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EXPERIMENTAL WATERSHEDS CONTRIBUTE USEFUL SEDIMENTATION FACTS(1)

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ABSTRACT

Considerable progress has been made in the evaluation of watershed factors that influence soil erosion, sediment transportation, and deposition. But the present-day intensive use of our water and soil resources requires that these basic relationships be more adequately understood and quantified to achieve economical designs for water-utilization structures and facilities.

The paper summarizes the past role of experimental watershed studies in furthering sedimentation knowledge, and discusses procedures for analyzing sedimentation data obtained through field studies. Some concepts for designing watershed studies, analysis techniques, and a more general reorientation of sedimentation research toward more basic objectives are also discussed.

Data from a field study of experimental watersheds cannot by themselves result in a sound statistical determination of many sedimentation phenomena. Too many interdependent and uncontrollable variables are at work in nature. Nor can the results of theoretical studies be applied, per se, to solve field problems in sedimentation. A combination of watershed and laboratory studies is required to best evaluate the variables affecting sedimentation processes.

INTRODUCTION

Sedimentation deals with the processes of detachment, entrainment, transportation, and subsequent deposition of soil particles. Sedimentation, as it is associated with the sequences of geologic and climatic events, can never be stopped. Such control probably would not be a sensible or desirable goal. However, the sedimentation that results from man's use of the lands and their drainage network, and the acceleration or alteration of natural processes by this use, can be minimized by applying understanding acquired through experience, evaluation, and research.

We learn about sedimentation by studying the forces involved as they occur in nature, or we try to model these forces in the laboratory. Sedimentation knowledge, in the geologic sense, is deduced from field observations of the historic macroprocesses of erosion. In the context of modern-day hydrology, however, we are interested in the dynamic microprocesses.

Sedimentation research is necessary to develop criteria for further optimization of soil and water conservation efforts, and to achieve economical designs for water-utilization structures and facilities. Most of the early sedimentation theory was developed along qualitative lines. Only recently have sedimentationists initiated field and model studies to answer, quantitatively, both applied and basic questions. The choice of the particular mode of study has depended on the nature of the problem. In general, the answer to applied problems have been sought through field studies ; basic sediment relations have often been modeled.

A cursory look at past accomplishments of field investigations of sedimentation processes will point out their significance. It will also serve to illustrate changing

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research goals, and the reasons for varying analytical procedures to complete our inquiry. The aspects of sedimentation presented will be discussed under two general topics: (1) sediment production and distribution, and (2) fluvial sediment transportation and channel processes.

Sediment Production And Distribution

Soil erosion results primarily from energies of rainfall impact, and from the overland flow due to excessive rains. This erosion is facilitated by freeze-thaw and wet-dry cycles, as well as by other natural phenomena; it is further assisted by cultural, construction, and other activities of man.

The downslope movement of eroded soil particles is governed by the quantity, velocity, and depth of entraining runoff; the nature of the land slope; and by cover conditions. The effect of any one of these variables is minimized on larger areas, but for many of the small watersheds we are considering, the range in sediment yield can vary greatly from the influence of a single variable.

Sheet and rill erosion

The bulk of our knowledge of sheet and rill erosion has been derived from small experimental watershed (plot) studies. A wealth of soil-loss information has been collected and analyzed, to the extent that we are able to predict the soil loss from most areas if we know the rate of erosion of the soil under a set of standard conditions, land use and management, length and steepness of slope, and certain characteristics of rainfall. (Musgrave, 1947; Smith, 1957; and Wischmeier, 1961).

Research is still directed toward refinement of the soil-loss relationships. Additional effort is being expended to better represent the climatological variables in an erosion equation (Wischmeier, 1958), and to compute sheet and rill erosion on a storm basis rather than on a long-term basis. We need to intensify efforts to describe soil erodibility in terms of physical and/or chemical properties of the soil.

