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Reprinted from
EOS
Vol. 56, No. 3, March 1975

Soil Erosion—Sediment Yield Research in Progress

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THE PACE OF RESEARCH to understand erosion processes and to determine soil erosion rates and sediment yields has quickened in recent years. Many soil and water conservation planners have recognized the need to more fully understand the complex forces affecting detachment and movement of soil from erosion source to point of deposition.

We learned long ago that deposited sediment limits the useful life of conservation structures and that we must optimize conservation designs because of a dwindling supply of good sites. More recently, with the advent of increased environmental concern, the necessity for the broadest consideration of all proposed developments and for predicting the environmental impact of optional soil and water conservation plans has been emphasized. The new awareness of the tremendous volume of urban and right-of-way construction erosion and its impact on society has intensified our concern. Furthermore, since sediment is a carrier of agricultural chemicals, the priority for a fuller understanding of soil erosion rates and watershed sediment yields has increased.

The great body of sedimentation research data that exists today is largely the product of directed investigations of particular phases of sedimentation for solving specific problems. Integrated consideration of the soil erosion—sediment yield subprocesses, made possible by the ability of computers to manipulate the mass of data accumulated and by newly gained insights into aspects of soil detachment and transport, has brought us to a turning point in sediment yield research. To a very large extent, even considering the basic stochastic nature of all sedimentation processes, design problems are solved more and more by application of scientific principles rather than by the empirical equations formerly used. Watershed sediment yield models, for example, account for the known physical forces of rainfall and runoff that affect soil detachment and movement. Although deficiencies in our knowledge of these basic forces exist and 'lumped' parameters that represent obscure relationships must still be used, we can use such models as prediction tools and learn from them.

In this report on research in progress in the United States we summarize the work under way by federal, state, and other groups under the three components of the sedimentation process (erosion, transport, and deposition) and then discuss the research of the integrated sedimentation process. Channel transport and deposition processes are mentioned only as they relate to sediment yield research.

Information for this report was obtained through personal correspondence with the sedimentation leaders in federal agencies, from papers given at the Sediment Yield

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This article is based on an invited paper presented at the Fifty-Fourth Annual Meeting of the AGU in April, 1973, and is a contribution of the Iowa-Missouri Area, North Central Region, Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Missouri Agricultural Experiment Station, University of Missouri, Columbia.

Workshop held November 28—30, 1972, at Oxford, Mississippi; from special abstracts of a research information system (CRIS) of the U.S. Department of Agriculture; and from other reports. Some of the research is unpublished. In this summary statement, we could not include great detail, but we have listed references for further study.

Soil Erosion

Soil erosion is the detachment and subsequent movement of soil particles in an entraining medium. Erosion research requires special insights into chemical, mineralogical, and physical properties of soil and an evaluation of eroding forces. Upland erosion is usually categorized into sheet, rill, and gully components; farther downstream, flood plain erosion usually includes valley scour and channel erosion. Mass wasting, including soil slippage and soil creep, is a special form of erosion that normally occurs on very steep or mountainous areas. Other aggravated erosion is caused by urban building activities, by strip and open-pit mining, and by highway and other right-of-way construction.

Factors Controlling Erosion

In general, erosion rates vary with climate, soil, topography, and land management. For example, *Langbein and Schumm* [1958] found that erosion rates and sediment yields in the United States are highest where the annual effective precipitation is between 10 and 14 inches. They reported that sediment yield dropped sharply as annual effective rainfall decreased from 10 inches because of lack of runoff to carry the sediment. Sediment yield also decreased, generally, with rainfall amounts of more than 14 inches per year because the increased rainfall produced a denser vegetative cover and thereby decreased erosion.

Sheet-rill erosion on upland areas. Much effort has been expended to measure the erosion-causing attributes of rainfall and resultant surface runoff. *Mutchler and Larson*[1971] recently quantified raindrop soil splash in terms of water drop diameter and ponded water depth. *Mutchler and Young* [1972] measured raindrop forces and showed raindrop splash to be the primary agent in soil detachment that causes soil transport from inter-rill (overland flow) areas to microchannels (rills). Detachment results from impact energy dissipation on a saturated soil surface not protected by sufficient plant canopy or water depth.

In 1969 a basic framework for describing the process of erosion by rainfall and runoff was proposed by *Meyer and Wischmeier* [1969]. The interrelationships of soil detachment and soil transport were approximated *[Meyer, 1971]* from published literature.

Soil detachment by rainfall was

$$D_R = C_1 A I^2$$

where A is the incremental area, I is rainfall intensity, and C_1 is a rainfall soil detachment coefficient.

Soil transport by rainfall was

$$T_R = C_2 S I$$

where S is slope steepness, I is rainfall intensity, and C_2 is a rainfall soil transport coefficient.

Soil detachment by runoff was

$$D_F = C_3 A q^{2/3} S^{2/3}$$

where A is the incremental area, S is slope steepness, q is runoff rate, and C_3 is a runoff soil detachment coefficient.

Soil transport by runoff was

$$T_F = C_4 q^{5/3} S^{5/3}$$

where q and S are as previously defined, and C_4 is a runoff soil transport coefficient.

