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# EROSION AND SEDIMENT YIELD MODELS - AN OVERVIEW

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## INTRODUCTION

Mathematical modeling of the processes in erosion and sediment transport has increased significantly since passage of the Clean Water Act, Public Law 92-500, in 1972. This session of the ASCE conference was planned to compile papers concerned with erosion models. Although erosion and sediment transport will be emphasized, the models generally are components of more comprehensive models that have evolved to meet the needs of PL 92-500. The purpose of this paper is to provide an overview of the modeling activities and at least partly describe the history of model development. It is impossible to give a complete background, but hopefully the more important works will be included to indicate the various developments. Although this session is devoted to erosion and sedimentation, we must consider hydrology as well.

## HISTORICAL DEVELOPMENTS

Observations, measurements, and research obviously are the forerunners of mathematical modeling. Although we think of research and modeling as relatively new, such philosophers as Homer, Plato, and Aristotle speculated about the hydrologic cycle (27). Most of these philosophies were erroneous, but about the time of Christ, Marcus Vitruvius postulated the first correct concepts of infiltration, and is considered the forerunner of those who conceptualized the hydrologic cycle. Many other noted people were involved in varying degrees. Leonardo da Vinci, although much more noted for his paintings in the 15th and 16th centuries, also conceptualized infiltration and resultant springflow.

Perrault (32), who was probably the first to measure rainfall and evaporation, worked in the Seine River basin in the 1670's. Shortly thereafter, Mariotte (26) calculated the flow of the Seine River at Paris from measurements of channel cross section and flow velocity.

The oldest and most famous hydrologic model is the rational formula,

$$Q = CIA \tag{1}$$

where Q is peak discharge in cfs, C is a runoff coefficient dependent upon drainage basin characteristics, I is rainfall intensity in in/hr, and A is drainage area in acres. Although the rational formula is often called the Lloyd-Davis formula (25), the principles were applied by

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Mulvaney in 1851 (29). The first appearance in American literature was in the Transactions of ASCE (22). This "model" was not developed until almost 200 years after the measurements of Perrault and Mariotte.

Sediment transport observers may not be as well known, or observations may not have been made as early, but model development began long before the days of modern computers. DuBoys (8) is one of the "modern" giants in sediment transport modeling with his deterministic model for bedload transport, which he published in 1879. DuBoys (8) was the first to postulate the theory of tractive force in streambed erosion, which has been used and built upon over the years.

In 1895, Kennedy (21) published his work on permissible velocity of flow for the design of stable canals in India. He related velocity (V) to depth of flow (D) as

$$V = cD^m \tag{2}$$

where c and m are coefficients, and c varies with characteristics of bed particles. He found that m was relatively constant for noneroding, nondepositing canals.

Lacy (23) followed up on DuBoy's (8) work with tractive force theory to determine permissible velocities for stable canals in the 1920's. Tractive force theory, as currently used in erosion equations, is

$$\tau_0 = \gamma RS \tag{3}$$

where $\tau_0$ is unit tractive force, $\gamma$ is specific weight of water, R is hydraulic radius, and S is slope of the channel bed.

Sherman (33) published his unit hydrograph theory in 1932, about the time that Lane's (24) famous work was underway in the design of stable canals.

The works of Horton (18, 19) span two decades and several topics that still provide the stimulus for works of others. In 1933, he published his theory on the role of infiltration (18). His interests were not confined to the hydrologic cycle alone; he is also noted for his efforts to quantify geomorphology (19). Although Horton is not well known for his work in erosion, he recognized the importance of complex slopes in erosion/deposition (19). One of the papers in this program session presents a model that considers erosion/deposition from complex slopes.

All of the work thus far had been concerned with canals, rivers, and river basins. However, the Soil Erosion Service and Soil Conservation Service were concerned with conservation of agricultural lands. Erosion experiment stations were established in the 1930's with the responsibility of measuring rainfall, runoff, and soil erosion from small plots. Bennett (2) made his crusade to interest people in the ravages of soil erosion and the need for soil conservation measures on farms to reduce erosion. As a result of the erosion plot research, the first erosion models (equations) were developed. Ellison (10) showed the effect of rainfall energy in sheet erosion by the equation

$$E = KV^{4.33}d^{1.07}I^{0.65} \tag{4}$$

where E is the grams of soil intercepted in splash samplers during a 30-min period, V is the velocity of drops in feet per second, d is diameter of the drops in millimeters, I is the intensity of rainfall in inches per hour, and K is a constant.