Practical, allowable soil-loss tolerances for sheet and rill erosion are being set; these are necessitated by economic and land-management considerations. Knowledge of these tolerances makes it possible to apply the soil loss prediction equation to the selection of the best land conservation methods.

We must also find the proper basis for extending the above prediction equation, or some such concept, in computing watershed sediment yield. In many regions, construction agencies have no alternative but to estimate sediment yield by utilizing such an equation and by applying an estimated delivery ratio. In our data collection programs--which include records based on suspended-sediment discharge measurements and complete reservoir sedimentation surveys--all affecting parameters, including erosion rates, must be inventoried and recorded. Analyses of these data in a relatively homogeneous region will provide an evaluation of the importance of each parameter, and will result in a quantitative procedure for computing the sediment yield for unmeasured watersheds.

Gully (upland channel) erosion

Past technology in gully research has involved the qualitative evaluation of factors that affect the gullying process; only approximate quantitative expressions for gully growth have been derived. Thompson (1962), in a study of the effect of watershed variables on the rate of gully advance, found the slope of approach channel and rainfall amount to be important. His most significant finding was the high correlation of gully advance rate with watershed size. Beer (1962), in a study of the causes of gullying in the loessial soils of western Iowa, found that unit runoff, length of watershed, and initial length of gully (incised channel) were related to the change in gully area. In a sense, all of these parameters, and especially the length of the watershed, are a measure

of watershed size. Woodburn (1949) determined an average annual erosion rate of about 2 inches from gullied uplands in north and central Mississippi-where there was little or no drainage into the gully.

These researchers have been handicapped in their work because none of the hydrologic and watershed variables which are postulated to affect gully growth has been studied under controlled conditions. A current ARS project intended to improve our knowledge of gullying processes has recently been initiated on watersheds in western Iowa. We are measuring all major gully-affecting variables--on a storm basis, or more often--over the widest possible range of conditions. With the recent advent of nuclear and electrical sensing devices, automatic recorders and data-logging apparatus, the collection of hydrologic data will be greatly facilitated. New, large-scale photogrammetric mapping techniques should provide a quantitative and pictorial record of even the most rapid landform changes due to gully erosion. Time-lapse photography may also be employed to help record the effect of subsurface moisture, freezing and thawing cycles, etc. Conventional survey methods cannot approach these capabilities. These aids, together with the computer, will allow us to better collect, analyse, and interpret the complex of variables involved in the gullying process.

Sediment yield and delivery

The total sediment outflow from a watershed or drainage basin during any given time is defined as the sediment yield for that period (Glymph, 1955). Sediment yields are obtained--in most sedimentation studies on experimental watersheds--by direct measurement of accumulations in reservoirs, by trapping outflow from small fields plots, or by sampling the sediment discharge of a stream. The ratio of sediment yield to the total quantity of material displaced from its original position in the watershed, expressed as percent, is the sediment delivery ratio.

We must be able to predict long-term sediment yield in order to efficiently design many water- and soil-conserving devices. Another facet of the problem is the determination of the sediment yield for large storms. This information is essential in the design of such upland conservation practices as terraces and other structural controls; the likelihood of their being damaged or negated by certain large storms is a part of these considerations. Also, many of our reservoir sites are irreplaceable and a planned reservoir "cleanout" program is needed, based on the remaining reservoir capacity and the likely sediment contribution of a given large storm.

The chief sources of sediment information have been the field-plot studies, sediment discharge measurements of streamflow, and surveys of deposited reservoir sediments. The Soil Conservation Service, in many states, publishes a bulletin describing the methods for computing sediment yield and reservoir storage requirements. Some publications are also available that provide sediment design criteria for specific soil or land resource regions (Gottschalk and Brune, 1950; Glymph, 1951). Others have attempted to show the overall pattern, by region, for the entire country (Rainwater, 1961).

