and valley plains. The Rillito series (forming about 75 percent of the mapping unit) consists of deep, well-drained, medium and moderately coarse textured gravelly soils formed in calcareous old alluvium. The surface layer, dominated by an erosion pavement, is light brownish gray gravelly loam 4 to 7 inches thick. The subsoil is light brownish gray or pinkish gray gravelly loam to a depth of 40 inches or more. Laveen soil is a well drained sandy to gravelly loam which is found on level terraces and alluvial fans above flood plains. The texture of the A horizon varies with 1 to 15 percent fine gravel on the surface. The numbers of soft lime masses and modules in the Cca horizons range from few to many with 20 to 35 percent carbonates.

The erosion pavement present on the soils of the watersheds used for this evaluation greatly reduces the splash erosion and provides additional roughness to reduce overland flow. However, due to very high rainfall rates associated with the short duration storms, high runoff rates are still encountered.

Slope Length (L) and Gradient (S)

In field practice, slope length and gradient are generally considered as one term. Agricultural Handbook 282 presents a graph for determination of the LS value to use in the prediction equation. The narrative discussion also states that when convex and concave slopes are involved, the erosion is not that of the average slope. Rather, when the lower end of the slope is steeper than the upper end, the gradient of the steeper segment should be used with the overall slope length to enter the slope-effect chart. This procedure was used for the two watersheds used in the analysis.

Table 3. "C" VALUES FOR PERMANENT PASTURE, RANGELAND, AND IDLE LAND1/

FROM SCS T.R. 51

VEGETAL CANOPY		COVER CONTACTS SURFACE						
TYPE AND HEIGHT OF RAISED CANOPY 2/	CANOPY COVER % 3/	TYPE 4/	PERCENT GROUND COVER 0	20	40	60	80	95-100
COLUMN NO.	2	3	4	5	6	7	8	9
NO APPRECIABLE CANOPY		G	.45	.20	.10	.042	.013	.003
		W	.45	.24	.15	.090	.043	.011
CANOPY OF TALL WEEDS OR SHORT BRUSH (0.5 m. FALL HEIGHT)	25	G	.36	.17	.09	.038	.012	.003
		W	.36	.20	.13	.082	.041	.011
	50	G	.26	.13	.07	.035	.012	.003
		W	.26	.16	.11	.075	.039	.011
APPRECIABLE BRUSH OR BUSHES (2m. FALL HEIGHT)	25	G	.40	.18	.09	.040	.013	.003
		W	.40	.22	.14	.085	.042	.011
	50	G	.34	.16	.085	.038	.012	.003
		W	.34	.19	.13	.081	.041	.011

1/ All values assume: (1) random distribution of mulch or vegetation, and (2) mulch of appreciable depth where it exists.

2/ Average fall height of waterdrops from canopy to soil surface.

3/ Portion of total-area surface that would be hidden from view by canopy in a vertical projection.

4/ G: Cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 2 inches deep.

W: Cover at surface is mostly broadleaf herbaceous plants (as weeds).

Cropping-Management Factor (C)

This term was developed primarily for conditions connected with crops and rotations in connection with cultivated agriculture. On rangeland areas, such as are encountered in most of the intermountain west, guidelines to a value of C are not generally available. In addition, the seasonal variation of the term due to the variation in crop stage will generally be of limited consequence in brush or grass dominated rangeland. Of greater consequence is the relative density of plants. On the brush-grass watersheds used in the evaluation discussed here, the vegetative ground cover as determined with line transects, is generally less than 10 percent by basal area and 30 percent for crown covers.

Wischmeier, working with SCS personnel, has postulated some cover term values for conditions such as those encountered in the sparse vegetation rangeland areas of the Western United States. A portion of the table from Soil Conservation Service Technical Release Number 51, appears as Table 3. Values of 0.38 and 0.36 for the brush- and grass-covered watersheds used subsequently were selected from this table.

Erosion-Control Practice Factor (P)

The erosion control practice factor (P) in the erosion equation is the soil loss ratio with the supporting practice to the soil loss with up-and-down-hill culture. In general, there are no cultivation practices in rangelands so the term would generally be 1.0. Rangeland rejuvenation is becoming increasingly common with treatments such as subsoiling to break up caliche layers, contour pits to hold water at times of reseeding with rangeland drills, etc., but none of these treatments were present on the watershed used herein so P was taken equal to unity. In most rangeland erosion prediction, the C and P terms can generally be lumped similar to the LS terms used for the topographic factor.

Erosion Prediction

Although the USLE is intended for estimating erosion only, some success has been encountered by using it to estimate sediment yield from very small watersheds. An illustration of these results follows for two small watersheds on Walnut Gulch with contiguous drainage areas of 8.3 and 11.0 acres. Data from a fairly intense thunderstorm on July 27, 1973, were used from these two brush-covered drainages to estimate the soil erodibility term (K). Both drainages had similar soils, a similar topographic factor, and the same brush dominated vegetative cover. EI values differed slightly as indicated by recording gages adjacent to the watersheds. The data used are summarized in Table 4.

Table 4.--Measured parameters of the four watersheds used in this analyses

Watershed	Area/Acres	R	K	LS	C	P	E_c	A(Tons/Acre)
63.103	8.3	39.2	.01	1.2	.38	1	3.86	.69
63.104	11.0	43.4	.01	1.2	.38	1	1	.20
63.214	372.0	82.3	.01	1.3	.36	1	1	.52
63.223	108.0	62.7	.01	1.4	.38	1	3.86	1.64

The stream channels, however, differed appreciably for the two watersheds. One watershed has a channel traversing fairly resistant caliche-conglomerate outcrops which also control the channel gradient. The watershed has a channel with an almost limitless supply of fine sand and silt. Thus, the sediment yield from this watershed contains not only watershed overland flow erosion but also erosion from the channel bed and banks. The sediment yield from these two areas was 0.20 tons/acre and 0.69 tons/acre for the July 27 event (Table 4).

The relationship: $K = \frac{A}{R*LS*CP}$,

was solved using the known data to obtain the soil-erodibility factor of 0.01 for the watershed without the erodible channel. For the watershed with the eroding channel, an additional term was felt to be warranted to convey the concept or role of the channel. Thus, the modified erosion equation postulated was:

$$A = (RKLSCP)E_c,$$

where the new term E_c refers to a factor reflecting channel erosion. Other terms being equal, the E_c term was evaluated using the K term from the watershed without the erodible channel. Thus,

$$E_c = \frac{A}{RK*LS*CP} = \frac{0.69}{39.2x.01x1.2x.38} = 3.86.$$

The channel erosion term, E_c, is analogous in many respects to the sediment delivery ratio used for watersheds when the onsite erosion is used to estimate sediment yield at the outlet. In most of these instances however, the sediment delivery ratio is less than unity (Roehl, 1963) and decreases with increasing watershed size. Although the research is presently incomplete, channel erosion may be a very significant part of the sediment yield from watersheds in semi-arid areas such as southeastern Arizona.