Foster and Meyer [1972*a*] further developed this deterministic view of erosion simulation and assembled more inputs for a sediment yield model that has the potential for describing soil erosion-transport-deposition phenomena, at any time, for any specified location in a watershed.

Some of the current research on the factors controlling erosion is intended to refine and extend the usefulness of a soil loss equation *[Wischmeier and Smith*, 1965] (1) by determining the effect of vegetative cover and management variables for undisturbed areas, such as forest and rangeland *[Wischmeier*, 1972] and (2) by determining the erodibility of a large number of soils and subsoils on the basis of fundamental physical and chemical soil characteristics [*Wischmeier et al.*,1971; *Barnett et al.*, 1971; *Wischmeier and Mannering*, 1969].

Meeuwig [1970*a*] found that the erosion rate from simulated rainfall applied to a large number of tiny (0.0001 acre) plots on seven mountain rangeland sites in Utah, Idaho, and Montana depended primarily on the proportion of the soil surface protected from direct raindrop impact by plants, litter, and (in some cases) stone. The organic matter content of soil also was very important. Soil organic matter tended to stabilize fine-textured soil, but the organic matter—soil loss relationship for three of the study areas definitely implied adverse effects of organic matter on the stability of sandy soils. Meeuwig hypothesized that these adverse effects were due to hydrophobic organic coatings on sand particles, which not only rendered them water repellent but appeared to cause the particles to repel each other, making them easily detached and transported. In another paper, *Meeuwig* [1971] developed a single multiple-regression equation that explained 74 % of the variation in soil erosion rate on 460 study sites. The relation between erosion and protective cover was strongly influenced by slope gradient. Meeuwig tells us that the erosion was about the same on a 5% slope with 40% cover as it was on a 35% slope with 80% cover.

Grissinger [1972] showed that, although a complex relationship existed, erosion rates measured in the laboratory varied directly with soil water content and with change in soil water content. Water entering cohesive soils produces internal stresses and should be considered with other erosive forces. Erodibility, however, decreases with increased soil wetting time (wet aging) because cohesive forces have time to develop, and strains produced by water sorption are dissipated.

Burgy [1973] is studying the relationships between precipitation intensity, runoff rates, and erosion rates as they are influenced by range improvement. Included in his study is a determination of the effectiveness of vegetation in controlling erosion. He is also attempting to determine the critical conditions of soil water saturation and movement that affect the stability of slopes on managed watersheds.

Meeuwig [1970*b*] measured infiltration and soil erosion rates on the Davis County (Utah) Experimental Watershed under simulated rainfall conditions. The ratio of plant and litter cover to total area explained 76% of the variation in eroded soil. Other factors—litter weight, slope gradient, and soil organic matter—in combination with vegetative cover, were responsible for 83% of the variation in eroded soil.

Farmer and Van Haveren [1971] report a laboratory study of sheet erosion by raindrop splash and overland flow on three mountain soils. Multiple-regression models were developed for both splash (raindrop) erosion and sheet (overland flow) erosion and affecting variables. Variables that increased raindrop splash erosion were (1) high rainfall intensity, (2) steeper slopes, (3) large proportion of the soil particles between 60 and 2000 microns in diameter, and (4) high soil bulk density. Variables that increased erosion rates by overland flow were (1) high rainfall intensity, (2) steeper slopes, and (3) low proportion of the soil particles larger than 2 mm in diameter. The influences of rainfall intensity and slope steepness on soil erosion rate were at least a full order of magnitude greater than the effect of any soil variable.

A central development in erosion research has been the universal soil loss equation [*Wischmeier and Smith,* 1965], which was based on more than 10,000 plot-years of data from fractional-acre (typically, 0.01-acre) erosion plots at 42 experiment stations in 23 states. Although the data originally were collected to demonstrate and evaluate the tremendous erosion damages, present research seeks to (1) refine and extend the applicability of the equation on the basis of existing and new data, (2) evaluate the erosion effectiveness of alternative crop and management schemes, and (3) furnish insights into basic erosion-affecting mechanisms.

For example, none of the factors in the erosion equation utilizes a reference variable that has direct geographic orientation. Yet the rainfall parameter cannot be applied in toto when raindrops are formed at low altitudes in warm clouds—with resultant small drops and low intensities. This type of rainfall is common in the Palouse region of Washington and western Idaho, where small rains accompanying early spring thaws cause serious erosion on the long, steep slopes of the region. This problem is the subject of intense research (D. McCool, personal communication, 1973).

Erosion of upland channels. Heede [1971] reported soil piping as a contributing factor to gully growth. High exchangeable sodium percentage (greater than 12 milliequivalents per liter), low gypsum content, and fine-textured soils with montmorillonite clay appeared to be prerequisites to the formation of pipes. Layer permeability of piping soils was only 2 to 12% of that of soils without pipes.