Studies by Wischmeier (1962) on plots and by Piest (1963) on watersheds are intended to help determine the most efficient use of agricultural land, and the need for structural conservation measures. These studies relate average annual soil loss (plots) and sediment yield (watersheds) to storms of various frequencies.

Plot studies.--Although measurement of the soil lost from fractional-acre plots has yielded much valuable data, the application of these data to areas of field and watershed size is not straightforward. The need to learn more about the factors which influence sediment delivery to downstream points has been recognized and research on these factors has been started on experimental watersheds. Some of these variables are watershed size, shape, topography, trapping characteristics, and channel properties.

Suspended-sediment studies.--Samples of suspended sediment at the outlet of experimental watersheds, together with accompanying runoff and other hydrologic data, also make possible the prediction of probable long-term sediment yields (Piest, 1964). The reliability of these predictions varies with the length and accuracy of the research data, and their reliability for predicting the performance of ungaged streams varies with the degree to which sediment yields are affected by differences in hydrologic conditions between the sampled and unsampled watershed and between the gaged and predicted periods.

Reservoir surveys - Surveys of the sediment deposited in reservoirs provide a basis for estimating long-term sediment yields from small watersheds. The survey data must include information on the volume-weight of the deposited sediment, and the quantity must then be adjusted for the trap efficiency of the structure. This facilitates the conversion of the deposit in terms of sediment yield from the upstream contributing area and permits an evaluation of sediment delivery ratio (Maner; 1953, 1958).

Much useful information is obtained from such reservoir sedimentation surveys. By carefully considering the parameters that affect erosion and sediment movement within the contributing drainage area, and by obtaining a range in the values measuring these conditions in the watersheds, their relative importance to sediment yield can be determined. In the region of deep loess soils of the Springfield Plain physiographic area in west-central Illinois, Stall and Ba telli (1959) learned that "The slope of third-order streams, age, gross erosion, capacity-inflow ratio, non-incised channel density and a watershed shape factor are combined to explain 88 percent of the variations in the sediment deposited" in the twenty reservoirs studies. Other variables included in recent and current sediment yield studies are original reservoir capacity, drainage area, channel densities, soil information, land use, and watershed trapping.

Studies of the sediment deposited in small reservoirs has also enabled us to predict the sediment distribution in such reservoirs periodically during the life of the structure (Heinemann, 1961). This information is useful in designing principal spillways and their crest elevations.

Analyses of data on reservoir sediments have indicated the compaction that takes place in a sediment deposit. It was also found that the percentage of clay (smaller than 2 microns) and depth in a deposit are the important parameters governing the volume weight or specific weight. The effect on the particle size distribution of material delivered by side tributaries to the main reservoir has also been shown (Heinemann, 1962).

The common deficiency of each of the three sources of sediment yield data--our inability to apply findings to ungaged areas with consistent accuracy-- is due to our incomplete understanding of sedimentation-affecting variables. Only recently has the recognition of this deficiency caused us to think of these variables as an integral part of any watershed experimental design.

When the variables needed for accomplishing given the study objectives have been specified, the watershed selections must be made with care. An approximate value must be known for each variable on all watersheds available for the study. The variables must be measured to a commensurate accuracy.

It is imperative that research watersheds be controlled so that basic interrelationships are not obscured by changing land management or man-made alterations of stream channels. The data collection program must continue until a broad range of all variables has been experienced. Methods are available for utilizing short-term records, but they are never as satisfactory as the longer-term records.

The use of "control" or "benchmark" watersheds also provides valuable sedimentation facts, and there is an urgent need for several types of control watersheds in future sedimentation research. We are aware that nearly all instrumented areas in this country are changing because of the impact of our civilization. For some purposes, a study is not invalidated if the control changes, because of overall progressive development.

There is, however, a need for control watersheds which record climatic and other variations through time and are uninfluenced by works of man.

