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ARS RESEARCH ON SEDIMENT TRANSPORT, YIELD, & PROPERTIES

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Cover photo: First International office tower (at right), tallest building in Dallas (56 stories, 710 ft.). Courtesy of AISC.

ARS RESEARCH ON SEDIMENT TRANSPORT, YIELD AND PROPERTIES

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INTRODUCTION

The Agricultural Research Service (ARS) is one of the research organizations of the U.S. Department of Agriculture that is responsive to needs for agricultural knowledge, particularly from the Soil Conservation Service. The ARS has recently prepared National Research Programs (NRP's) to describe all ARS research. There are 67 NRP's and 8 Special Research Programs (SRP's) covering research in animal science; plant and entomological science; soil, water and air sciences; and marketing, nutrition and engineering sciences. The SRP's are for special programs like energy research and remote sensing. The NRP's and SRP's were developed for program and budget planning, and for coordinating research within ARS and with other agencies.

The ARS research on erosion and sedimentation is described under NRP 20800, "Control of Water Erosion, Wind Erosion, and Sedimentation," (6). This research is a companion program to one on hydrology, NRP 20810, "Conserve and Manage Agricultural Water Resources." These two programs supplement and support other NRP's, particularly those for pollution, tillage, surface-mine reclamation, irrigation, and range management.

The research program on erosion and sedimentation is divided into five Technological Objectives (TO's):

1/ Staff Scientist, Soil, Water and Air Sciences, National Program Staff, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland 20705.

2/ Hydraulic Engineer and Director, Southwest Rangeland Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, Tucson, Arizona 85705.

1. Improved water erosion prediction and control to preserve and improve productivity of land and prevent water quality degradation.
2. Improved wind erosion prediction and control to protect crops and soils and decrease air pollution.
3. Improved evaluation and prediction of sediment transport, yield, and properties.
4. Improved prediction and control of sediment deposition in reservoirs, valleys, and channels.
5. Improved stabilization of stream channels and control of gullies.

The total research effort for this NRP is about 45 Scientific Man-Years (SY's) including 16.8 SY's for TO No. 3 on sediment transport, yield and properties. The subject of this paper is the research under TO No. 3, presently conducted at six locations, with one having 9.7 SY's.

CONCERNS

Agricultural research in the United States has been concerned for more than 60 years with the continuing depletion of soil resources from erosion. About 4 billion tons of soil are eroded each year in the United States (1). Of this amount, about 1 billion tons are discharged by streams into the oceans, with the remaining 3 billion tons being deposited along the way on the land, in the channels, and in reservoirs. The amount of sediment loading in our streams is estimated to be 500 to 700 times greater than the sewage loading. Sediment is the greatest pollutant of water in terms of volume; however, sediment may also be a carrier of other pollutants, removing them from their source and redepositing them elsewhere. Of the 450 million acres of cropland in the United

States, soil erosion is the dominant problem on more than one-half (234 million acres) (5). More than three-fourths of the cropland is affected by water erosion, as a major problem, and one-fourth by wind erosion. The main source of sediment in streams is from water erosion on agricultural lands. A recent estimate of sediment sources in the United States (3) is as follows: Agricultural lands, 40 percent; pasture, range and forest lands, 25 percent; stream channel erosion, 26 percent; urban, roads, mining, miscellaneous, 9 percent.

Sediment has a threefold effect on the environment: (1) It depletes the productive capacity of the land from which it is eroded; (2) As a physical entity, it impairs the quality of water in which it is transported and may impair the quality of the land on which it is deposited; and (3) Depending on its physicochemical properties, it can be a carrier of other pollutants like pesticides, toxic metals, plant nutrients, viruses, fungi, and disease producing bacteria. Thus, water quality is influenced by both sediment itself and by its physical, chemical and biological properties.

Recognition and evaluation of sediment sources in a watershed is a necessary requirement for planning ways to control sediment movement. Summation of the sediment produced from the many sources within the watershed is the estimate of gross erosion. Sediment yield is the amount of eroded material passing a geographical point, like the outlet of a watershed system or of any of its subwatersheds. It is that part of the material generated by gross erosion that is not deposited within the watershed.