The utility of this data evaluated for one storm event was tested with data from two watersheds with drainage areas of 108 acres and 372 acres. The 108-acre area contains the 8.3-acre subwatershed and has similar but proportionally larger channels. For this area, the annual erosion was estimated by determining the loss in storage volume of a

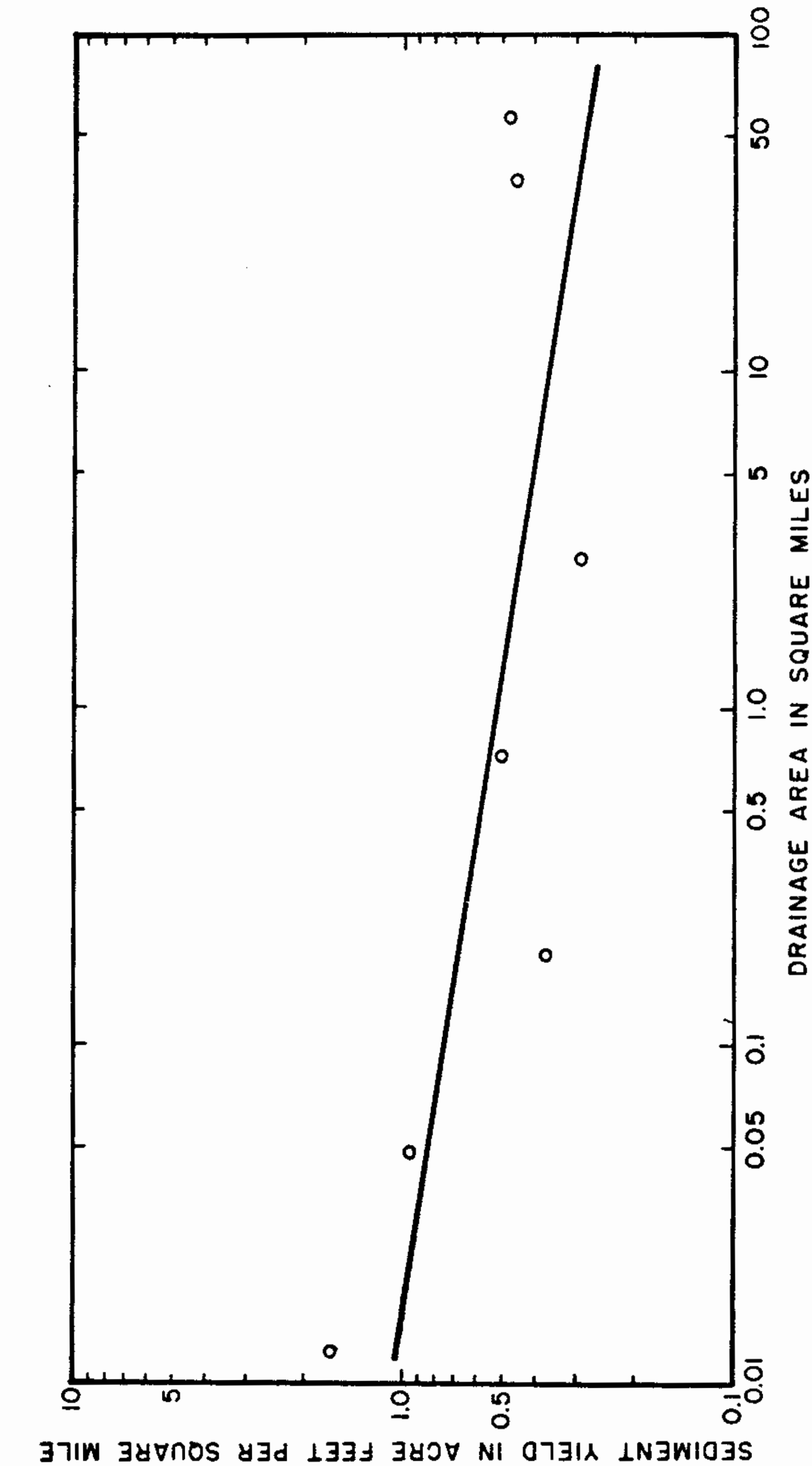

Figure 1.--Sediment yield change with increasing watershed size simulated with a stochastic runoff model and a deterministic sediment transport relation for watersheds in southeastern Arizona

Table 5.--Sediment yield prediction for three stock ponds on the Walnut Gulch experimental watershed near Tombstone, Arizona

	Drainage area (Mi.^{2})	Actual	Sediment yield (ac-ft/mi^2/yr) Predicted
201	0.17	0.33	0.60
214	0.58	0.31	0.55
223	0.17	0.38	0.60

RELATION OF ON-SITE EROSION TO SEDIMENT YIELD

Much of the sediment yield data that are available for evaluation of land use or land treatment practices have been collected in watersheds less than 5 square miles. These data have been used to develop relationships with drainage basin characteristics and predictive equations for sediment yield from upland areas. An equal, or greater, amount of data have been collected on experimental plots a few tens of square feet in area with the objective of determining on-site erosion. At the downstream end of the system on major streams there are very few records of sediment discharge in most river basins. Therefore, it always has been a nagging problem for hydrologists to develop a satisfactory relationship between the sediment yield from plots and small headwater basins and the sediment discharge measured at stations on larger streams.

Sediment yield is the total sediment outflow from a watershed or drainage basin, measurable at a point of reference and in a specified period of time (ASCE Sedimentation Manual, 1970). The sediment yield is dependent on the gross erosion in the watershed and the transport or conveyance efficiency of the channel network. In arid or semiarid regions the conveyance is often poor because of the ephemeral nature of the streamflow. Some of the sediment eroded from hillslopes is deposited at the base of the slopes or on the valley floors and floodplains before reaching through-flowing streams. Sediment that reaches channels suspended in the flow during storm runoff events often is deposited within a watershed because of absorption of the flow in the channel bed. Also, diversity of topography in larger drainage basins provides sites for deposition that are not available in steep headwater areas. Direct extrapolation of sediment yield rates from plots or small watersheds to larger basins is not possible because of the variation in drainage basin characteristics. The sediment delivery ratio, which is the ratio of the sediment yield at a measuring point to the gross erosion from the watershed, usually expressed as a percentage, can be estimated if something is known about the soils, climate, topography, and geomorphic characteristics.

pond used to provide water for cattle grazing in the area. The annual yield from a 4-year average was determined to be 1.64 tons/acre/yr. By the erosion prediction equation,

$$A = (62.7x.01x1.4x.38)\ (3.86) \approx 1.29 \text{ tons/acre/yr.}$$

The two values agree quite well.

