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Systems for Evaluating Nonpoint Source Pollution -- An Overview

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A SYSTEM OF MODELS FOR EVALUATING NON-POINT-SOURCE POLLUTION—AN OVERVIEW

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PREFACE

The pollution of the aquatic environment by sediments, nutrients, and pesticides is one of the unfavorable impacts of agricultural activity. These kinds of pollution are very complex phenomena in themselves but become even more complicated because they are very often interrelated and all are based on rather complex hydrological and hydrogeological processes. It is obvious that the systems approach is the best tool for assessing pollution from agricultural land (non-point-source pollution) and for quantifying its changes under various alternative agricultural management practices.

A large, qualified group of experts is now tackling this problem in the United States under the U.S. Department of Agriculture, Science, and Education Administration—Agricultural Research. The ultimate goal of this group is to develop a system of mathematical models dealing with non-point-source pollution at the field level. This corresponds to one of the objectives of the IIASA task on "Environmental Problems of Agriculture" [1].

Dr. Walter Knisel, a coordinater of this US group, was invited by IIASA to participate in the planning workshop held at IIASA June 27-30, 1978. Later he was nominated by USDA-SEA-AR to liaise between USDA-SEA-AR and IIASA. The following paper was presented and discussed at the aforementioned workshop and reflects the US basis for our cooperation.

Gennady Golubev
Task Leader

SUMMARY

The approach of the US working group to the development of a hierarchy of mathematical models dealing with non-point-source pollution at the field level is described. The objective of the group is to use this system of models for assessing non-point-source pollution, quantifying responses from alternative management practices, and evaluating the best ones. Each model should be simple, but physically based. The following phenomena are described consecutively, with discussions of approaches to their modeling: surface and subsurface flow, deep percolation, erosion, sediment transport, and dissolved and adsorbed chemical output due to use of fertilizers and pesticides. The system is not considered to be an end in itself, but a first step towards the development of user-oriented comprehensive models.

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INTRODUCTION

The U.S. Department of Agriculture, Science and Education Administration--Agricultural Research (USDA-SEA-AR) has begun a national research project to develop systems for evaluating non-point-source pollution. Emphasis is being placed on field-scale systems, since management practices will be designed and evaluated on a farm basis. Longer-term efforts are being organized to consider watersheds and basins. Approximately 50 scientists are participating in the overall project. In 1978, state-of-the-art models are being assembled and tested for applicability. This overview describes the current year's efforts and presents some of the problems and approaches that must be considered in the system development.

The principal objective of the project is to develop a hierarchy of mathematical models for use at a field level to (1) assess non-point-source pollution, (2) quantify responses from alternative management practices, and (3) evaluate best management practices. Either existing models or some modifications thereof will be assembled for agency use. The models must be simple, physically based, and capable of simulating surface and subsurface flow, deep percolation, erosion, sediment transport, and dissolved and adsorbed chemical output from fields under different management practices. The system is shown schematically in Figure 1. Precipitation, radiation, and temperature are the driving forces of the watershed system, together with man's management of the system through land use, cultural practices, and the use of chemicals. Output from the system includes surface runoff, which results in erosion and sediment transport and the associated dissolved and adsorbed chemicals. Some infiltrated water may become subsurface flow and/or percolation, both of which may carry dissolved chemicals. Evapotranspiration is shown as an output since it affects the uptake of chemicals by the plants.

HYDROLOGIC COMPONENT

The hydrologic component must be capable of representing a wide range of conditions across the Land Resource Areas (LRA) of the nation. The various flow regimes are shown in Figure 2. The schematic shows relative magnitudes of rainfall, snow, evapotranspiration, surface runoff, subsurface flow, and deep percolation for selected regions of the United States. Although the width of bars for each component is scaled to indicate magnitude, the figure is somewhat generalized to represent the varied conditions