The connecting link between sediment sources and sediment yield is sediment transport. Erosion and sediment transport is a selective process in which the fine-grained sediments (clays, organic matter, and amorphous materials) are transported farthest. This fine fraction of eroded soil particles is generally accepted as being involved in the sorption and transport of certain chemicals.

1. Sediment Transport:

Sediment transport encompasses processes by which sedimentary materials are removed from one location, transported sequentially through other locations, and deposited usually to have this cycle restart eventually. The material included in sediment transport may be clastic streambed material ranging in size from silt to boulders, or it may be heterogeneous clay material, which moves as discrete soil particles of some size, as flocs, or as the dispersed phase of a relatively stable suspension of particles of near-molecular size. Sediment transport includes inception of particle motion, transport by traction, saltation, or suspension, and deposition by single-particle settling or flocculation. Sediment transport is dependent on aspects of fluid mechanics, notably lift and drag generation, mass and momentum transport, turbulence generation, and boundary layer and wake development. After over 200 years of development, the field of sediment transport is still showing little evidence of emergence from the empirical state.

If principles of sediment transport are ever sufficiently understood, they will be of practical importance in attacking problems like:

Predicting rill and interrill erosion and transport rates;

Defining the motion of fine material that carries attached pollutants;

Designing settling basins and detention structures;

Augmenting flocculation by turbulence;

Designing reliable riprap for structure and channel protection;

Predicting channel stability;

Predicting channel capacity;

Evaluating actual channel sediment load.

Current technological efforts along these lines are at best very approximate, because of the extreme uncertainty in the knowledge of the sediment transport principles involved. Areas in which understanding of principles and theoretical development are perhaps most advanced are designing settling basins and studying fine material motion; areas of least advancement are predicting channel capacity and evaluating sediment load.

Major factors retarding the understanding of sediment transport principles are the difficulty of developing adequate laboratory and field measurement equipment or experimental apparatus, and the relatively late appearance of badly needed stochastic theories, concepts, and analytical procedures. New fluid mechanics principles, derived mainly from the fields of aeronautics, naval architecture, and astrophysics, are being accepted by sedimentologists, and ways to use them are becoming better understood.

2. Sediment Yield:

Among the factors recognized as influencing sediment yield are physiographic features of drainage areas, soils and vegetation, precipitation, stream channel and flow characteristics, and water temperature. Also significant are management and conservation practices, like modification of tillage methods, terracing, channel stabilization, and construction of debris basins or detention reservoirs. There is continuing need in resource management for both improved and new techniques for predicting sediment yield under the various physiographic, climatic, and management alternatives.

Several methods are used to estimate sediment yield, and each presents unique data needs. In each method, there is an associated uncertainty that requires a safety factor when used in a design application.

(a) The sediment rating curve-flow duration method depends highly upon the adequacy of field measurements of concentration and the adequacy of sampling during high discharge periods. The method uses concurrent measurement of stream discharge and sediment concentration with subsequent development of a relationship between the two. It is difficult to obtain data for using this method for small upstream watersheds where discharges of water and sediment vary appreciably in both time and space. The number of existing upstream watersheds alone precludes obtaining field data on more than a few select areas. Thus, the use of hydrologic models (NRP 20810) should assist with development of this method.

(b) The sediment delivery ratio method is a percentage relationship for a similar time period, between sediment yield from a watershed and the gross erosion in the watershed. Sediment delivery ratios have been developed for many areas of the United States and have been found to relate to drainage area size. In operation programs, like watershed planning, derived quantities of watershed erosion are multiplied by the sediment delivery ratio to estimate sediment yield.

(c) Reservoir sediment deposition surveys can be used and converted to rates of accumulation (weight basis) based on the age of the reservoir or the time interval between the last two surveys. Such data must then be adjusted for the reservoir trap efficiency. When used with the results from several reservoir sedimentation surveys in a land resource area or river basin, this method can yield a relationship between sediment yield and drainage area. The approach provides good information on magnitude and variation of sediment yield in the region, but must be used with discretion to forecast sediment yield of an individual watershed without measurements.

(d) The difference between erosion and deposition estimates can be used to estimate sediment yield. The inherent uncertainty of both the erosion and deposition estimates can lead to a large error margin when this method is used.