The 372-acre watershed in another portion of the Walnut Gulch Watershed contains more grass but has a channel very similar to that of the 11.0-acre area. Assuming the channel erosion factor (E_c) is equal to unity,

$$A = (82.3x01x1.3x.36)\ 1.0 = 0.39 \text{ tons/acre/yr.}$$

This value agrees favorably with the measured value of 0.52 tons/acre/yr from seven years of data.

Although the coincidence of agreement is encouraging, one must recognize that a large amount of additional work is needed before the method can be applied widely. The inclusion of an additional term to reflect the channel erosion is certainly warranted because in some instances, the erosion from the land surface may be less than that measured downstream, i.e., the sediment delivery ratio is less than unity as has been widely presented in the literature. In other instances, the channel may be producing quantities of erosion comparable to the quantity eroded from the land surface.

One of the methods selected for the prediction of sediment yield was developed by Flaxman (1972) and revised (March, 1974). The predictive equation that resulted from his analysis relates sediment yield as a dependent variable to five independent watershed characteristics; climate, topography, hydrology, and two soils characteristics (percent of soils particles coarser than 1 mm and aggregation or dispersion characteristics of clay-size particles, 2 micron or finer in size), (see appendix). Flaxman's method was tested against field data from the following areas--Boco Mountain watersheds, Colorado; three Bell Canyon watersheds, California; and Walnut Gulch watersheds, Arizona.

The Boco Mountain study near Eagle, Colorado, is an investigation on four small watersheds (5 to 10 acres) designed to measure the hydrologic effects of conversion from sagebrush to bunchgrass (Shown, Lusby, and Branson, 1972). Two of the watersheds remain in their natural state, with predominantly big sagebrush cover and a sparse understory of perennial grasses and forbs. The watersheds are underlain by Mancos Shale and the soils are silty loams and silty clay loams.

Using the sediment yield data for 7 years from one of the watersheds that is in its natural condition, the Flaxman method (1972), revised (1974), was tested to verify its agreement with the collected data. The parameters X_1, (precipitation-temperature ratio), X_2 (weighted land slope), X_3 (percent of soil particles coarser than 1 mm), X_4 (soil aggregation index) and X_5 (50 percent chance peak discharge) were determined.

A summary of the findings is shown below:
Factors to include in equation:

$$X_1 = \frac{\text{Average Annual Precipitation (inches)}}{\text{Average Annual Temperature (°F).}} \text{ or P/T ratio in}$$

Which runoff from snowmelt is determined to be only 40 percent as effective in causing erosion as rainfall runoff.

Average annual precipitation = 13.5 inches
of which 9.0 inches is rain,
4.5 inches is snow.
Average annual temperature = 43.5°F.
The P/T ratio = 0.310

However, a paper by Shown, Lusby, and Branson (1972) states that of the annual runoff of about 1.3 inches, 0.3 inches consisted of overland flow from rainstorms and the remaining 1.0 inch was from snowmelt. Therefore, 23 percent of the total runoff was from rainfall and 77 percent from snowmelt. Since snowmelt was found to be only 40 percent as effective as rainfall in producing erosion, the P/T ratio is increased in the following manner:

Unadjusted P/T ratio = 0.310

77 percent of $\frac{0.310}{40}$ = 0.597

23 percent of 0.310 = 0.071

0.668 = adjusted P/T ratio

X_2 = Weighted average slope = 5.5 percent

X_3 = Percent of soil particles coarser than 1 mm - 1 percent

X_4 = Soil aggregation index = +43 (See size distribution graph + ph value attached)

X_5 = 50 percent chance peak discharge = 168 csm

Solving the sediment yield prediction equation using the above variables gives a computed value of 0.48 acre feet per square mile (assuming deposits have volume weight of 80 lbs./cu. ft.). The actual annual sediment yield as measured in the reservoir is 0.65 acre feet per square mile for the period of record. The lack of agreement between the Flaxman method and the field data is probably attributable, in part, to the high percentage of runoff that occurs as snowmelt at Boco Mountain. The adjustment of the P/T ratio (X_1) for the effectiveness of snowmelt in causing erosion probably needs further study.

A second test of the Flaxman predictive equation was made using field data from the Bell Canyon No. 4 watershed, near Glendora, California. The Bell Canyon watersheds are located in a rugged, deeply dissected mountain mass with steep side slopes, which are underlain by crystalline rocks. The soils are loamy sand with an average depth of 45 cm.

The five parameters (X_1 X_2 X_3, X_4, and X_5), described earlier, were determined. The results of the test are summarized below:

$$X_1 = \frac{\text{Average Annual Precipitation (inches)}}{\text{Average Annual Temperature (°F)}} \text{ or P/T ratio}$$

Average Annual Precipitation = 24.6 inches

Average Annual Temperature = 57.4°F

X_1 = P/T ratio = 0.429
Snowmelt is not involved

X_2 = Weighted average slope = 65 percent

X_3 = Percent of soil particles >1mm = 18 percent

X_4 = Soil Aggregation Index = 0

X_5 = 50 percent chance peak discharge = 314 csm

Solving the sediment yield prediction equation, using the above variables gives a computed value of about 3.02 acre-feet per square mile (assuming deposits have volume weight of 100 lbs per cu. ft.).

The Bell Canyon Watershed is about 37 acres. Sediment has been caught in a debris basin of about 1 acre-foot capacity since 1933. The accumulation in 39 years has been 3189 cubic yards or about 82 cubic yards per year on the average or 1420 cubic yards per square or 0.88 acre-feet per square mile.

However, a basin of the size of Bell Canyon No. 4 is likely to have a low trap efficiency. Four samples are composited to provide the size distribution. The watershed soil D_{50} or size of which 50 percent is finer, for example, is about 0.25 mm. The sediment D_{50} is about 2.0 mm, indicating that much of the fines have been carried through the basin.

The available trap efficiency curve, that of Brune (1953) indicates that the trap efficiency of Bell No. 4, runoff of about 160 acre-feet per square mile and debris basin capacity of about 1 acre-foot, is only slightly over 30 percent using the median trap efficiency curve. When the sediment yield is corrected for trap efficiency, the agreement with the Flaxman method is good.