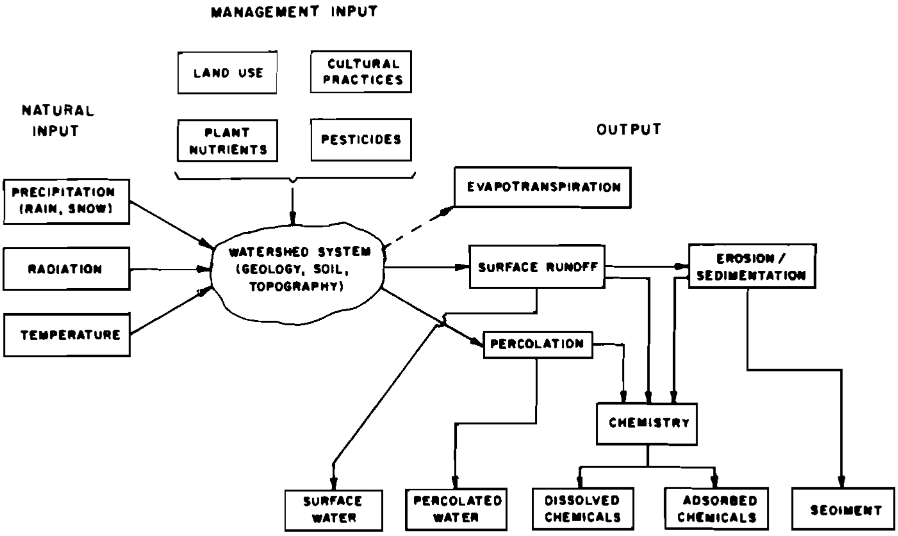
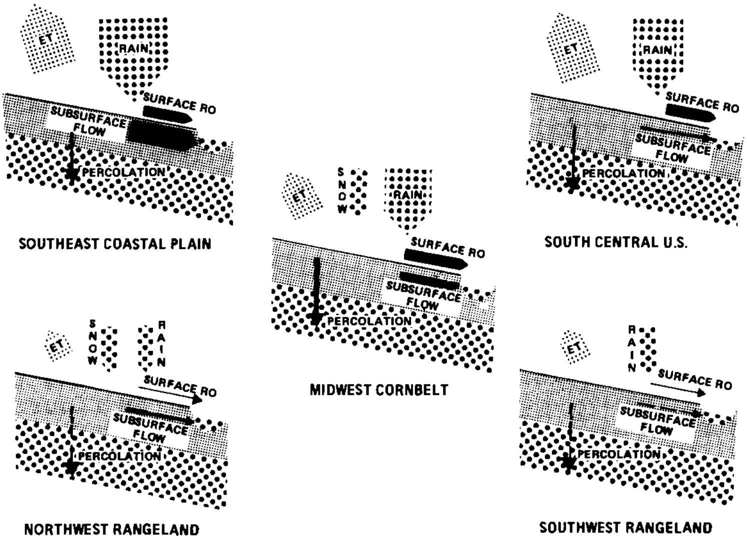


Figure 1. Flow chart of system for evaluating non-point-source pollution.



SOUTHEAST COASTAL PLAIN

MIDWEST CORNBELT

SOUTH CENTRAL U.S.

NORTHWEST RANGELAND

SOUTHWEST RANGELAND

Figure 2. Schematic representation of water balance for selected locations in the United States.

that models must handle. Also, the various hydrologic components indicate the relative potential for erosion, dissolved chemicals, and adsorbed chemicals. For example, the potential for dissolved chemicals in the subsurface flow is greater in the Southeast Coastal Plain than in the South Central United States because the subsurface component is larger, even though rainfall amounts are not vastly different.

Models for evaluating non-point-source pollution must be capable of differentiating between such conservation practices as contour tillage, strip cropping, inpoundment-type terraces, and no-till cropping systems. This is obviously not an all-inclusive list, but to some extent it indicates the importance of such practices, particularly as they affect erosion potential, plant nutrient runoff, and the wide range of pesticides that might be used. For example, no-till corn is recommended in many parts of the United States, especially because of its lower energy requirement. Such practices may have conflicting consequences. In the Cornbelt, no-till planting is commonly done in previous-crop residues. This often results in heavy insect carryover, and a wide range of insecticides may be needed for adequate control. The crop residue reduces raindrop impact and splash erosion. However, dense residue will also reduce evaporation from the soil surface and, depending upon the temporal distribution of rainfall, surface runoff may be greater than from conventional tillage. In the Southeast, no-till corn is often planted in fescue grass sod killed with a herbicide such as paraquat, which increases the pollution potential from the herbicide.

The most significant potential for non-point-source pollution in the United States is in the intensively farmed areas of the Southeast, Midwest, and Great Plains. There are also pollution problems in the rangelands of the Western United States. Sediment is the biggest pollutant but plant nutrients and herbicides also cause concern. Range management practices must be considered in the systems to estimate non-point-source pollution.

Two methods are being evaluated for predicting runoff from field areas. One is the USDA Soil Conservation Service (SCS) curve number system [2] as adapted by Williams and LaSeur [3]. The system relates runoff to total storm rainfall with a family of curves dependent upon hydrologic soil group, antecedent soil moisture, land use, and practice. Figure 3 shows the rainfall/ runoff relationship. The inset diagram shows the relationship between the initial abstraction of rainfall and the infiltration curve superimposed on the rainfall histogram. The inset figure is merely for definition. It does not indicate that storm duration or intensity is used in determining runoff volume. Initial abstraction is considered as a constant proportion of total soil water storage irrespective of duration and intensity of rainfall. The curve number method is simple to apply.