Recent gully research has emphasized isolation and measurement of basic processes of gully erosion—to a large extent using new measurement techniques. Gully studies [*Piest et al.,* 1972*a*] in some corn belt watersheds show that two complementary processes must be present before significant erosion can occur. These are: (1) sufficient weathering or mass wasting (or both) of channel banks to furnish soil debris for transport; and (2) runoff, above some threshold level, to transport channel debris. Tractive forces of runoff caused only minor gully erosion in these watersheds. These forces may be more important in other areas.

Most ongoing laboratory studies concerned with gullying have focused on the stability of channel banks, especially as related to soil moisture and seepage changes [*Bradford et al.,* 1973; *Burgi,* 1969; *Muir,* 1968].

Channel and Flood Plain Erosion

J.D. Dewey (U.S. Department of the Interior, personal communication, 1973) is studying channel sedimentation and defining cross-section changes with time in a 60-mile reach downstream of the new Cochiti Reservoir on the Rio Grande in New Mexico. Preconstruction data on cross sections, size of channel bed material, and hydraulic variables will be available for a period of about 3 years before closure of the dam. Data will be collected for a number of years after the dam is closed to document channel adjustments due to the construction of the dam.

Greathouse et al. [1971] of Michigan State University are evaluating the effects on water quality and bank erosion of wintering and pasturing cattle along rivers and streams. They are measuring damage by surveying the banks at 6-month intervals.

Schumm [1973], studying channel erosion and deposition phenomena in Colorado, resurveyed channel cross sections and collected sediment samples along 4 ephemeral stream channels containing reaches of active, natural aggradation. These channel surveys were compared with similar surveys made in 1957. The comparison provided information on 14 years of natural erosion and aggradation, the sedimentary character of channels, and recent deposits. His data also provide information on seasonal changes of channel sediment storage and transportation in small drainage basins.

D.A. Parsons (personal communication, 1972) is completing an extensive study of small channels in southeastern Nebraska. Included in his evaluations are channel soil and hydraulic characteristics as they affect channel stability and sediment characteristics. Parsons is also evaluating the use of jacks and car bodies for bank erosion control on Tillatoba Creek in northern Mississippi.

Erosion by Mass Wasting

Erosion by mass wasting is often

underestimated because processes such as soil creep and earth flows are difficult to measure, and landslides occur infrequently. These processes have been measured in a few instances, however, and have produced significant sediment. For example, a large flood on the Eel River in California produced nearly 160 million tons of sediment (an average of almost 80 tons per acre (T/A) on the drainage basin) [U.S. Geological Survey, 1971], and most of this sediment reportedly was derived from landslides and earth flows.

Rice and Foggin [1971] found that a prevalent trend for improving land use—the conversion of brush areas to grassland—increased soil slip erosion rates on mountainous watersheds in the San Dimas Experimental Forest in southern California during the intense winter storms of 1969. Mass movement averaged 470 T/A for the area converted to grass and 166 T/A for the brush areas. Soil slippage occurred on 5.5% of the brush areas; the values for the grass and brush areas were about twice those measured in 1966 for a less intense storm period.

Barr and Swanston [1970] used strain gage pairs bonded to spring steel strips to measure creep in a steep, weathered glacial-till soil. The most significant short-term soil movement, exclusive of rapid slope failure, consisted of a moderate but measurable creep in the organic debris and upper weathered-till layer, which ranged from 0.15 to 0.46 m thick. The surface soil apparently moved as a flow mass with no well-defined shear zones. The soil tended to creep throughout the year, although the movement was greatest in the fall and spring when soil moisture is highest.

In another study, *Swanston* [1970] used soil mechanics techniques to evaluate and quantify the factors affecting debris avalanching in the shallow and permeable glacial till soils located on the steep slopes of southeast Alaska. Analyses included the determination of effective cohesion, effective angle of internal friction, unit weight, pore-water stresses, and a 'critical circle' of the sliding surface. Stability analyses based on the 'method of slices' allowed determination of shear strength-stress relationships and of factors of safety with reasonable accuracy. The upper limit of till (Karta soil series) slope stability is about 34°. High pore water pressure is the primary avalanche-triggering force, and rainfall exceeding 6 inches in 24 hours will provide the necessary degree of saturation.

Karta soil has an apparent cohesion that is not reflected by the physical properties of the soil. This cohesion probably results from the anchoring effect of tree roots growing through the slide-prone weathered till and into the underlying, compacted, unweathered till. A study of root deterioration showed that the contribution of tree roots to soil shear strength deteriorated within 3 to 5 years after tree felling. This was about the observed lag time for landslide acceleration following clear-cutting. Swanston also found that, by delineating slopes in excess of 34° on a contour map, areas of general slope instability could be located to show where special consideration was needed in planning timber harvesting and road construction.

Swanston [1971] studied the dominant and natural mass movement activities on watersheds of the western United States, including (1) debris avalanches, flows, and torrents; (2) slumps and earth flows; (3) deep-seated soil creep; and (4) dry creep and sliding. All but dry creep and sliding occurred when soil moisture was high and usually developed, or were accelerated, during periods of abnormally high rainfall. Also, all activities were accelerated by destruction of natural mechanical support on the slopes. Road building was considered the most damaging activity, with soil failure resulting largely from slope loading, back slope cutting, and inadequate slope drainage. Logging activities and forest fires adversely affected stability primarily through destruction of natural mechanical support for the soils, removal of surface cover, and obstruction of main drainage channels by debris.