Musgrave (30) analyzed 40,000 plot-years of data to develop his relationship to incorporate land characteristics:

$$E = IRS^{1.35}L^{0.35}P_{30}^{1.75} \tag{5}$$

where E is soil loss in acre-inches, I is the inherent erodibility of the soil in inches, R is a cover factor, S is degree of slope in percent, L is the length of slope in feet, and $P_{30}$ is the 2-yr, 30-min rainfall amount in inches.

The Soil Conservation Service (SCS) was responsible for estimating runoff from agricultural lands, and about the time of Musgrave's (30) work, the SCS began a concerted effort to develope rainfall-runoff relationships. The SCS curve number method was developed in the mid 1950's, and several interim editions were published before the present version (37).

About the time SCS began work on the curve number method for runoff estimation, Einstein (9) developed his famous works on bedload functions and bedload transport. Although his work was developed for rivers and other major streams, the transport relationships have been applied on small channels as well.

Wischmeier and Smith (40) reexamined the erosion plot data used by Musgrave (30) and U.S. Weather Bureau rainfall data and in 1958 published their first results toward development of the universal soil loss equation (USLE) (41, 42),

$$A = RKLSCP \tag{6}$$

where A is average annual soil loss in tons/acre, R is a rainfall factor, K is a soil-erodibility factor, LS is a slope length and steepness factor, C is a cropping factor, and P is a conservation practice factor. The rainfall factor is

$$R = \frac{\Sigma EI}{100} \tag{7}$$

where E is the storm energy in foot-tons per acre-inch, and I is the maximum 30-min rainfall intensity in inches per hour.

## RECENT DEVELOPMENTS

The hydrology and the erosion/sediment transport models generally were developed independently. The erosion and sediment transport equations were developed without corresponding hydrologic relationships. All calculations were made with desk calculators or slide rules. It was not until the development of the digital computer that model components were put together. This is really where we are today, and the rest of this paper will be devoted to models with more than one component even though this program session is for erosion/sediment transport models. Models range from deterministic to stochastic with various combinations of the two.

In 1962, Crawford and Linsley (5) published one of the earliest hydrologic simulation models. The model became widely known as the Stanford watershed model (SWM). It used conceptual simplifications of the physical processes for overland flow, interflow, upper and lower zone soil water storage, deep percolation, groundwater storage, and evapotranspiration to estimate streamflow from rainfall records. The model required calibration to specific watershed conditions, and was primarily intended to show how watershed changes affect streamflow.

Glymph and Holtan (15) developed an infiltration-based hydrologic model, known as the USDAHL (U.S. Department of Agriculture Hydrograph Lab) model, to estimate streamflow and uses a concept of soil zones in the watershed. Snowmelt, separation of flow regimes, and ground water contributions to streamflow have been incorporated recently (17).

Passage of the Federal Water Pollution Control Act Amendments, Public Law 92-500, (commonly known as the Clean Waters Act) in 1972 created an awareness among many agencies and consultants of the need for models to simulate processes affecting water quality. This act emphasized the need for mathematical models to evaluate nonpoint source pollution (35). The enactment of PL 92-500 not only made consideration of the several environmental components desirable, it is now essential. Talking about pure hydrology, pure erosion and sedimentation, or pure water quality is no longer enough. The digital computer has made possible the development of comprehensive models that represent the complex interrelated processes.

Some of the models described previously, (that is, the SCS curve number, the USLE, the USDAHL, and the Stanford watershed model), were used later as the basic components, with or without modification, for water quality models. There was little precedent for chemical transport models, especially for upland areas, although diffusion models had been applied in river channel systems. Since water is the carrier of sediment and chemicals, most water quality models were developed by selecting a hydrologic model, and "piggy-backing" sediment and chemistry components to produce a model package.

Crawford and Donigian (4) developed the Pesticide Transport and Runoff (PTR) model with a revised Stanford watershed model (5) as the hydrologic component. The sediment loss component of PTR consists of a part of Negev's (31) relationships for sediment detachment and transport. Although Negev simulated the entire sheet, rill, and channel erosion, the PTR model only uses the sheet and rill erosion components which include the detachment and transport of soil particles by overland flow. Pesticide simulation was included in the PTR model; this was perhaps the first field-scale model for evaluating nonpoint source pollution.