(e) Bedload functions have been used with very limited success to estimate the coarse fractions of sediment yield. Mathematical relationships, developed primarily from laboratory flume studies, relate the movement of the materials comprising the bed of alluvial channels to flow conditions. These equations, when used with suspended transport data, often provide widely differing sediment yield estimates for the same set of field conditions as illustrated by Vanoni et al (7).

(f) Predictive equations based on watershed parameters, like drainage area, runoff, temperature, slope, soil and cover, have been derived for watersheds in specific areas. Transferring such predictive techniques to areas with differing conditions can be accomplished only with additional data for the new conditions.

(g) In current research, soil detachment, transport, and deposition relationships are being incorporated into hydrologic models to estimate sediment yield. This method offers great potential for refining sediment yield estimating procedures (2) (4). Development work in hydrologic models incorporating the changes in hydrologic response anticipated for different management schemes and the wide availability of computing equipment at low cost, should greatly facilitate progress in developing runoff-sediment yield models.

3. Sediment Properties:

Knowledge of the role of sediment in farm chemical sorption, desorption, transport, deposition, and degradation is limited, but such knowledge is urgently needed. For example, pesticides transported into streams and lakes by sediments in runoff from Mississippi Delta farmlands have been implicated as a source of pollution. Lakes have been closed to commercial fishing because of DDT and toxaphene residues in fish and bottom sediments. It is often assumed that surface water contamination by pesticides results in part from sediments with sorbed residues; however, the magnitude and significance of the problem is poorly defined. Furthermore, eutrophication of impounded waters has been attributed to plant nutrients such as nitrogen and phosphorus and to organic matter associated with sediments. The magnitude and biological significance of the sediment-phase fractions of these nutrients are unknown.

The physicochemical properties of sediments and farm chemicals (pesticides and nutrients) will determine the distribution of chemicals between sediment and solution phases. These properties will also define, for a given hydrologic/hydraulic condition, pollutant transportation and deposition. In general terms, coarse sediments serve as a buffer, modifying the erosive potential of streamflow, whereas fine sediments modify the sediment-chemical and dissolved chemical loads. Little is known, however, about the surface chemical properties responsible for chemical sorption and their effect on the chemical concentration in the solution phase. Both sediment and solution phase transport must be evaluated fully to assess agricultural chemical transport.

The Federal Water Pollution Control Act Amendments of 1972, Section 304(e) of Public Law 92-500, requires that information be provided on (1) guidelines for identifying and evaluating the nature and extent of nonpoint sources of pollution, and (2) processes, procedures, and methods to control pollution resulting from agricultural activities, including runoff from fields and croplands. Hence, information on hydrology, erosion, sedimentation, and sediment-water-chemical interactions is essential in developing rational guidelines for the control of sediment and farm chemicals.

Mathematical models will be used by regulatory agencies in the future to develop guidelines for controlling the movement of water, sediment, and chemicals from farmlands. Attention must be given to the temporal and spatial distributions of water, sediment, and chemicals. Modes and mechanisms of chemical transport must be defined by evaluating the physicochemical properties of sediments affecting the distribution of chemicals between the sediment and aqueous phases. Present data on physical and chemical properties of sediment are inadequate for computer-based model development; and an adequate data base for model development and verification must be acquired by experimental research. Such information will be needed not only in carrying out the mandate of PL 92-500, but will assist in preserving production of an adequate supply of food and fiber with a minimum of environmental pollution.

Apparently, total farm chemical yield (solution plus sediment phases) is reduced when sediment yield is reduced, e.g., by conservation tillage. Preliminary research indicated, however, that the "apparent" soluble chemical concentrations of some sparingly-soluble chemicals may be increased when sediment concentration is decreased. This increase in soluble chemical concentration may be due to changes in the physical and chemical properties of the sediments. Diluents, emulsions, and surfactants commonly used in pesticide spray programs, as well as soluble organic leachates from crop residues associated with minimum and no-till practices, may facilitate the transport for some chemicals as films and emulsions. This may explain the increase in soluble ortho- and organic-phosphorus concentrations observed in the runoff from no-till practices, where sediment concentrations are low. Few data are available on the sediment-water chemistry of runoff from conservation farming.