Fredriksen [1970], in studies on 3 small western Oregon watersheds, found that, in 2 steep headwater drainages, landslides were the predominant source of increased sedimentation of streams following timber harvest. Patch-cut logging with forest roads increased sedimentation, compared with a control watershed, by more than 100 times over a 9-year period. Landslide erosion was greatest where roads crossed high-gradient stream channels. In an adjacent, clear-cut watershed with no roads, sedimentation was 3 times that of the control.

Paeth et al. [1971] studied 4 soils derived from tuffaceous rock in the western Cascades of Oregon to determine relationships of various properties to slope stability. Soils prone to slope failure were characterized by high amounts of smectite clay, an absence of kaolin, and moderate amounts of free iron oxide. Stability of these soils did not appear to correlate with clay content, the amount of amorphous clay, or proportions of exchangeable cations.

Erosion Aggravated by Construction

Burns [1971], in South Fork Caspar Creek watershed, California, found that the immediate effects of road building and bridge construction on turbidity, suspended sediment, bed load movement, and fish habitat did not extend far downstream nor persist for more than a year.

Dyrness [1970] found that amounts of soil lost from an unprotected, newly constructed road back slope were 2 to 4 times greater than the loss from a comparable mulched slope in the fifth year after construction. Of 6 roadside treatments studied, only the 2 without a straw mulch covering produced consistently high erosion rates during the first critical rainy period.

In another study of the effect of construction of secondary logging roads on steep slopes in the Idaho batholith area, *Megahan* [1972] reported that, for a 6-year study period, sediment yields (expressed per unit of area subjected to tree felling and log skidding) averaged about 1.6 times more (0.056 T/A/yr) than sediment yields from nearby undisturbed watersheds (0.035

T/A/yr). Sediment produced by surface erosion from roads (expressed per unit of area disturbed by road construction) averaged 220 times more than yields produced from nearby undisturbed lands for the same study period; mass erosion from roads (expressed in similar units) averaged 550 times greater (19.1 T/A/yr). Sediment production (per unit area of the entire watershed above the sediment retention dams) was more than 150 times that from the undisturbed area. Further analysis indicated that construction effects can decline very rapidly with time. *Megahan* [1972] urges that (1) erosion control measures be initiated as soon as possible after road construction, and (2) measures be included that exert some immediate control over erosion.

Megahan and Kidd [1972] found that about 32% of the surface erosion on road fills in steep terrain of the central Idaho batholith was eliminated simply by planting Ponderosa pine on a 4- by 4-foot spacing. Deep-rooted species such as Ponderosa pine are particularly effective because they help reduce mass erosion hazards as well. Adding a straw mulch to the Ponderosa pine treatment eliminated about 95% of the total surface erosion on road fills.

H.P. Guy (U.S. Department of Interior, personal communcation, 1973) is studying erosion rate and sediment yield variations due to construction of the U.S. Geological Survey headquarters building at Reston, Virginia. Data were collected before, during, and after construction to evaluate erosion control methods and the effect of construction on downstream channels. Sediment yields will be correlated with soil types, changes in hill slopes precipitation, and other pertinent variables relating generally to changes in land use.

Becker and Mulhern [1972] tell about two studies pertaining to erosion and sediment yield from urbanizing areas. The first study, conducted by the Purdue Research Foundation of Lafayette, Indiana, is to extend an erodibility factor previously developed for surface soils for use on unevaluated subsoils encountered at construction sites. This will be accomplished by (1) using simulated rainfall to test the soil erosion equation [*Wischmeier and Smith,* 1965] on the heavier-textured subsoils; (2) relating various chemical, mineralogical, and physical properties of selected surface and subsurface soils to the erodibility factor K previously determined by field experimentation; and (3) arriving at an equation by using data obtained in (1) and (2) that can be used to more accurately predict soil losses at construction sites. The second study is a sediment yield monitoring program on a demonstration project being conducted in the Village of Long Reach, Columbia, Maryland. This project consists of the installation and evaluation of erosion control practices in an urbanizing area.

Meyer et al. [1971] reported on measurements of soil erosion and runoff from several conditions typical of construction sites after they have been reshaped for residential and commercial developments or highway construction. The effectiveness of various revegetation practices for reestablishing vegetative cover was subsequently studied on the same areas.

A series of simulated rainstorms, totaling 5 inches, was applied at an intensity of 2.5 inches per hour on several 35-foot subsoil plots with 12% slopes. The only treatment that effectively controlled erosion was straw mulch, which reduced soil loss to less than 10 T/A. In contrast, the loose-fill treatment and the treatment with 4 inches of applied topsoil each lost 31 T/A. The compact-fill treatment lost 48 T/A, and the scarified and scalped-only treatments each lost 54 T/A. Approximately 80% of the rainfall became runoff for all conditions except the loose-fill treatment, which lost about 70%.