The third test of the Flaxman method was made by Renard and Simanton (1972) in southeastern Arizona. The hydrologic and sediment records of three livestock watering ponds on the Walnut Gulch Experimental Watershed in southeastern Arizona are used to supplement the material prepared by the author. The parameters X_1 (precipitation-temperature ratio), X_2 (percent land slope), X_3 (percent soil particles >1 mm), X_4 (soil aggregation), and X_5 (50 percent chance peak discharge) were determined using the method described by the author. A summary of these data is presented in the following table:

Hydrologic and sediment records of Stock Pond watersheds near Tombstone, Arizona

Watershed number	Area	Precipitation	X_1	X_2	X_3	X_4	X_5	Sediment yield Actual	predicted
	(mi^2)	(inches)						(Ac-ft./mi^2/yr)[a]	
201	0.17 ($0.44km^2$)	12.42 (31.6cm)	0.192	5.3	72	0	446	0.33	0.26[1/]
214	0.58 ($1.50km^2$)	11.30 (28.7cm)	0.179	8.6	52	0	292	0.31	0.30
223	0.17 ($0.44km^2$)	11.02 (28.0cm)	0.172	9.4	65	0	405	0.38	0.46

[a] Ac-ft/mi^2 multiplied by $4.76x10^{-4}=m^3/m^2$
[1/] Assuming deposits have volume weight of 90 lbs. per cu. ft.

The agreement of the method with actual data is encouraging. The writers feel that the X_1 parameter modification as an index of vegetative cover response for a particular climate might warrant additional investigation. It seems that more specific guidelines of rangeland vegetation cover are needed. A correction applied to plant density departures from some mean value for a specified precipitation-temperature ratio might be one approach.

Table 5 shows sediment yield estimates for these watersheds using the method developed by Renard and shown in Figure 1. This method which was developed from data for larger watersheds, appears to overestimate the yield appreciably. The method which produces synthetic runoff data and computes the sediment in transport for each hydrograph, is very sensitive to the runoff estimate. For example, a 50 percent reduction in the average water yield for a 450-acre watershed with this computer model would result in a 63 percent reduction in the predicted sediment yield.

The sediment yield reduction with increasing watershed drainage area (Figure 1) is similar to the trend shown in Figure 2 for the Wyoming watersheds. This reduction reflects both the sediment delivery ratio concept discussed subsequently, and the reduction in the water available to transport sediment due to transmission losses.

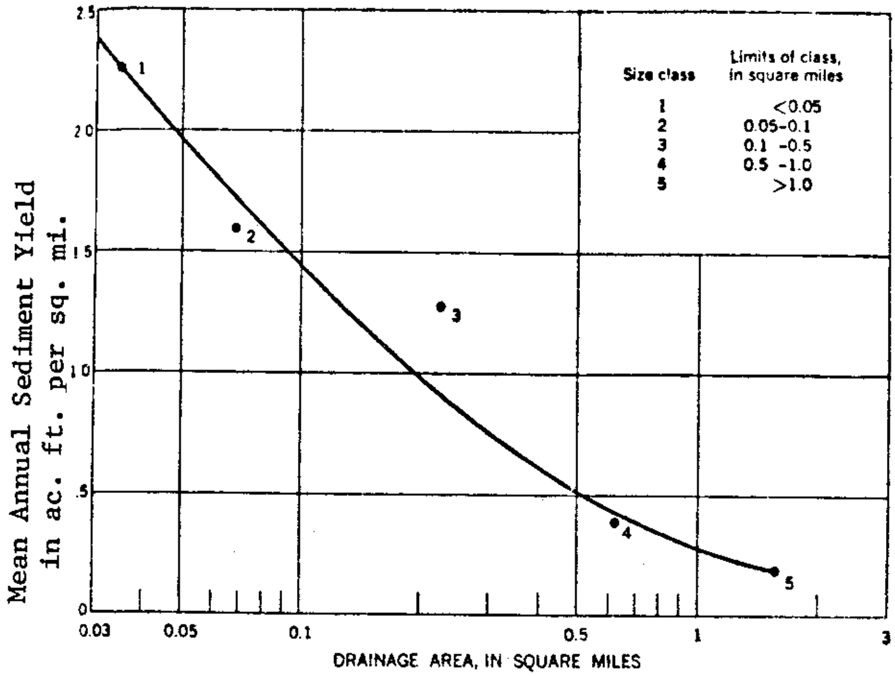

Figure 2.- Relation of mean annual sediment yield to drainage area for 99 small waterhseds in eastern Wyoming