Fluvial sediment transportation and channel processes

The sediment discharge of a stream in equilibrium, already a complicated product of watershed hydrologic factors, is both the cause and the result of channel size, shape, gradient, and other hydraulic or conveyance characteristics. Under the non-equilibrium conditions that have resulted from our accelerated use of soil and water resources, many waterway problems have developed.

In their efforts to understand particular aspects of this cause and effect relationship between variables, individual researchers have concentrated on areas of study that were of primary interest to them. As a result we have many theories and empiricisms concerning fluvial sediment transportation, channel regime, tractive force, stream regimen, permissible velocity, and other aspects of the interrelation.

Fluvial sediment transportation

Bogardi (1965) states that sediment transport processes are affected by more than hydromechanical factors, and concludes that the actual sediment load of a stream is governed by hydrological conditions of the watershed as well as by the laws of hydromechanics. It seems, therefore, that although many special phases of sediment transport can be investigated in the laboratory, we must always be watershed-oriented in our quest for new information about the quantities of sediment in natural streamflow.

A significant aid to the study of sediment transport phenomena has been the development of various samplers for measuring the suspended-sediment discharge of a stream (ICWR, 1959, 1963). They have also helped to substantiate the theory of suspended-sediment transport (O'Brien, 1933; Vanoni, 1946; and others) by facilitating accurate measurement of the distributions of suspended sediment in natural streams.

The development of satisfactory samplers to measure the sediment load moving near the streambed has been slow. It is, in fact, very difficult to measure any of the attributes of turbulent flow and the accompanying sediment movement near the channel boundary. Much of the existing information has been developed from laboratory wind-tunnel studies of simplified turbulence, utilizing the hot-wire anemometer. Other inferences have been drawn from studies of the behavior of the coarser sediments traveling in suspension and from measurement of the total sediment discharge of a stream, the latter made possible by placing the bedload in suspension with natural or artificial turbulence devices.

The most complete theoretical treatment to date on sediment transportation (Einstein, 1950) has been field tested with some success, but has undergone several modifications (Colby and Hembree, 1955). Einstein's original equations are still considered the best basis for refining sediment transport theory. He improved on basic concepts by various researchers and developed additional ones for use in a comprehensive theory that makes possible the computation of the coarse fraction of the sediment discharge. Until further breakthroughs are made, however, there is some justification for relying upon simplified methods (Colby, 1957). Colby's mean velocity method, with adjustments for a few major variables, is especially adapted for use in preliminary design work.

Fluvial morphology' channel regime' and stable channels

One of man's earliest concerns in water resources utilization was to maintain drainage networks in proper balance so that sedimentation and flood damages could be minimized.

Solutions to the problems of stable channel design have been approached:

1. By studying the streamflow and channel characteristics of existing natural streams and canals, and determining the interrelationships between these characteristics.

2. By developing some criteria whereby the hydraulic forces exerted on the stream boundary were adequate to convey the water-sediment mixture entering the system, but would not introduce damaging scour of the boundary.

Leopold and Maddock (1953), in a comprehensive analysis of an extensive stream-gage network, related channel dimensions, velocity and sediment load with water discharge to determine stream equilibrium conditions. Their work has encouraged many others to examine historic fluvial land forms.

Lacey (1930), Blench (1957), and others developed empirical criteria that were based upon successful canal designs in India. They describe channel shape and slope requirements after due consideration of the characteristic streambed and bank material. These criteria are used much today, especially in regions where bank materials are cohesive and streambed materials are non-cohesive.

DuBoys (1879), one of the earlier researchers concerned with stable channels, introduced the concept of a tractive or shear force at the streambed. This tractive force theory, as further developed by Lane (1955), was used to design stable channels based on discharge, channel material, and slope considerations. From these parameters, the velocity, channel width, depth, and other hydraulic factors were selected so that a critical tractive force was not exceeded.