Of the original treatments on which revegetation was studied, applied topsoil was by far the most successful treatment. Mulched subplots were greatly superior to unmulched. Reworked, scalped areas had better stands than did areas where no tillage was performed after the erosion tests. This research has strongly indicated that a layer of good soil over a denuded area plus surface mulch is the best combination of those treatments tested for minimizing soil erosion and enhancing rapid revegetation on reshaped land.

Transport and Deposition

The amount of suspended sediment transported by rivers to the seas each year is tremendous. *Holeman* [1968], extrapolating available data by continents, estimated a world total sediment yield to the oceans of 20.2 billion tons per year. He also estimated the average annual suspended sediment discharge of the rivers of North America at 245 T/mi^2 of drainage area. *Curtis et al.* [1973], in a more recent report, estimated the average annual fluvial-sediment discharge to oceans and estuaries from the conterminous United States for the 20-year period 1950—1969 at 491 million tons. Bed load is estimated to be an additional 10% of the suspended sediment transported. They tabulated data from 27 drainage areas, using 60 sampling locations as bases for this estimate.

Transport

Pemberton [1972] is continuing his research and development of a reliable sediment transport equation for predicting sediment movement. He is studying the total bed material discharge, consisting of sand and coarser material, in three river channels where total load sampling stations provide a check on the computations. The bed load function developed by *Einstein* [1950] provided a basic procedure that requires only two limited adjustments to reliably predict total transport for all sand fractions larger than 0.062 mm. In channel design problems for sand bed channels, the transport of all sediments should be considered. Estimates of river degradation below a dam also require an analysis of the transport by size fraction to assess the armoring effect in the degradation process.

Beer and Johnson [1973] are determining sediment sources that contribute to the pollution of streams and rivers and the pattern of sediment movement in fields to evaluate theoretical mechanics of erosion equations. The field procedure involves mixing lanthanum radioisotopes in soil to produce a 'seeding' batch. Another aspect of the study is the change in total sediment load per unit area as watershed size increases. *Taylor* [1970] evaluated the universal soil loss equation for predicting watershed sediment yield.

Willis et al. [1969] described the methods used to estimate the transport of both fine and coarse sediment on Coles Creek and Buffalo River near Natchez, Mississippi. Coarse sediment transport rates were estimated by using observed channel hydraulic and sediment factors, the Einstein bed load function, and a Froude model analysis of some flume tests.

Direct and accurate measurement of the total sediment transport rate has been studied by *Bowie et al.* [1972] who used a specially constructed measuring station on a small alluvial channel in the Pigeon Roost watershed in Marshall County, Mississippi. The concentration difference of sands at the normal and total load sections increased with increasing particle size. Several procedures were tested for calculating the transport rates of sand fractions.

Coleman et al. [1972] then attempted to predict the sediment transport capacity, using similitude principles, for Bowie's channel section. This transport calculation method generated, for a given channel section and a given bed material median diameter, a series of sediment transport curves for each water temperature.

Ruff et al. [1972] showed that aerial color infrared photography is a practical, qualitative tool for locating inflow of sediment-laden waters to a river system from tributaries. These studies were conducted on the Clarks Fork Yellowstone River, Rock Creek, and Red Lodge Creek in south-central Montana and northwestern Wyoming. Color infrared photography detects small changes in low concentrations of suspended particles in water by a color difference. In this study the suspended solids concentration and the turbidity level appeared to vary linearly within the normal scatter associated with field sampling procedures.

Mahmood [1974] has stated the equilibrium sediment transport criteria needed to successfully route water through a branching irrigation canal system. *Simons et al.* [1973] are working to improve erosion and sedimentation theories involving sediment transport and degradation and aggradation resulting from construction of dams and diversion works. They also hope to develop better measurement of turbulence in open channels as it relates to sediment transport by using a hot film device. These researchers are also endeavoring to show the necessity of developing river basins in an integrated and coordinated manner. Special emphasis is being given to the design and stabilization of canals and rivers and the river response to development. Design methods to stabilize channels considering concepts of channel geometry, hydraulics, the properties of bed and bank material, turbulence, seepage, wave forms, and other related factors have been developed. Similarly, techniques were devised to stabilize channels at culvert outfalls and at various types of spill-through structures, such as bridge abutments and spur dikes.

Deposition

Sediment deposition may occur at nearly every point in the downslope and down-channel migration of eroded soil particles. Deposition affects watershed sediment delivery rates when soil is deposited (1) as colluvium at the base of upland slopes, (2) as alluvium in river valleys and channels, (3) as soil debris filling reservoirs, and (4) as deltaic deposits in rivers and estuaries.

Onstad et al, [1967], *Onstad* [1973], and *Meyer et al.* [1970] have been especially interested in the basic mechanisms of upslope deposition that would accurately portray the kinematics of hillside sediment movement for use in constructing a workable mathematical model. *Piest et al.* [1972*b*] and *Williams* [1972] are investigating aspects of upland deposition to make soil loss equations more adaptable for field and watershed use. *Happ* [1972] also emphasized the importance of quantifying deposition by citing recent studies in Mississippi and Wisconsin, which show that valley sedimentation may account for more than 75% of the soil loss from small agricultural watersheds. Current valley sedimentation rates at these locations are lower than the rates during the one or two decades before the 1939 surveys, apparently as a result of conservation programs and land use changes.