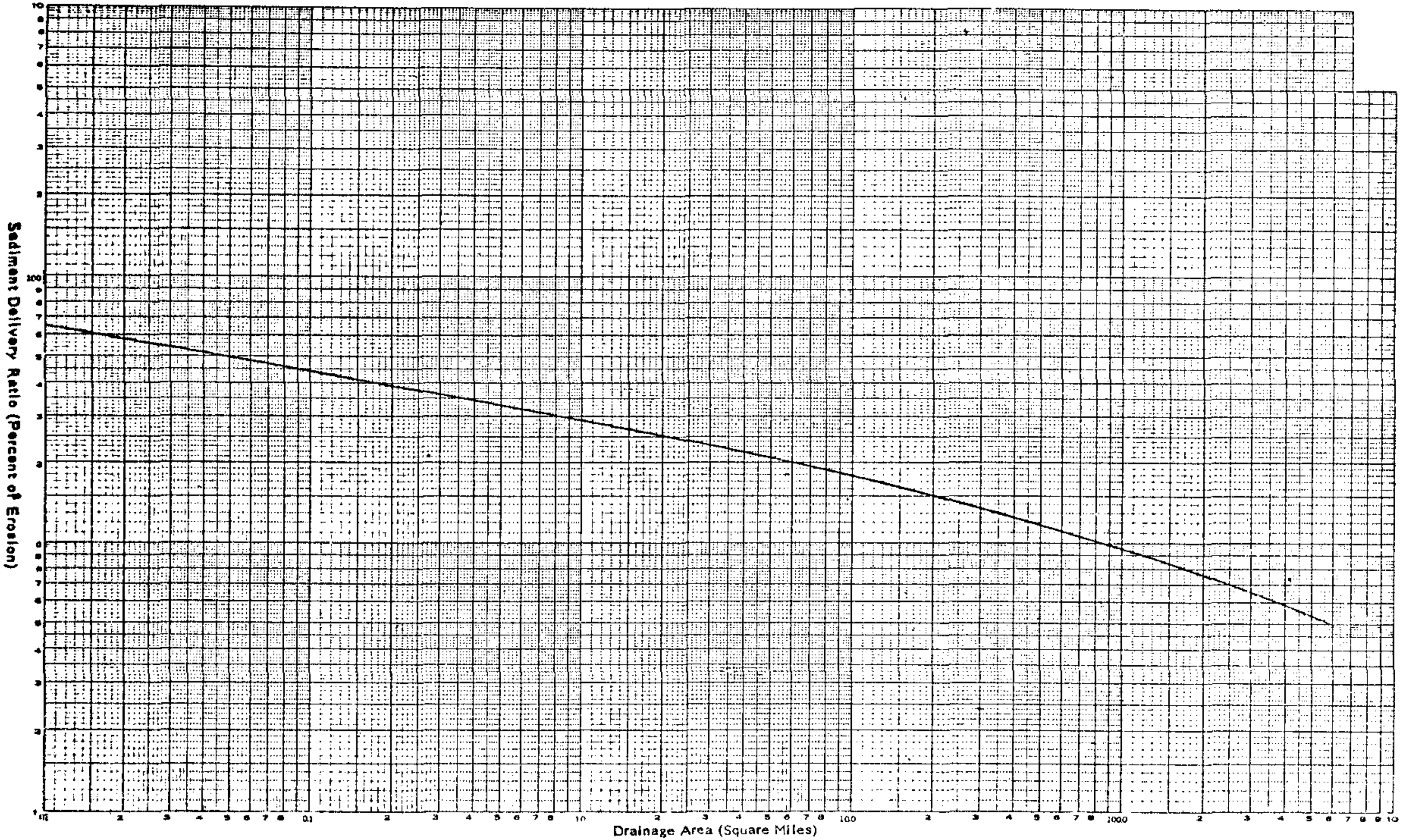

Figure 3.- Sediment delivery ratio vs. size of drainage area (Roehl, 1963)

The one parameter that integrates many of the watershed variables is drainage area. In a study in the Cheyenne River basin in eastern Wyoming, sediment yield was determined for 99 small watersheds (Hadley and Schumm, 1961). The data from this study indicate a progressive reduction in sediment yield per unit area with increasing area size: less than 0.05 sq mi, .05-0.1 sq mi, 0.1=0.5 sq mi, 0.5-1.0 sq mi, and greater than 1.0 sq mi. The relationship between sediment yield and drainage area is shown in figure 2. These data represent a sediment delivery-gross erosion ratio inasmuch as the points of measurement are reservoirs that trap virtually all of the sediment eroded from the contributing watersheds. The decrease in sediment yield per unit area can be attributed to the drainage basin characteristics previously discussed.

Many other investigators have developed similar curves for sediment delivery ratios related to drainage area. Roehl (1963) analyzed the data from several widely scattered areas and produced a general curve (see figure 3) that shows a similarity in sediment delivery ratios throughout the United States that varies as about the 0.2 power of the drainage area. As Renfro (1974) points out, however, the use of a sediment-delivery curve must be tempered with experienced judgment of the characteristics of the drainage basin such as the texture of soils, drainage density, relief, and opportunities for deposition within the basin being studied.

These studies emphasize the inherent problems involved in extrapolation of sediment yield data, not only in a downstream direction but from one physiographic province to another. There is a need for reasonable estimates of sediment delivery ratios in many areas in order to determine sediment yields from basins. Consideration should be given to this type of analysis when available data are limited.

SUMMARY AND RECOMMENDATIONS

The objectives and goals of the task force at the outset of this investigation were tempered by our experience in erosion and sedimentation studies, which cover a wide range of both experimental and watershed studies. However, the scope of this report had to be limited because many of the complex questions regarding the relation of erosion at a source area and sediment yield at a downstream point are still unanswered.

This report has met the objective of evaluating and summarizing some of the pertinent methods of estimating on-site erosion and downstream sediment yield based on data requirements, applicability to field projects, reliability of method and particular physical situations. Considerable time will be saved by field investigators desiring to survey the published literature on methods of estimating erosion and sediment yield inasmuch as this report contains a list of the most pertinent references.

The wide variety of physiographic and climatic variability encountered in the western United States make it difficult to estimate erosion and sediment yield. With such heterogeneous conditions, the confidence bands on individual sedimentation estimates are wide. A great amount of research is warranted in the region to improve the estimating procedures.

Based on the work of the Task Force, it is very difficult to specify preference for one of the six methods for estimating on-site erosion. Rather, the choice of methods undoubtedly falls to the experience of the person faced with making the prediction. The most desirable procedure undoubtedly is to use the method developed for conditions nearest to those requiring the estimate.

A similar situation exists concerning the methods of predicting sediment yield. Here, however, the Flaxman method, of the six methods surveyed, offers promise because it was developed from data encountered throughout the western area. It was also tested against some watershed data not included in the original development and observed to agree quite closely with some actual data. It, additionally, has the advantage of being straightforward to use, yet detailed enough to handle most anticipated variables observed to influence sediment yield.

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APPENDIX I

Evaluation summaries for on-site and sediment yield prediction methods

Methods for estimating erosion

Bryan, Rorke B., 1968, The development, use, and efficiency of indices of soil erodibility: Geoderma, v. 2, no. 1, p. 5-26.

Summary

In this method soil erodibility indices were developed by comparison of actual soil loss as determined by rainfall simulation to several other methods. Soil samples from 36 profiles were used from a variety of pedogenic environments. The rainfall simulation consisted of three 30-minute rainfall sequences, the first on air-dry soil, the second on soil at field capacity, and the third on saturated soil. The rainfall intensity was 125 mm per hour, the drop size ranged from 0.84 to 3.98 mm, and the fall height was 1.66 m. The laboratory plots were inclined at a slope of 20°.

Correlation coefficients were determined to define significant differences in patterns between differing measures of soil loss and other variables. Percentage-weight of water-stable aggregates less than 0.5 mm shows the closest approach to a universal index of erodibility. Tests show that none of tested indices have universal application and it is doubtful that such an index can be derived. Because of the prospect that it may be impossible to develop a universal procedure, the author suggests further study of an index of aggregate stability and distribution.

Methods for estimating erosion

Foster, G. R. and L. D. Meyer, 1972, A closed form soil erosion equation for upland areas: Sedimentation Symposium in Honor of H. A. Einstein, Chap. XII.

Summary

Erosion in upland areas is decribed by a mathematical relationship for the continuity-of-mass transport and an equation relating detachment of sediment by runoff and sediment load. This interaction relationship is given as

$$\frac{D_f}{D_c} + \frac{G_f}{T_c} = 1$$

where D_f = detachment rate by flow; D_c = detachment capacity; G_f = sediment load in the flow; and T_c = transport capacity of the flow. The detachment and transport capacities are assumed equal to the 3/2 power of the flow shear stress. Using the Chezy uniform flow equation, the closed-form erosion equation for a uniform slope with steady conditions is:

$$G_* = X_* - (1-\theta)\ (1 - e^{-\alpha X_*})\ /\alpha$$

where G_* = sediment load relative to the transport capacity at the slope end; X_* = distance from the slope top; θ= rainfall detachment parameter; and α = runoff detachment parameter. With the interaction equation, deposition prediction where the slope flattens and the flow leses its transport capacity is possible without using a gradually varied flow analysis.