Other studies in alluvial streams have shown that the regime of flow and, therefore, the sediment-carrying capacity of the stream, are intimately related to bed form and channel roughness. Colby's (1960) investigations in stream channels in northern Mississippi showed that an effective increase in channel conveyance was accompanied by a change in bed form. These findings confirmed the implications of laboratory studies by Brooks (1955), who showed that several velocities (and discharges) could occur with a given depth and slope .These phenomena are attributalbe to concomitant changes in channel friction and bed form.

These are but a few of the many significant advances that have been made from studies of fluvial processes as related to sediment movement in the field. Our present knowledge of sediment transport characteristics would be broadened considerably if we knew the effect of depth of flow, size distribution of bed material, and channel shape on the forms of bed roughness, regimes of flow, flow resistance, and sediment transport capability. These interrelationships can be studied in the laboratory, but they must be tested in the field in order to evaluate the effect of extraneous hydraulic and superimposed hydrologic variables.

There is also some necessity to examine, and perhaps improve, simplified methods such as Colby's (1957) mean velocity procedure for computing the bed load, total load, bed material discharge, or unmeasured sediment discharge of an alluvial stream. The mean velocity method, with a few appropriate adjustments, has already been shown to compare favorably with the few existing field measurements at total load stations and with the more tedious calculations by well-know equations; we feel that a concerted effort to improve the method will give us an even more useful working tool.

Our objecttives in watershed sedimentation research are not the same as they were a few decades ago. This is due tot he progress we have made, and to the fact that new problems have been introduced by the increased management of our water resources. Thousands of upland conservation and flood control reservoirs are being planned and built. Many of these are quite large and expensive. The basic factors influencing sediment yield and delivery to these structures must be understood. Many downstream changes have been brought about by an accelerated dam-building program. These structures, much needed for irrigation, flood control, navigation, and power purposes, aregenerally causing an undersupply of fluvial sediments (instead

of the previous oversupply), with attendant problems of channel degradation anc bank stability.

There are many challenges, old and new, which must be met by continuing watershed sedimentation research.

REFERENCES

BEER, C.E., Relationship of factors contributing to gully development in loess soils of Western Iowa, Ph. D. Dissertation, Iowa State University, 1962.

BLENCH, T., Regime behaviour of canals and rivers, Butterworth Scientific Publications, London, 1957.

BOGARDI, J.L., European concepts of sediment transportation, *ASCE Journal, Hydraulics Division*, Vol. *91*, January 1965.

BROOKS, N.H., Mechanics of streams with moveable beds of fine sand, *Trans. ASCE*, Vol. *123*, Paper 2931, 1955, pp. 526-594.

COLBY, B.R. and HEMBREE, C.H., Computations of total sediment discharge, Niobrara River near Cody, Nebraska, *U.S. Geological Survey, Water-Supply Paper 1358*, 1955.

—, Relationship of unmeasured sediment discharge to mean velocity, *Trans. American Geophysical Union*, Vol. *37*, No. 5, 1957, pp. 708-717.

—, Discontinuous rating curves for Pigeon Roost and Cuffawa Creeks in Northern Mississippi, *U.S. Department of Agriculture, Agricultural Research Service* 41-36, 1960.

DUBOYS, P., Études du Régime du Rhône et l'action excercee par les eaux sur un lit a Fond de graviers indéfiniment affouillable, *Annales des Pont et Chaussées*, Séries 5, Vol. *17*, pp. 141-195, 1879.

EINSTEIN, H.A., The bed-load function for sediment transportation in open channel flow, *U.S. Department of Agriculture, Soil Conservation Service, Tech. Bul.*, No. 1026, 1950.

GLYMPH, L.M., Jr., Relation of sedimentation to accelerated erosion in the Missouri River Basin, *U.S. Department of Agriculture, Soil Conservation Service*, TP-102, July 1951.

—, Studies of sediment yields from watersheds, Tenth General *Assembly of International Union of Geodesy and Geophysics*, Rome, Italy, 1955.