Sediment Yield

Evaluations

This section includes research in progress, or just completed, that analyzes variations in sediment yield, determines the effectiveness of various conservation practices, develops equations for estimating sediment yields, and summarizes sediment yield modeling. Although sediment yield study is being increasingly directed toward specific objectives, there is still some need for research programs to define regional trends. The design of regional sediment networks to accomplish this goal is typified by *Johnson* [1971]. He also analyzed errors in sediment yield prediction due to sampling frequency.

Wilson [1972] advocated the use of a sedihydrogram, a double logarithmic plot of mean monthly sediment yield versus mean monthly water yield, as a tool in sedimentation studies. A line connecting consecutive months indicates the seasonal rhythm of erosion and runoff in a drainage basin. Qualitative analyses of sedihydrograms for U.S. rivers have shown that there are two basic seasonal patterns of sediment yield in this country. One occurs in areas with a mediterranean climate, the other in areas with a continental climate.

To predict sediment yield variations, both in space and in time, one must consider climate type and seasonality as well as a variety of nonclimatic factors. Each factor affecting sediment yield must be analyzed in terms of its specific effect.

Lusby et al. [1971] compared changes in vegetation, runoff, and sediment on grazed and ungrazed watersheds in a semiarid region of the Badger wash basin in western Colorado over a period of 12 years. Sediment yields from the grazed watersheds averaged 151% of those from ungrazed watersheds. These differences were attributed to (1) the effects of trampling by livestock, and (2) an increase in bare soil and rock, with commensurate decreases in litter, moss, and groundcover on grazed watersheds.

The Tennessee Valley Authority (C.D. Eklund, personal communication, 1972) is monitoring suspended or total sediment loads (or both) on several watershed projects to investigate the effects of improved land management practices, such as improved farm practices, reforestation, and simple gully control structures. For example, complete reforestation of the Pine Tree Branch watershed in western Tennessee, reduced sediment yield from 24 T/A/yr to less than 1 T/A/yr. Current plans for this watershed include investigation of the effect of clear-cutting the watershed in four steps over a 4-year period. The application of streamflow models developed on the Upper Bear Creek Experimental Watershed Project during 1962 to 1972 [*Tennessee Valley Authority,* 1973] to simulate the transport of water quality constituents, including suspended sediment, has been demonstrated, and further applications are being developed.

Renfro [1972] cited reductions in sediment yield that can be realized from the application of various vegetative and mechanical conservation measures for the control of sheet, gully, roadway, and stream channel erosion. Three or four surveys of selected floodwater-retarding structures over a 15- to 20-year period showed that sediment yields have been reduced 25 to 60% by land treatment and land use adjustments. In several instances, when combined land treatment and structural measures were applied, sediment yields were reduced 60 to 75%.

Renfro also reported on the special study by *Allen and Welch* [1971] of sediment movement in a central, 1130-mi^2 segment of the Washita River basin in Oklahoma. He compared several years of suspended sediment data obtained on selected watersheds in this reach before the installation of floodwater-retarding structures with data obtained after their installation; reductions in sediment yield ranged from 48 to 61%.

Spraberry and Bowie [1969] reported on sediment yields from the experimental watersheds of Pigeon Roost Creek basin in northern Mississippi. They presented a relationship of the 9-year average measured sediment yield at each of 13 stream-gaging stations with the computed total soil loss for these watersheds. Computations were based on (1) total land area, (2) cultivated land area of 2% and greater slope, and (3) bare gully areas. The computed gross erosion from the two major sediment source areas, cultivated land with 2% or greater slope and bare gullies only, correlated better with the total measured sediment yield than the erosion computed from the entire contributing area. The procedure of using only the two major source areas simplified and greatly reduced the field work involved in the computation of gross watershed erosion.

In connection with nutrient enrichment studies, *Schmidt and Logan* [1973] are sampling and measuring runoff from microwatersheds on three major soil types in the Maumee River basin of northwestern Ohio. Sites for these small watersheds on Paulding clay will be further instrumented to measure nutrient and sediment losses in surface runoff under several cropping systems. Schmidt and Logan will endeavor to determine the source of downstream sediments through chemical and mineralogical analyses of samples.

Flaxman [1972] studied the sediment accumulation in 28 reservoirs with watersheds ranging from a few acres to more than 50 mi^2 in the western states. His objective was to describe the influence of changes in land use and treatment on sediment yield with a minimum of variables. This is difficult to do in the western United States because an infinite variety of climate and vegetation exists owing to orographic influences. A multiple-regression analysis showed that four watershed characteristics can describe the variation in sediment yield:

1. The response of vegetation to climate. A ratio of the average annual precipitation (in inches) divided by the average annual temperature (in degrees Fahrenheit).
2. Watershed slope, area-weighted, expressed as a percentage.
3. The percentage of soil particles larger than 1 mm in diameter in the surface 2 inches of the soil profile. This variable was intended to reflect the resistance of coarse particles to entrainment and transport and the influence of armoring by coarse particles on erosion—and therefore on sediment yield.
4. The aggregation or dispersion characteristics of clay soil particles 2 microns or finer. Flaxman's reasoning was based on his observation that particles that tend to aggregate resist erosion, whereas particles that disperse are easily eroded. He used soil pH as an index for classifying soils that tend to aggregate or disperse.