In the past, concern has been largely with annual sediment and total (sediment plus solution) farm chemical yields in runoff. However, nonpoint pollution controls in runoff will likely be based on storm sediment and chemical concentrations because the concentration of a specific chemical is causing nuisance algal blooms, or acute fish kills, or limiting the reproduction of aquatic life.

POTENTIAL FOR IMPROVED TECHNOLOGY

In the next 10 years, technological advances will lead to computerized sediment and chemical yield estimates for operational problems. Also, they will forecast the effect of sediment control measures before they are installed. These prediction methods will detail and justify the need for any remedial control measures. Current technology will be strengthened and improved, while major technological advances are being made.

1. Sediment Transport:

Before any further significant technological advance can be made in the area of sediment transport, major efforts must be made to overcome inadequate equipment and instrumentation. This can be accomplished as a result of an integrated program of instrument development, carried out with the Interagency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

The new fluid mechanics theory and stochastic analytical techniques will be increasingly incorporated into sediment transport research. In experimentation, the fullest potential of the new instruments will be put to use as fast as the instruments are developed.

Projected priority laboratory investigations include, but are not restricted to:

Studying the stochastic nature of turbulent shear stress fluctuations at channel beds;

Studying the turbulence generation characteristics of various boundary types, including soil surfaces and vegetated surfaces under wide ranges of flow conditions;

Studying the diffusive ability of turbulent flows over various boundary types;

Examining the mechanics of soil particle detachment as opposed to the inception of motion of clastic particles;

Experimenting on the motion of all types of sediment material through common flow situations, like contractions, divergences, bends, hydraulic jumps, nappes, etc.;

Laboratory testing of total sediment load measuring devices for subsequent use in the field.

Developing equipment to facilitate the above studies include:

Dynamic densitrometric devices for automated monitoring of sediment concentration both in the laboratory and in the field;

Devices for detecting instantaneous fluctuations of sediment concentration; these devices must also have the capacity to evaluate concentrations by various sediment sizes;

Velocity meters of very small size, capable of following turbulence fluctuations in sediment-laden flows, without interference from trash, vegetation, and temperature changes.

In field locations, the coarse material (bedload) must be sampled under a variety of conditions known to affect transport in this mode (e.g., slope, bed form, turbulence, size gradation, etc.) and compared with the suspended load transport so that total yield of a watershed can be quantified. This bedload transport must then be tested against available empirical prediction equations or new ones developed to include both the suspended and bedload transport.

2. Sediment Yield:

Continuing research will improve current technology for predicting and controlling sediment yield. Existing watershed data bases will be fully utilized to improve and extend current methods for predicting the portion of gross erosion that results in sediment yield. The data base will be increased to accommodate testing and verification of watershed sediment yield models currently visualized.

Needs for predicting sediment yield and sources are widely varied, therefore, research will be directed to developing varied and different methods to meet these needs. Methods for estimating sediment sources within a watershed will be developed to guide decisions on the types and extent of watershed treatment measures needed for erosion control. Methods for estimating rates of gully and stream channel erosion and equations for calculating erosion on farm, rangeland, and woodland fields, construction sites, and other sediment sources will be refined and associated with sediment delivery ratios for operational use. Remote sensing methods will be improved and adapted for determining land use patterns present on project watersheds. New erosion equations that consider selective particle-size erosion will facilitate agricultural chemical yield estimation.

Laws regulating the amount of sediment that may leave a field or very small watershed or cross a property line will require a detailed deterministic model because small areas tend to deliver sediment yields closer to gross erosion. Also, gross erosion on small areas varies widely because of differences in cover within the areas. Larger watersheds usually have a greater variety of sediment sources and a larger number of depositional areas. Therefore, less variability in sediment yield is observed and the models for large watersheds need be less detailed.

Models with a detailed reliance on land use will be developed both for accurately estimating sediment yield and for guiding land-use planning. Sediment yield becomes more dependent on runoff for larger watersheds. Since land use greatly affects direct runoff and runoff rates, sediment yield prediction models involving varying land use will probably require a runoff model base. This type of model will be most useful when runoff is also a concern.