A closed-form erosion equation was derived using basic hydraulic, sediment transport, and erosion processes principles. The equation characteristics were compared with field data of erosion.

Although the method has sound theoretical development, it needs further testing beyond the area for which it was developed. The paper presents schemes for quantifying each term of the continuity equation. For known soil, precipitation and topographic characteristics, the deposition (erosion) pattern along a slope can be predicted using this theoretical method.

<u>Methods for estimating erosion</u>

Meeuwig, Richard O., 1971, Soil stability on high elevation rangeland in the intermountain area: U.S. Dept. of Agriculture, Forest Service, Research Paper INT-94, May 1971, 10 p., 4 figures.

Summary

A method is developed for relating erosion from small plots to site factors of cover, slope, soil texture, and organic matter content. Measurements were taken of the amount of soil eroded from 460 small plots (20 in. x 30.5 in.) in seven study areas in Utah, Idaho, and Montana and at altitudes from about 5,000 feet to 10,000 feet.

The erosion was produced under the impact of a fixed amount of simulated rainfall. A rainfall simulator was used to apply 2.5 inches of water to these plots at a constant intensity of 5 inches per hour for 30 minutes.

After screening of the combined data from the seven study areas, a predictive equation was developed using soil, cover, slope, and organic matter content parameters in a computerized regression analysis. These were:

A--Proportion of soil surface covered by plants and litter
L--Air-dry weight of litter in pounds/milacre
G--Slope gradient of plot in percent
C--Proportion of the surface inch of soil composed of clay
D--Proportion of the surface inch of soil composed of sand
M--Proportion of the surface inch of soil composed of organic matter

The following equation resulted:

$$Y = -.6935 - 6.456A^3 + 17.483A^5 - 12.403A^6 - .0582A^3L + .0306G - .0217A^3G + 8.21C - 10.59C^2 8.45M + .651M/C - 1.38CD + 35.48M^2D$$

The equation explains 74 percent of the variance of the log of erosion. The relation between erosion and cover is strongly influenced by slope gradient. Regression analysis indicates that erosion is about the same on a 5 percent slope with 40 percent cover as it is on a 35 percent slope with 80 percent cover. Organic matter is the most important soil parameter affecting erodibility, but the direction and magnitude of its effects depend on soil texture. Organic matter decreases erosion of clay soils but tends to increase erosion of sandy soils. The author cautions that the empirical equation should not be applied indiscriminately because it is derived from erosion measurements caused by fixed amounts of simulated rainfall on small plots. This equation, however, provides some indications of the combined effects of cover, slope, and basic soil properties on soil stability.

Methods for estimating erosion

Meyer, L. D., and Wischmeier, W. H., 1966, Mathematical simulation of the process of soil erosion by water: Trans. Am. Soc. Agr. Eng., v. 12, no. 6, p. 754-758.

Summary

The framework for a mathematical model to describe the process of soil erosion by water was developed. The approach (a) soil detachment by rainfall, (b) transport by rainfall, (c) detachment by runoff, and (d) transport by runoff as separate but interrelated parts of the soil erosion process. Mathematical relationships to describe the dynamics of these subprocesses were introduced into the basic model, and the resulting masses of soil (erosion) and water (runoff) were routed along successive increments of slope.

The equations for the various components of the model are:

(1) D_r (soil detachment by rainfall = $S_{DR}AI^2$ where A = area, I = intensity (30 minutes), and S_{DR} = soil parameter

(2) D_f (detachment by runoff) = $S_{DF}A^{\cdot 1/2}(S_s^{2/3}Q_s^{2/3}+S_E^{2/3}Q_E^{2/3})$ where S is the slope, Q is the discharge rate and the subscripts S and E refer to start and end of a slope increment. S_{DF} is the soils susceptibility to detachment by runoff as a function of its properties.

(3) T_R (transport capacity of rainfall)=$S_{TR}SI$ where S_{TR} is the soil effect.

(4) T_F (transport capacity of runoff)=$S_{TF}S^{5/3}Q^{5/3}$ where S_{TF} is the soil term accounting for the effect of particle size and density.

The sediment load carried from each slope increment was the lesser of: (a) the sediment load from the previous increment plus the detachment on that increment or (b) the transportation capacity from that increment. Net erosion or sedimentation for an increment was the difference between the sediment load entering or leaving it.

Methods For Estimating Erosion

Musgrave, G. W., 1947, The Quantitative Evaluation of Factors in Water Erosion . . . A First Approximation. Journal of Soil and Water Conservation, 1947, vol. 2, p. 133-138.

Summary

An equation is developed relating measurements of erosion from plots to site factors including a soil factor, degree of slope, length of slope, vegetative cover, and precipitation intensity. The measurements were obtained from 20 soil erosion experiment stations located in various parts of the U.S. The plots had a down-slope length of 72.6 feet and were 6 feet wide.

The erosion resulted from natural rainfall over a period of time ranging from 5 to 15 years. Eroded material was trapped at the lower end of the plots for measurement of soil loss. Site characteristics, that is slope, cover, etc., were adjusted, by trial and error, to determine varying influences of observed and computed values.

Comparison was made to determine the appropriate variables and their coefficients. The variables are:

- E--Sheet erosion, tons per acre per year.
- F--Soil factor, basic erosion rate in tons per acre per year for each soil series or unit.
- R--Cover factor.
- S--Degree of slope - ft/100 ft.
- L--Length of slope - feet.
- P--Precipitation - maximum 30-minute, 2-year frequency rainfall in inches.

The following equation resulted:

$$E = FR\left(\frac{S}{10}\right)^{1.35}\left(\frac{L}{72.6}\right)^{.35}\left(\frac{P_{30}}{1.375}\right)^{1.75}$$

The equation has had wide application in the computation of average annual sheet erosion. In more recent years modifications in the equation have been made by substituting the "K" factor and the "R" factor in the Universal Soil Loss Equation as presented by Wischmeier and Smith.

Methods for estimating erosion

Wischmeier, W. H., and D. D. Smith, Predicting rainfall-erosion losses from cropland east of the Rocky Mountains: Agricultural Handbook No. 282, Agricultural Research Service, U.S. Department of Agriculture, Washington, D. C., 1965.

Soil Conservation Service, USDA Procedure for computing sheet and rill erosion on project areas: SCS Technical Release No. 51 (Geology), Washington, D. C., 1972.