These four watershed characteristics were correlated with volume of sediment, expressed in acre-feet per year; they explained 92% of the variation in sediment yield. Flaxman excluded the effect of substantial gully and stream channel erosion from this study. His equation shows a considerable scatter for computed versus measured sediment yield at computed rates of less than 1 T/A/yr; the sediment yields ranged to 8 T/A/yr. Flaxman also evaluated topography, other soil characteristics, and climatic data, but these did not add significantly to the explanation of sediment yield variations.

Anderson [1972] said that past land use, forest fires, road building, poor 'logging' and conversion of steep woodlands to grass have increased sediment discharge from north coast watersheds of California by factors ranging from 1.24 to more than 4. Soil creep contributed 1.17 T/A/yr, which is 15% of the total sediment discharge; channel bank erosion contributed 55% in some areas. Turbidity of streamflow after major floods doubled, and the silt-clay content of soils increased from 19 to 29%. Stream turbidity was also heavily influenced by a change in a surface erodibility index and the gravel content of the soils.

The sediment yields from a variety of reduced tillage systems on agricultural watersheds are consistently much lower than sediment yields from conventional tillage (a sequence of plowing, disking, harrowing, planting, and mechanical cultivation). *Harrold*'s [1972] studies on 2-acre corn-cropped watersheds with minimum tillage (plow and plant only) showed that sediment yield for a 3-year period was 0.4 T/A/yr compared with 2.7 T/A/yr for conventionally tilled cornland. Sediment yields for an 8-year period from 2-acre nontilled watersheds (using chemical weed control) averaged 0.01 T/A/yr compared with 1 T/A/yr for a conventionally tilled watershed.

Whitaker et al. [1972] examined the soil losses to be expected with different land treatments. A 17-year comparison between conventional tillage (plow, disk, and plant) and no-plow tillage (cultivate and plant) showed no-plow soil losses averaged less than half the losses from conventional tillage; for the wet years of 1969 and 1970, the no-plow soil losses were only one-third those of conventional tillage. The effect of corn residue management was also measured in several ways: corn plots harvested for silage showed greater soil losses than those harvested for grain only; continuous corn, treated only with starter fertilizer each year, showed greater soil losses than similar treatments with full fertility during a 12-year period. On plowed seedbeds, chemical weed control caused significantly higher soil losses than conventionally cultivated cornland; on no-till seedbeds (chemical weed control) with good residue management, soil losses were negligible.

Spomer et al. [1973] measured sediment yield from a level-terraced cornfield and a bromegrass pasture and showed that losses from these field-size watersheds (75 to 150 acres) for an 8-year period averaged 1 T/A annually, compared with a 20-T/A loss for corn planted on the contour. They are now evaluating the effect of a new minimum tillage system and a less expensive structural control for sediment yields from these same field-size watersheds.

Allen and Welch [1971] reported that flood-retarding structures on four tributaries to the Washita River, controlling 40 to 63% of the drainage area, reduced sediment yield 48 to 61%.

Rhoades et al. [1972] summarized sediment yields from 4 small pasture watersheds (18 to 27 acres) in Oklahoma. Average annual sediment yield for the 5-year record varied from 0.05 T/A to 6.0 T/A among the watersheds. One of the watersheds, formerly cultivated but returned to grass, lost 2 T/A of soil; 51% of the sediment leaving the most erodible watershed was derived from a gully occupying 1% of the area. Thus any past disturbance to grassland, such as overgrazing or prior cultivation, which even temporarily increases runoff causes higher sediment yields when the land is returned to grass. But erosion can still be controlled within acceptable limits. Sediment yields from 7 nearly level cropland watersheds in Oklahoma (13 to 44 acres in size) ranged from 0.26 T/A/yr to 1.65 T/A/yr for the 5-year period.

Williams and Berndt [1972] extended the universal soil loss equation for use on watersheds by modifying the soil, topographic, and management factors. Sediment delivery ratios (the sediment yield to any downstream point divided by the total source erosion above that point) were computed by using measured sediment yields and this modified universal soil loss equation; these annual sediment delivery ratios, from 8 years of data on 5 watersheds, were closely related to slope of the main channel drainageway. With this relation known, it was possible to use the modified universal soil loss equation for estimating Texas Blackland sediment yields.