Concentration of sediment in streams and impoundments is important biologically and as an aspect of agricultural chemical transport. Models designed specifically to predict maximum sediment concentrations will assist action agencies to plan sediment yield controls.

Because of the vastly different watershed characteristics and problems, action agencies must develop a modeling and simulating capability. Environmental impact statements for watershed planning require a detailed account of the results of proposed watershed changes. Rather than applying a model for conditions before and after changes are made, it may be more efficient to simulate the watershed behavior on a computer and evaluate the changes with the simulation. This may require the establishment of monitoring stations in the watershed for 1 or 2 years to provide feedback to the simulation. Research will develop techniques to guide action agencies to design the simulations.

In all of the above envisioned prediction techniques, research will furnish operating principles, developed through application of basic sediment transport principles to watershed situations. The existing data base can be exploited for only a limited part of these; concurrent research will be needed to furnish the missing details.

3. Sediment Properties:

The role of sediment in the transport of pesticides, plant nutrients, and organic matter from farmlands into surface waters will be evaluated on experimental plots and watersheds varying in climate, soils, topography, and in management of soils, crops, and pests. This will provide needed information on the extent and magnitude of sediment and chemical concentrations and yields from different agricultural practices. The relative significance of sediment and solution phase transport of farm chemicals will be determined.

Research on the physical and chemical properties of sediment controlling the distribution of chemicals between suspended sediment and aqueous phases will permit evaluation of the chemical sorption-desorption mechanisms, which determine the chemical-supplying potential of sediments. This information will assist in the development of sediment-water-chemical mathematical relationships needed in predicting the transport of farm chemicals into surface waters. Sediments may serve as a source or sink for certain agricultural chemicals depending on the physicochemical properties of the sediments and chemicals involved. Data on the availability of chemicals sorbed on sediments will assist in evaluating sediment as contributors of plant nutrients in accelerated eutrophication and in determining the fate and persistence of certain pesticides in the aquatic environment.

Watershed research on the sediment-water-chemistry of runoff from conventional, minimum, and no-till practices will provide new knowledge on erosion, sediment transport, and solution-chemical and sediment-chemical concentrations and yields as related to sediment concentrations and yields in runoff. This information will assist in the development of soil and water conservation practices to improve the quality of surface runoff from agriculture while maintaining and improving agricultural production.

Future technology will aid regulatory agencies in developing realistic guidelines for the control of farm chemical concentrations and yields in runoff.

RESEARCH APPROACHES

The following specific approaches are needed for improved technology for managing watersheds for optimum sediment and chemical yields. Much of this research is in progress at the locations indicated.

1. Adapt erosion prediction and control methods for use in controlling sediment yield (ARS research at several locations).
2. Use remote sensing methods and techniques to determine sediment sources and yields from watersheds and develop predictive models for sediment yields based on remotely sensed data (Limited ARS effort).
3. Determine how sediment transport is affected by flow variables (velocity, depth), channel geometry (cross section, curvature,

gradient), fluid properties (density, temperature, viscosity), and sediment properties (density, shape, size gradation) (Oxford, MS; Chickasha, OK; Temple, TX; Columbia, MO; Tuçson, AZ; and Boise, ID).

4. Determine how bedload transport is influenced by incipient motion (critical tractive force), motion of individual particles (forces on particles, grain resistance), bed form development and propagation, and form resistance. Develop improved bedload transport relationships as needed (Oxford, MS; Chickasha, OK; Tucson, AZ; and Boise, ID).

5. Determine how suspension mechanism (turbulence and interparticle forces), boundary roughness effects on turbulence, and diffusion mechanisms affect suspended load sediment equation(s), and determine the range of conditions to which they apply. Develop instrumentation techniques to make these measurements (Oxford, MS).

6. Determine sediment delivery ratios for relating downstream sediment yields to the estimates of material eroded from a field. Prediction equations for deposition and for sediment accretions from runoff-induced field erosion will be developed separately, derived as a function of the parameters pertinent to that process. Improved concepts of sediment routing will also be developed to estimate downstream sediment yield (Oxford, MS; Temple, TX; Chickasha, OK; Columbia, MO; Tucson, AZ; Boise, ID; and Pullman, WA).