Summary

This method is one of the most widely accepted and proven ways to estimate hillslope erosion. The method which was developed from plot records with many soil and vegetation combinations is presently being adapted to conditions encountered in western portions of the United States. The general form of the prediction equation is

$$A = RKLSCP$$

when A = the computed soil loss, R = the rainfall factor, K = a soil-erodibility factor, L = a slope-length factor, S = a slope-gradient factor, C = a cropping-management factor, and P = an erosion-control practice factor.

Tables, figures and nomographs are presented in the original paper and the cited subsequent references which enable assigning values to each term in the equation for most conditions encountered. Although the relationship has been used for predicting slope erosion from individual storms, it is generally intended for estimating the annual soil loss. Provisions are made in the handbook to vary the rainfall factor and the crop management factor throughout the year to account for varying precipitation patterns and crop growth stages.

Because of its wide use and testing, it should provide satisfactory erosion estimates for most design applications except for frozen ground conditions or for excessively steep slopes.

Prediction of Sediment Yields Without Prior Erosion Determinations

Anderson, H. W., 1954, Suspended sediment discharges as related to streamflow, topography, soil and land use: Trans. Amer. Geophysical Union vol. 35, No. 2, April 1, 1954, p. 268-281.

Summary

A method is developed of studying the responses of suspended sediment load discharge to watershed variables. These responses were used to estimate the contribution to sediment discharge of the individual parts of a watershed with different values of the variables. The area of study was the mountain and valley watersheds of western Oregon, from the California border to the Columbia River. The suspended sediment load records of from one to three years were available from 29 streams.

The study included the calculation of average annual suspended sediment discharge, relating this dependent variable by multiple regression analysis to watershed characteristics that would enable an estimation of the erosion potential. This included a prediction of how much actual erosion would differ from the erosion potential with deviations of land use from average.

The following watershed variables were among those used in six equations that were developed. Two of these equations were used to graphically demonstrate the comparison between observed and computed suspended sediment load discharge.

ss--Average annual suspended sediment load, tens of tons/sq.mi.yr.
SS--Average annual suspended sediment load, thousands of tons/yr.
SSf--Average annual suspended sediment load from forest lands, thousands of tons/yr.
A--Area of watershed, sq.mi.
FQp--Discharge peakedness
MAq--Mean annual runoff, cfs/sq.mi.
S--Slope of streams of 1 mile mesh, length ft/mi.
SC--Silt and clay, fraction <0.05 mm.
S/A--Surface aggregation ratio cm^2/gm pct.
BC--Portion of watershed in row crops and small grain, pct.
OC--Other cultivation, pct.
R--Roads - portion of watershed area in roads.
RC--Portion of watershed cutover in last 10 years, pct.
C--Area of watershed in bare ground and cultivation sq.mi.
Eb--Length of main channel eroding bank, ft.

The two multiple regression equations with logarithms being to the base 10 are:

$$\log ss = -3.721 + 0.116 \log A + 1.673 \log FQp + 1.244 \log MAq + 0.401 \log S + 0.0486\ SC + 0.482\ S/A + 0.0280\ BC - 0.0036\ OC + 0.942\ R + 0.0086\ RC$$

and

$$SS\text{-}SS^{f} = -1.639 + 0.240\ C + 0.00514\ EB$$

A comparison of observed and computed suspended sediment load discharge (Figures 13 and 14 in the paper) indicate that a satisfactory separation of the high from the low sediment producing watersheds can be made using the equations. In addition, the regression coefficients of the individual variables measure the importance of the various sources of suspended sediment discharge. A map is included which shows the erosion potential for land areas in western Oregon defined as the average annual sediment yield in tons per square mile under 1950 watershed conditions.

Prediction of sediment yields without prior erosion determinations

Branson, F. A. and Owen, J. R., 1970, Plant cover, runoff, and sediment yield relationships on Mancos Shale in Western Colorado: Water Resources Research, v. 16, no. 3, p. 783-790.

Summary

Relationships between geomorphic variables, watershed cover, and hydrologic measurements were investigated for 17 watersheds near Grand Junction, Colorado. Six years of vegetation measurements, four vegetation measurement methods, and 15 years of hydrologic records were used in the analyses.

Step-wise multiple regression analysis was used to develop the regression equation for sediment yield which is:

$$\hat{Y} = 40.87X_1+0.03X_2-1.27$$

where $\hat{Y}$ is the estimated average annual sediment yield in acre feet per square mile, X_1 is the relief ratio; and X_2 is the percent bare soil in the watershed. The multiple correlation coefficient is 0.86, which is significant at the 1 percent level of probability.

Geomorphic variables considered in the analysis included relief ratio, angle of stream channel junction, mean slope, drainage density, and watershed shape. Relief ratio had the highest simple correlation coefficient with sediment yield (0.78, p<.01). The other geomorphic variables were either correlated with relief ratio or did not improve the relief ratio-sediment yield relationship.

The percentage of bare soil was shown to be a good expression of watershed cover that relates to hydrologic measurements on arid lands. Although it was not highly correlated with sediment yield by itself, it significantly improved the sediment yield estimate regression equation.

Prediction of sediment yields without prior erosion determinations

Flaxman, E. M., 1972, Predicting sediment yield in Western United States: Journal Hydraulics Division, Proceedings American Society of Civil Engineers, v. 98, no. HY12, Dec. 1972, p. 2073-2085 (Revised March 1974)

Summary

A method is developed for relating sediment yield as measured in small ponds and reservoirs to watershed characteristics identified by five variables. Data from 27 watersheds in 10 western states were used in a multiple regression analysis. The watersheds vary in size from 12 acres to 54 square miles and the cover consists of either forest, brush, grass or desert pavement of rock fragments.

Evaluation of a number of watershed characteristics resulted in the statistical determination that factors expressing cover density by either vegetation or desert pavement, slope, an index of soil erodibility, and runoff intensity would explain most of the variance in sediment yields. These variables are:

- Y --Average annual sediment yield, tons per sq. mi.
- X_1--The ratio of average annual precipitation in inches to average annual temperature, Farenheit
- X_2--Watershed slope, percent
- X_3--Soil particles, percent >1.0 mm
- X_4--Soil aggregation or dispersion, percent <0.002 mm
- X_5--50 percent chance peak discharge csm

The following equation resulted:

$$\log (Y+100) = 524.37231 - 270.65625 \log (X_1+100) + 6.41730 \log (X_2+100) - 1.70177 \log (X_3+100) + 4.03317 \log (X_4+100) + 0.99248 \log (X_5+100)$$

The logs are to the base 10.