The second method is an alternative approach developed by Smith [4]. The concept, shown in Figure 4, considers the initial

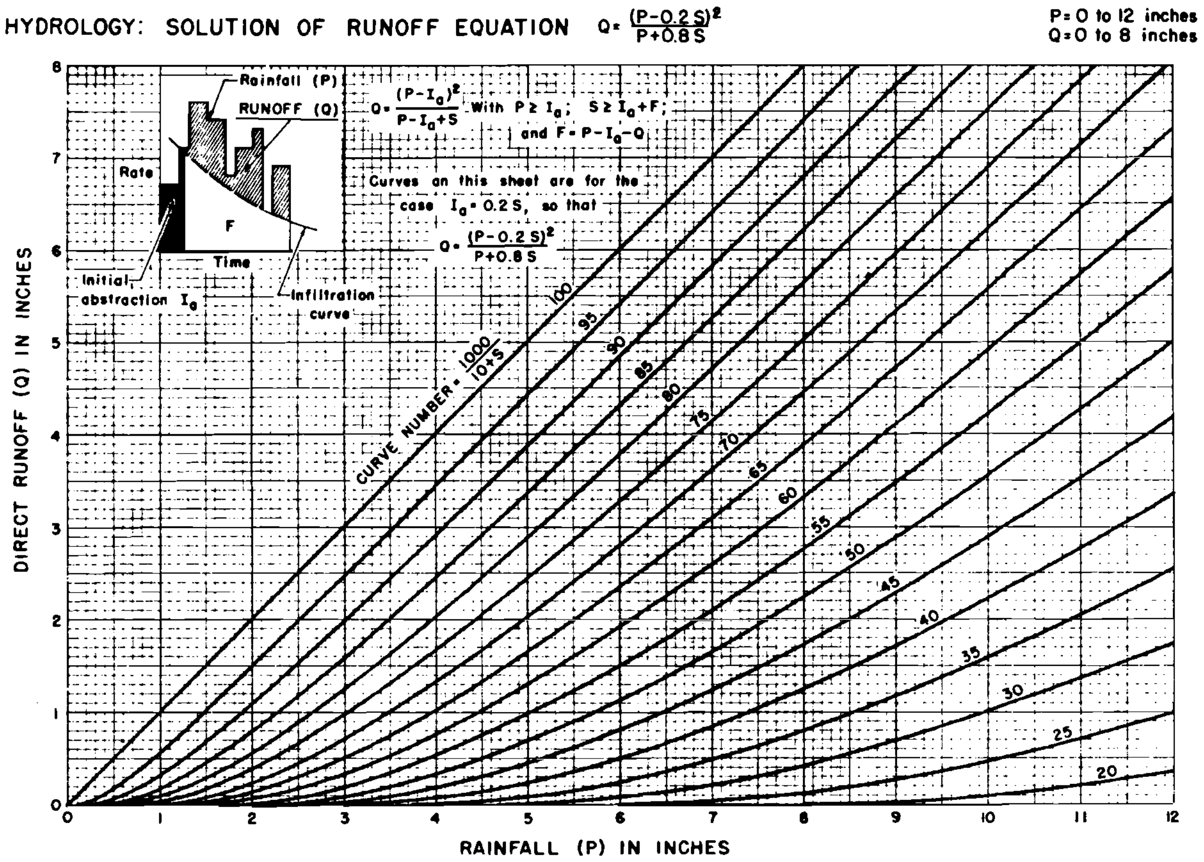


Figure 3. Soil Conservation Service curve number method of storm runoff estimation (courtesy of SCS).

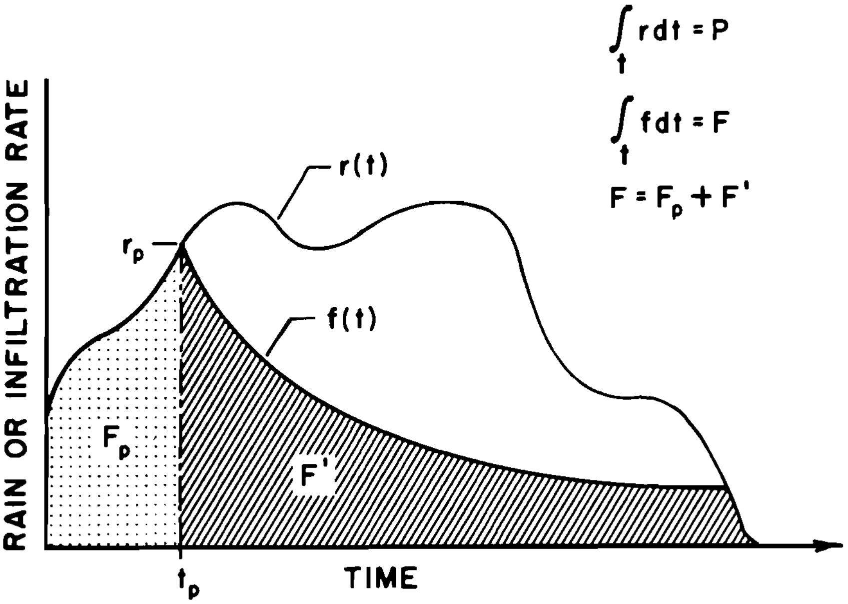


Figure Schematic representation of runoff model using infiltration approach.