7. Determine how sediment dispersion and flocculation are influenced by dissolved solids, adsorbed chemicals, sediment mineralogy, and water temperature (viscosity). Develop methods for their control and beneficial management (Oxford, MS).
8. Develop information to show if sediment affects the dissolved oxygen in streams, the capacity of a stream to assimilate organic wastes, and the turbidity and transmission of light (Oxford, MS).
9. Determine the physical and chemical properties of sediments responsible for the sorption and transport of pesticides and plant nutrients from agricultural watersheds, and how these properties change as a function of sediment concentration (Oxford, MS; Baton Rouge, LA; Watkinsville, GA; Beltsville, MD; Columbia, MO; and Morris, MN).
10. Determine the extent and manner of streambed sediment contamination from agricultural chemicals, heavy metals, and radioactive fallout (Durant, OK; and Oxford, MS).
11. Determine if reductions in sediment concentration from soil and water conservation programs affect the physical and chemical properties of sediment and, hence, the solution-chemical and sediment-chemical concentrations and yields in runoff. Determine if soluble phosphorus concentrations are independent, proportional, or inversely related to sediment concentration and runoff volume (Oxford, MS; Baton Rouge, LA; Temple, TX; and Columbia, MO).
12. Evaluate conservation tillage practices for their success in reducing sediment and agricultural chemical concentrations and

yields in runoff (Temple, TX; Oxford, MS; Watkinsville, GA; Baton Rouge, LA; Stoneville, MS; Morris, MN; Coshocton, OH; Columbia, MO; Pendleton, OR; Pullman, WA; and Sidney, MT).

13. Determine the extent to which the organic matter load and, hence, the chemical oxygen demand of sediments are reduced by conservation tillage (Oxford, MS; Morris, MN; and Columbia, MO).
14. Develop mathematical models to predict the transport of sediment and chemicals from agricultural lands to assist in environmental planning. The models would include soil detachment, transport and sediment deposition as routines in watershed hydrologic models which should facilitate predicting the effects of conservation management programs on sediment, water, and chemical yields (Oxford, MS; Morris, MN; and Columbia, MO).
15. Evaluate and develop soil and water conservation programs for watersheds to control transport of sediment and agricultural chemicals from watersheds (Several ARS locations).

RESEARCH EFFORT

Current Level.--The ARS current effort on sediment transport, sediment yield, and sediment properties is about 17 SY's, with the USDA Sedimentation Laboratory, Oxford, MS, having a large portion of the effort. Smaller efforts are centered at the Southern Great Plains Watershed Center, Chickasha, OK; the Northwest Watershed Research Center, Boise, ID; the Southwest Watershed Research Center, Tucson, AZ; the North Central Watershed Research Center, Columbia, MO; and the Blackland Conservation Research Center, Temple, TX.

ARS is conducting about one-fifth of the national research effort in this area related to soil and water resources. At the present level of support and personnel only a part of the research listed under "Research Approaches" can be conducted. Many ARS locations already have unique research facilities, including field watersheds and plots, simulated rainfall equipment for both field and laboratory use, specialized laboratories for sedimentation studies, and sophisticated analytical equipment. Many of these facilities are not being fully utilized at the present funding and staffing level.

Expanded Level.--The pollutional aspects of sedimentation are of increasing concern and new information is needed on sediment yield, transport, and properties. Studies currently being initiated under Section 208, PL 92-500, demand a higher level of knowledge on non-point pollution than presently exists. Agencies, particularly the Environmental Protection Agency and the Soil Conservation Service, are requesting better information on the environmental aspects of sediment and associated chemicals. There are also increasing needs for maintaining and improving land and water resources for stabilizing and increasing the production of food and fiber. The current ARS staffing of scientists and engineers is sufficient to furnish only a portion of the needed information. The effort needs to be more than doubled in number of personnel and funding.

SUMMARY

The ARS is conducting extensive research in the fields of sediment yield, transport and properties. However, there are many unanswered questions and many new demands for additional knowledge, due both to food and fiber needs and to environmental concerns. There are numerous possibilities for new and additional research that can be applied to sedimentation problems arising from agricultural sources. Recently, developed instrumentation together with modeling and simulation techniques can be used to accelerate this research. The research effort in this very important area should be doubled using existing facilities.

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