Frere et al. (13) developed an agricultural chemical transport model (ACTMO) with the USDAHL model (17) for the hydrologic component. The erosion-sediment transport component of ACTMO is a modification of the USLE to reflect both rainfall and runoff erosivity and transport processes (12). The erosion component estimates the contribution of rill and interrill sources to sediment load. ACTMO includes a chemical component and was developed for watershed or small basin size areas.

Bruce et al. (3) developed a parametric model for water-sediment-chemical (WASCH) runoff for single storm events. The hydrologic component consists of a retention function, a characteristic function, and a variable state function. Two-stage convolution is used to produce nonlinear response of watersheds. The sediment component of WASCH considers the rill-interrill erosion concepts developed by Foster and Meyer (11), but uses erosion and routing functions for both rill and interrill erosion. Sediment transport capacity in the WASCH model is a function of overland flow discharge rather than velocity. The chemical component of WASCH considers pesticides.

Donigian and Crawford (6) modified the PTR model and the revisions resulted in the Agricultural Runoff Management (ARM) model. Although the model was revised, the original basic components were the same -- the Stanford watershed model for the hydrology component and Negev's equations for the sediment component. A plant nutrient component was incorporated into the new version.

Donigian and Crawford (7) developed a Nonpoint Source Pollutant loading (NPS) model to simulate pollutant contributions to stream channels from nonpoint sources. The NPS considers a maximum of five pollutants from each of a maximum of five different categories of land use. The hydrology and erosion components are identical with those in ARM (6). The water quality component relates pollutants to sediment by specifying pollutant strength or potency factors. The NPS does not have a component for channel processes, but simulates loads of pollutants reaching the stream channels.

Williams and Hann (39) developed a basin scale model to consider surface runoff, sedimentation, and plant nutrients. The hydrologic component is a modification of the SCS curve number model. The USLE was modified for the erosion component by replacing the rainfall energy term with a product of storm runoff volume and peak rate of discharge raised to a power. The plant nutrient component of the model considers most elements of the nitrogen cycle. The phosphorus component of the nutrient model considers only that portion adsorbed to soil particles. The model routes runoff, sediment, nitrogen, and phosphorus to the basin outlet. Linear programming techniques are used to select the best management practices among the alternates considered.

Gianessi et al. (14) developed a water pollution network model, referred to as the RFF model (Resources For the Future), to link sources of pollutants to concentrations in water bodies throughout the nation. The water network identifies 1,051 node points along rivers of the U.S. to correspond with U.S. Geological Survey (USGS) gaging station locations. Each county in the U.S. is assigned to at least one node. The average distance between nodes is 66 miles. Streams were classed by ranges of mean discharges, and USGS periodic stream gaging measurements at the nodes are used to determine velocity at the nodes. The RFF model emphasizes pollutants, including sediment, that enter the streams at node points, and it assumes uniform input between nodes. Loading functions are applied on a county basis. Sediment amounts from construction, forestry, and mining activities are determined by prorating national estimates to each county based on the county's share of employment in these activities and weighted by an estimate of runoff. The RFF model is basically a routing technique for 66-mile river reaches with generalized loadings of pollutants without identity of conservation systems on less than a county basis.

Beasley et al. (1) developed a distributed deterministic model (ANSWERS) for predicting runoff and erosion/sediment transport for different agricultural management systems for basin size areas. The basin hydrologic component (20) describes surface runoff, subsurface flow, and channel flow in a system of square grids laid over the watershed. The infiltration element of the model is basically the infiltration function of the USDAHL model (17). The erosion component of ANSWERS is a modification of the USLE (41). Two soil detachment processes were included:

(a) rainfall detachment, described by Meyer and Wischmeier (28), and (b) overland flow detachment, described by Foster and Meyer (11). Sediment transport of both overland and channel flow is based on transport capacity. Channel erosion is assumed to be negligible, and only deposition is allowed in channel flow.