GOTTSCHALK, L.C. and BRUNE, G.M., Sediment design criteria for the Missouri Basin Loess Hills, *U.S. Department of Agriculture, Soil Conservation Service*, TP-97, July 1950.

HEINEMANN, H.G., Sediment distribution in small floodwater retarding reservoirs, *U.S. Department of Agriculture, Agricultural Research Service* 41-44, February, 1961

—, Volume-weight of reservoir sediment, *Journal of the Hydraulics Division Proc., ASCE*, Vol. *77*, No. HY 3, September 1962.

HOOKER, E.H., The suspension of solids in flowing water, *Trans., ASCE*, Vol. *36*, December 1896.

Inter-Agency Committee on Water Resources, A study of methods used in measuremen and analysis of sediment loads in streams, *Report AA, Federal Inter-Agency Sedimentation Instruments and Reports*, May 1959.

—, A study of methods used in measurement and analysis of sediment loads in streams, *Report No. 14, Determination of Fluvial Sediment Discharge*, December 1963.

LACEY, G., Stable channels in alluvium, *Proc. ,Inst. of Civil Engineers*, Paper No. 4736, London, 1930.

LANE, E.W., Design of stable channels, *Trans., ASCE*, Vol. *120*, 1955, p. 1234.

LEOPOLD, L.B. and MADDOCK, T., The hydraulic geometry of stream channels and some physiographic implications, *U.S. Geological Survey*, Prof. Paper No. 252, 1953.

MANER, Sam B., Factor affecting sediment delivery rates in the Red Hills Physiographic Area, *Trans. AGU*, Vol. *30*, No. 4, August 1958.

MANER, Sam B. and BARNES, LELAND H., Suggested criteria for estimating gross sheet erosion and sediment delivery rates for the Blackland Prairie Problem Area in Soil Conservation, USDA, SCS, Ft. Worth, Texas, February 1953.

MUSGRAVE, G.W., The quantitative evaluation of factors in water erosion, A first approximation, *Journal Soil and Water Conservation*, *2*, 133-137, 1947.

O'BRIEN, M.P., Review of the theory of turbulent flow and its relation to sediment transporation, *Trans. Amer. Geophysical Union, Section of Hydrology*, 1933, pp. 481-491.

PIEST, R.F., The role of the large storm as a sediment contributor, presented at *Federal Inter-Agency Sedimentation Conference*, Jackson, Mississippi, January 1963.

—, Long-term sediment yields from small watersheds, *International Association of Scientific Hydrology*, Pub. No. 65, 1964.

2239

RAINWATER, F. H., U.S. Geological Survey Hydrologic Investiagtions Atlas, 1961.

SMITH, D.D., and WISCHMEIER, W. H., Factors affecting sheet and rill erosion, *Trans., Amer. Geophysical Union*, *37*, 889, 1957.

STALL, J. B. and BARTELLI, L.J., Correlation of reservoir sedimentation and watershed factors, Springfield Plain, Illinois, Illinois State Water Survey, 1959.

THOMPSON, J.R., Quantitative effect of watershed variables on the rate of gully head advancement, presented at ASAE National Meeting, Chicago, Illinois, December 11-14, 1962.

VANONI, Vito A., Transportation of suspended sediment by water, *Trans., ASCE*, Vol. III, 1946, pp. 67-133.

WISCHMEIER, W.H. and SMITH, D.D., Rainfall energy and its relationship to soil loss, *Trans., Amer. Geophysical Union*, *39*, 285-290, 1958.

—, A universal equation for predicting rainfall-erosion losses—an aid to conservation farming in humid regions, *Agricultural Researh Service*, 22-66, March 1961.

—, Storms and soil conservation, *Journal of Soil and Water Conservation*, Vol. *18*, No. 2, 1962.

WOODBURN, Russell, Science studies a gully, *Soil Conservation*, *15*, 11, 1949.