In a further modification of the universal soil loss equation, intended to make it applicable for predicting storm sediment yields, *Williams* [1972] substituted the product of storm runoff amount and rate for the rainfall energy factor. This procedure overcame two important obstacles in the application of the universal soil loss equation to watersheds. First, there is no single-valued relation between sediment yield and a rainfall energy factor, and for identical rainfall amounts and intensities, it is possible to obtain widely varying runoff rates and sediment yields if antecedent moisture conditions are not identical. Second, both *Williams and Berndt* [1972] and *Piest and Spomer* [1968] found that the universal soil loss equation often overpredicted sediment production for storms having low rainfall energy factors and underpredicted sediment production for storms with high rainfall energy factors. Williams used 18 watersheds in Texas and Nebraska to evaluate the modified equation of the form

$$G = \alpha(Qq_p)\beta \; KSLCP$$

where G is sediment yield for storm or period, Q is runoff volume, q_p is peak runoff rate, alpha and beta are constants, and $KSLCP$ are variables from the universal soil loss equation, modified for watershed use.

This modified equation explained 92% of the variation in sediment yield. It eliminated the need for a delivery ratio and was judged more accurate than the original universal soil loss equation for watershed use.

Piest et al. [1972*b*] were similarly concerned with the application of the universal soil loss equation for determining watershed sediment yields. The apparent lack of correlation between sediment delivery and watershed size for loessial soil areas, as previously determined by *Beer et al.* [1966], was especially disconcerting because such correlation was a requisite to the standard sediment delivery procedure for predicting sediment yields. On the basis of 7-year sediment records from research watersheds near Treynor, Iowa, it was possible to show that much of the variation in sediment delivery ratios was related to seasonal occurrence of storms, antecedent soil moisture levels, and rainfall-runoff variables. Moreover, it was shown that, even though the universal soil loss equation was improved to perfectly forecast upland sheet-rill erosion rates, it would have to be combined with some routing function that would express the sediment conveyance-retardance characteristics of a watershed. For the Treynor watersheds, such a routing function was roughly proportional to the fourth power of the *C* (crop) factor of the universal soil loss equation.

Models

The recent interest in sediment as a pollutant, and as a carrier of pollutants, has emphasized the need for procedures that will enable fast and relatively accurate sediment yield estimates from a number of watersheds where little or no background hydrologic or sediment data are available. Several types of models have been proposed to meet this need, ranging from an entirely stochastic approach by *Woolhiser and Todorovic* [1972] and *Woolhiser and Blinco* [1972]—to the combining of a model relating runoff and sediment yield to a stochastic runoff model [*Renard and Lane,* 1972]—to a simulated mathematical watershed sediment model that characterizes the time-space progression of sediment from its erosion source [*Onstad,* 1973].

Negev [1967], in his early mathematical watershed sediment model, considered such basic erosion-transport processes as rainfall soil splash, entrainment by overland flow, and rilling and gullying, along with separate channel transport of fine and coarse sediment. He pointed out that many of his terms were related to climatic, soil, and topographic conditions, which must be considered for a workable model. *David* [1972] introduced additional concepts into a sediment yield model and tested it on data from watersheds near Traer, Iowa.

Present emphasis is directed to development of a comprehensive model that considers the initial soil detachment and transport mechanisms in more detail. *Meyer and Wischmeier* [1969] summarized plot erosion data, rainfall simulator erosion rates, and laboratory flume results, along with theoretical considerations to postulate soil detachment and transportation rates by rainfall and runoff. *Rowlison and Martin* [1971] stated that many variables—land slope, soil type, soil unit weight, rainfall intensity and drop size, and depth of water on the soil surface—could limit the rate of soil erosion by creating either a transport limiting or a particle detachment limiting condition. They represented the potential soil detachment and transportation rates as response surfaces dependent upon soil slope and water depth. In the composite, these surfaces can be combined to represent a single surface of maximum erosion rate.

Several researchers [*Foster and Meyer,* 1972*a, b, c; Meyer et al.,* 1972] have similarly defined limiting conditions of transport and detachment and have suggested expressions for calculating soil detachment and transport rates and capacities along the hillslope. Members of a task committee (C. A. Onstad, personal communication, 1974) are now using these concepts in the continuing development of a sediment yield model. Sediment yields are based on a hydrologic model that routes sediment-entrained runoff through watershed subzones. Other bases for different versions of the model include a modified universal soil loss equation and a regionalized runoff-sediment relation.

Concluding Remarks

We were impressed with the amount and scope of research in progress on erosion and sediment yield processes. We found (1) considerable work and excellent progress in research to isolate and quantify basic variables affecting erosion, including methods of determining soil erodibility; (2) much-needed effort to identify problem areas of mass wasting and to quantify sediment yield from these sources; (3) good research on erosion due to construction, including a quantification of the sources of this type of erosion (as well as regulations designed to control such erosion); and (4) some excellent work on developing models for predicting sediment yield. In our literature studies, we also noted several advances in measurement technology. Included are several new devices for measuring bedload, such as the sampler being developed by L.B. Leopold in Wyoming (U.S. Department of Interior, personal communication, 1973) and W.W. Emmett's work (J. K. Culbertson, personal communication, 1973) with the *Helley and Smith* [1971] sampler; several excellent automatic pumping samplers, such as the Interagency Sedimentation Project's PS-69 sampler; and other equipment to measure sediment yield more accurately. All of these developments are very encouraging.

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