Simons et al. (34) developed an event model to predict runoff and sediment from small basins. The hydrologic component consists of the kinematic wave model for overland flow and channel flow with infiltration approximated by the Green and Ampt (16) infiltration equation. The sediment component considers erosion by raindrop splash and shear stress of overland flow. Raindrop erosion is expressed as a power function of rainfall intensity and an empirically determined erodibility factor. Erosion by overland flow uses a detachment coefficient that requires calibration for specific soils. Sediment transport in the model considers transport capacity for individual sediment sizes. Bedload and suspended load transport are estimated.

Wade and Heady (38) developed an economic model based on agricultural crop production considering sediment as a pollutant. The model, referred to as the National Water Assessment (NWA) model, does not contain a hydrologic component, but estimates average annual erosion with the USLE (41) for 105 Producing Areas (PA) covering the U.S. Sediment delivery ratios, estimated for each PA by using measured and computed data, are used to estimate sediment delivery. River basin sediment accounting is made by sediment ratios estimated for the rivers of the PA's. River flow is not used in the accounting system, and the transport ratios are determined subjectively to give river sediment yields. Where lakes are involved in the river systems, estimated trap efficiencies are used in determining transport ratios. Linear programming is used with the NWA model to consider five sediment control alternatives to calculate the associated sediment yield to the oceans from 18 river basins of the United States.

Engineers and scientists of the U.S. Department of Agriculture, Science and Education Administration-Agricultural Research (26) developed a field-scale model to estimate chemicals, runoff, and erosion from agricultural management systems (CREAMS). The CREAMS model is a physically-based, daily simulation model that estimates runoff, erosion/sedimentation, plant nutrient and pesticide yield from field-size areas. The hydrologic component consists of two options: the SCS curve number model (37) and an infiltration-based model (16) for estimating surface runoff. The erosion component maintains elements of the USLE, but includes sediment transport capacity for overland flow. A channel erosion/deposition feature of the model permits consideration of concentrated flow within a field. The chemistry component considers dissolved and adsorbed plant nutrients and pesticides.

The nonpoint source pollution models are summarized in Table 1. The table lists the basic hydrology, erosion/sedimentation, and chemistry components.

## SUMMARY

Various erosion and sediment transport models have been developed over the past 100 years, and hydrologic models have evolved during the last 130 years. Early modeling efforts were primarily for river basins and canals. Field hydrology and erosion models have evolved over the

TABLE 1.—NONPOINT SOURCE POLLUTION MODELS, BASIC COMPONENTS, AND SCALE OF APPLICATION

| MODEL (REFERENCE) | DATE | COMPONENT | EROSION/SEDIMENTATION COMPONENT | CHEMISTRY COMPONENT[1] | SCALE OF APPLICATION |
|---|---|---|---|---|---|
| PTR(4) | 1973 | SWM | Negev | PEST | Field |
| ACTMO(13) | 1975 | USDAHL | Modified USLE | PEST, PN | Basin |
| WASCH(3) | 1975 | Parametric | Parametric | PEST | Field |
| ARM(6) | 1976 | SWM | Negev | PEST, PN | Field |
| NPS(7) | 1976 | SWM | Negev | None | Basin |
| ANSWERS(1) | 1977 | USDAHL Infiltration, kinematic flow, channel routing. | Interrill-rill detachment overland and channel flow transport capacity. | None | Basin |
| Simons et al. (34) | 1977 | Infiltration, kinematic flow, channel routing. | Raindrop and overland flow detachment and transport capacity, channel flow detachment and transport capacity. | None | Basin |
| Williams(39) | 1978 | SCSCN | Williams-Modified USLE. | PN | Basin |
| Wade and Heady (38) | 1978 | Mean River Flow | Sediment delivery ratios, sediment transport ratios. | NONE | Basin |
| RFF(14) | 1978 | Mean River Flow(?) | Loading Functions | PEST, PN | Basin |
| CREAMS(36) | 1980 | SCSCN, Infiltration | Interrill-rill detachment; overland flow transport capacity; concentrated flow detachment and transport capacity; impoundment deposition. | PEST, PN | Field |

[1] PEST = pesticides; PN = plant nutrients

last 40 years. The development of the high-speed digital computers brought about a new era in model development. Only in the last 10 years have comprehensive models evolved. This program session is designed to present some of the more important erosion/sedimentation models.

Examination of the erosion model reveals that the Universal Soil Loss Equation (42) is the basic element of most models. The USLE represents a significant development in the history of models, and this significance is recognized by the many modifications to adapt it to storm erosion predictions.

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