The equation explains about 91 percent of the variance in average annual sediment yield. The choice of the variables was based on a conceptual model which included expressions for the following characteristics: a vegetative cover factor which is expressed by the precipitation-temperature ratio. The numerical value of this ratio is adjusted if vegetative cover in the watershed is less than that to be expected by a natural response to climate or because an appreciable amount of runoff is from snowmelt, deemed less erosive than rainfall runoff. Mean weighted slope (X_2) is a strong variable indicating that erosion increases as slopes increase, assuming other factors are constant. Variable X_3 expresses the effect that desert pavement or rock fragments in the soil profile have as a cover factor. In the variable indicating the effect of aggregation or dispersion on soil erodibility (X_4) the percent less than 0.002 mm is subtracted from the constant 100 if the soil pH is acid, the percentage is added to 100 if the pH is alkaline. The 50 percent chance peak discharge in csm (X_5), the variable most highly correlated with sediment yield, is determined by the procedure in Section 4, Hydrology, Soil Conservation Service National Engineering Handbook.

Prediction of Sediment Yields Without Prior Erosion Determinations

Negev, Moshe, 1967, A Sediment Model on a Digital Computer: Dept. of Civil Engin., Stanford Univ. Tech. Report No. 76, March 1967, 109 p., 7 figures.

Summary

A method is presented for the simulation of suspended sediment load records from rainfall and total flow data, and from the simulated overland flow produced by the Stanford Watershed Model. Simulation of the suspended sediment load is achieved by modeling the sediment yield and transport processes on a digital computer. The model distinguishes between two main sources of sediment: the land surface when rainfall and overland flow play the major role in sediment yield, and the stream system where the total flow is the most significant parameter.

Suspended sediment yield and runoff measurements used in development of the model were those from the Napa and San Antonio Rivers in Napa and Monterey Counties, California. Data on rainfall in the form of hourly amounts are required as a part of the data input. The minimum conditions for the fulfillment of this requirement were stated to be the continuous hourly rainfall data for a single gage and continuous daily rainfall for a second gage.

The following watershed measurements were selected on the basis of theoretical and supporting experimental evidence. The functions used were obtained by trial and error.

A. Soil characteristics
   1. Hourly quantity of soil splash, tons
   2. Daily soil splash storage, tons.
   3. Hourly quantity soil splash pickup, tons.
   4. Hourly quantity from rills and gullies, tons.
   5. Fraction of impervious area in watershed.

B. Runoff
   1. Overland flow, mean hourly, inches.
   2. Total flow, mean daily, cfs.

C. Sediment
   1. Wash Load.
   2. Interload.
   3. Bed material load.
   4. Grain size.

An accurate reproduction of the recorded suspended sediment load in the two watersheds was obtained with the model using the same functions for both, but with differing coefficients. The author recommends that further testing of the model be done in regions of different climatic and soil conditions in order to verify its general applicability.

Prediction of sediment yields without prior erosion determinations

Renard, K. G., 1972, Dynamic structure of ephemeral streams. Ph. D. dissert., Dept. Civil Eng. and Eng. Mech., Univ. Arizona, Tucson, Arizona.

Renard, K. G., 1972, Sediment problems in the arid and semiarid southwest: Soil Conserv. Soc. Amer. Proc. 27th ann. meeting, Aug. 6-9, Portland, Oregon, p. 225-232.

Summary

A method is presented which predicts sediment yield for a watershed varying from several tens of acres to one over 60-square-miles, given that a runoff model is available to produce synthetic (or actual) data for each storm (peak flow and runoff volume). The annual totals are then obtained by summing the values for each storm in a year. The sediment portion of the model uses the Manning equation with the Laursen transport relationship.

The method which was developed in Southeastern Arizona, should be universally applicable when a runoff model is available or when hydrographs are available from actual measurements. For the work reported, a stochastic runoff generating model was used which relates the model parameters to the size of the watersheds involved.

To use the method, channel cross section and slope data are required, along with an estimate of Manning's roughness. Concentrations of sediment are related to the characteristics of the bed material, i.e., percentages of material in various sizes. The Laursen relationship, which is based on laboratory and field data, predicts suspended load, bed load, or total load.

The form of the prediction equation is:

$$Q_s = \sum_j B \int_T q_s \, dt = \sum_j B \int_T \frac{\bar{c} q_w}{265} \, dt$$

where Q_s = sediment yield
q_s = sediment discharge rate per unit width
q_w = water discharge rate per unit width
B = stream width
T = time for each flow event
j = flow events per season
$\bar{c}$ = sediment concentration
p = bed material fraction of size d

$$\bar{c} = \sum_i P_i \left(\frac{d}{y}\right)^{7/6} \left(\frac{\tau'_o}{\tau_o}\right) - 1 \qquad \frac{\sqrt{\tau_o/\rho}}{w}$$

d = sediment size
y = depth of flow
τ'_o = boundary shear stress associated with sediment diameter
τ_o = tractive force at the streambed
τ^o_c = critical tractive force for beginning of sediment movement
ρ = density of water
w = fall velocity of sediment

For wider applications, the method needs to be tested with data from other climatic and physiographic areas. The method is physically based and should have wide application.

Prediction of sediment yields without prior erosion determinations

Tatum, Fred E., 1963, A new method of estimating debris-storage requirements for debris basins: Fed. Inter-Agency Sedimentation Conf. Proc., 1963, U.S. Dept. Agr. Misc. Pub. no. 970, Agri. Research Service, p. 886-897.

Summary

The method computes the debris production for areas for which debris basins are to be built. The method, based on observed data, predicts results from floods that occurred when the ground was conditioned for runoff by prior rain and from areas that have been partially burned one to more than ten years prior to the flood. Observed debris amounts were adjusted to a common base and curves developed by trial and error to represent separate adjustments for the major factors affecting debris production. The general prediction equation for adjusting the data to a common base is

$$X_o = X_{10} A_n + X_v A_b$$

where X_o = the observed debris production, X_{10} = debris production 10 or more years after a burn, X_v = debris production for "v" year (between 1 and 10) after 100 percent burn, A_n = portion of drainage not burned, and A_b = portion of the drainage burned.

Thus, the debris potential for an area is taken as the product of the ultimate debris-potential index and the percentage values for each of four factors representative of the area. The factors are slope, drainage density, hypsometric-analysis index and 3-hour rainfall, each of which if not the ultimate for the area, reduce the potential index by a percentage representing the difference between the ultimate and actual. Curves are presented in the paper for obtaining the values of the four parameters plus the ultimate debris production index which is related to the size of the drainage area.

The method which is based on storms experienced in the Pacific Ocean slopes of Southern California may have applications elsewhere but the method has not been widely tested. In addition, its use in the steep mountain slopes along the coastal range may be quite different for storm prediction in other climatic provinces.

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