Soil Erosion—Sediment Yield Research in Progress

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THE FACE 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...
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

\[ D_P = C_3 A q^{1/3} S^{1/3} \]

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

\[ T_P = C_4 q^{1/3} S^{5/3} \]

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

Foster and Meyer [1972] 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, 1968].

Meeuwig [1970] 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 was also 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 pro-
duced by water sorption are dissi-
pated.

Burgi [1973] is studying the rela-
tionships between precipitation in-
tensity, 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 con-
trolling erosion. He is also attempt-
ning to determine the critical condi-
tions of soil water saturation and
movement that affect the stability
of slopes on managed watersheds.

Meeuwis [1970] measured in-
filtration and soil erosion rates on
the Davis County (Utah) Experi-
mental 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 respon-
sible for 83% of the variation in
eroded soil.

Farmer and Van Haveren [1971]
report a laboratory study of sheet
erosion by raindrop splash and over-
land 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 ero-
sion 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 tre-
mendous erosion damages, present
research seeks to (1) refine and ex-
tend the applicability of the equa-
tion on the basis of existing and new
data, (2) evaluate the erosion effec-
tiveness of alternative crop and
management schemes, and (3) fur-
nish 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 ap-
plied 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 accom-
panying 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 communica-

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

Recent gully research has
emphasized isolation and measure-
ment of basic processes of gully ero-
sion—to a large extent using new
measurement techniques. Gully
studies [Piest et al., 1972a] 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)
rainfall, above some threshold level,
to transport channel debris. Trac-
tive 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 communica-
tion, 1973) is studying channel sedi-
mentation and defining cross-sen-
tion 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 chan-
nel bed material, and hydraulic
variables will be available for a
period of about 3 years before
closure of the dam. Data will be col-
clected for a number of years after
the dam is closed to document chan-
nel adjustments due to the construc-
tion of the dam.

Greathouse et al. [1971] of
Michigan State University are eval-
uating the effects on water quality
and bank erosion of winter-
ing 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 sedi-
ment samples along 4 ephemeral
stream channels containing reaches
of active, natural aggradation.
These channel surveys were com-
pared with similar surveys made in
1957. The comparison provided in-
formation on 14 years of natural
erosion and aggradation, the sedi-
mentary character of channels, and
recent deposits. His data also pro-
vide information on seasonal
changes of channel sediment
storage and transportation in small
drainage basins.

D.A. Parsons (personal com-
munication, 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 sedi-
ment 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 Foggia [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 168 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. 

Burr 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 0.16 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 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, unwelthered 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 harvest 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 on the slopes. Removal of surf ace 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.

Dyreness [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).
T/A/yr). Sediment produced by sur-
face 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 re-
tention dams) was more than 150
times that from the undisturbed
area. Further analysis indicated
that construction effects can
decline very rapidly with time. Megenah [1972] urges that (1) ero-
sion control measures be initiated
as soon as possible after road con-
struction, and (2) measures be in-
cluded that exert some immediate
control over erosion. Megenah and Kidd [1972] found
that about 32% of the surface ero-
sion on road fills in steep terrain of
the central Idaho batholith was
eliminated simply by planting Pon-
derosa pine on a 4- by 4-foot spac-
ing. 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 Pon-
derosa pine treatment eliminated
about 95% of the total surface ero-
sion on road fills.

H.P. Guy (U.S. Department of In-
terior, personal communication,
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 col-
clected before, during, and after con-
struction to evaluate erosion control
methods and the effect of construc-
tion on downstream channels. Sedi-
ment yields will be correlated with
soil types, changes in hill slopes pre-
cipitation, and other pertinent
variables relating generally to
changes in land use.

Becker and Mulhern [1972] tell
about two studies pertaining to ero-
sion and sediment yield from ur-
banizing areas. The first study, con-
ducted by the Purdue Research
Foundation of Lafayette, Indiana, is
to extend an erodibility factor pre-
viously developed for surface soils
for use on unevaluated subsoils en-
countered 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-text-
tured subsoils; (2) relating various
chemical, mineralogical, and physi-
cal properties of selected surface
and subsurface soils to the
erodibility factor K previously
determined by field experimenta-
tion; 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 sedi-
ment yield monitoring program on a
demonstration project being con-
ducted in the Village of Long Reach,
Columbia, Maryland. This project
consists of the installation and
evaluation of erosion control prac-
tices in an urbanizing area.

Meyer et al. [1971] reported on
measurements of soil erosion and
runoff from several conditions typi-
cal of construction sites after they
have been reshaped for residential
and commercial developments or
highway construction. The effec-
tiveness of various revegetation
practices for reestablishing vegeta-
tive 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 treat-
ment 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 treat-
ments each lost 54 T/A. Straw mulch, which reduced soil loss
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each lost 31 T/A. The compact-fill
treatment lost 48 T/A, and the
scarified and scalped-only treat-
manship for minimizing soil erosion
during construction 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 sedi-
ment transported by rivers to the
seas each year is tremendous. Hole-
man [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 an-
nual suspended sediment discharge
of the rivers of North America at
245 T/m² 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 con-
tinuous United States for the 20-
year period 1950—1969 at 491
million tons. Bed load is estimated
to be an additional 10% of the sus-
pected 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 equa-
tion for predicting sediment move-
ment. 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 ad-
justments to reliably predict total
transport for all sand fractions
larger than 0.062 mm. In channel
design problems for sand bed chan-
nels, 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 armor-
ing effect in the degradation pro-
cess.

Beer and Johnson [1973] are
determining sediment sources that
contribute to the pollution of

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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.

Wills 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 Clark Fork Yellowstone, 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.

Oonstad et al. (1967), Oonstad (1973), and Meyer et al. (1970) have been especially interested in the basic mechanisms of upland deposition that would accurately portray the kinematics of hillside sediment movement for use in constructing a workable mathematical model. Piast et al. (1972b) 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 1959 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 sedihyrogram, 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 sedihydrometographs 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 movement from 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 165% 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 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 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 micro-watersheds 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 50,000 m² 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 diameter in the surface 2 inches of the soil profile. This variable was intended to reflect the resistance of coarse particles to entainment 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/ Ayr; 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 in-
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/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 (sequence of plowing, disk, 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/yr compared with 2.7 T/yr for conventionally tilled cornland. Sediment yields for an 8-year period from 2-acre no-till watersheds (using chemical weed control) averaged 0.01 T/yr compared with 1 T/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/yr annually, compared with a 20-T/yr 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.

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/yr to 6.0 T/yr among the watersheds. One of the watersheds, formerly cultivated but returned to grass, lost 2 T/yr 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/yr to 1.65 T/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 drainage. 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

$$G = a(q^p)^b KSLCP$$

where G is sediment yield for storm or period, Q is runoff volume, qa and q 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. (1972b) 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-hydrologic or sediment data are available. Several types of models have been proposed to meet this need, ranging from an entirely water-demanding 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 mathematical watershed sediment model that characterizes the time-space progression of sediment from its erosion source [Onstad, 1973].

Negeu [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 steep 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. Rowellson 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 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, 1972a, 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, 1972) and W.W. Emnett'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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