Source: [4].

abstraction of rainfall based on soil water deficit and rainfall intensity. In Figure 4, r is rainfall rate, f is infiltration rate, t is time, P is total rainfall, F_p is infiltration to time of ponding, F' is infiltration after time of ponding, and F is total rainfall infiltrated during the storm. When rainfall intensity exceeds the infiltration rate of the soil, runoff begins. Runoff is determined as the accumulation of rainfall excess, i.e., intensity greater than the hydraulic conductivity. By using breakpoint rainfall data, Smith's model responds to different storm intensities and durations.

Runoff volumes are estimated by the two models, but hydrographs are not being generated in this initial effort. Peak rate values of runoff are needed for the erosion/sedimentation component, as will be discussed later. A method is being developed to estimate peak rate from 15-minute excess rainfall intensity. Conservation practices will affect peak rates more than runoff volume. For example, a terrace system on a field will produce a significantly lower peak rate than an unterraced field. If the runoff volume is the same, this will result in different runoff durations and,, ultimately, different hydrograph shapes.

A considerable number of research watersheds in 8 Land Resource Regions (LRR) and 13 LRAs of the United States have been selected for the initial testing of the systems developed to determine their accuracy and applicability. (One LRR may contain between 3 and 22 LRAs.) The watershed locations are shown in

Figure 5. Hydrologic data are available on all watersheds, but sediment data are available for about two thirds only, and chemical data for about one third of the watersheds. The testing of the model for wide-scale applicability with these limited data is minimal, but more extensive testing is planned.

The two hydrologic models are being statistically evaluated for the selected watersheds to determine which model's behavior conforms more closely to observed runoff in the different LRAs. The testing also will provide an indication of the expected accuracy of estimates.

Evapotranspiration is estimated by the Leaf Area Index (LAI) method [5]. Evapotranspiration controls soil moisture, which in turn affects the transformation of chemicals in the soil and their uptake by plants. The hydrologic component also contains a snowmelt routine given by Stewart et al. [6]. The hydrologic component is structured such that the evapotranspiration and snowmelt routines can be replaced as improvements are developed.

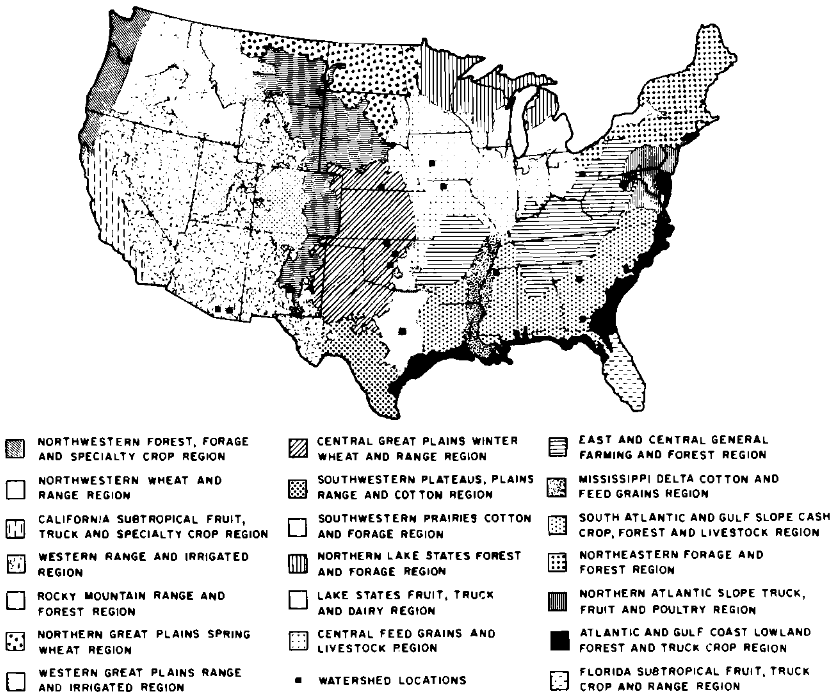


Figure 5. Land Resource Region map of the United States showing locations of research watersheds selected for model testing.

EROSION/SEDIMENTATION COMPONENT

Principles of the erosion/sedimentation component are shown in Figure 6 [7]. Raindrop impact detaches soil particles, and the overland flow carries them into some concentrated flow. Concentration of runoff may result in rilling. With continued development of rills, the sediment load may exceed the transport capacity of the water and settle, or, if the transport capacity is greater than the sediment load, gullying may occur.

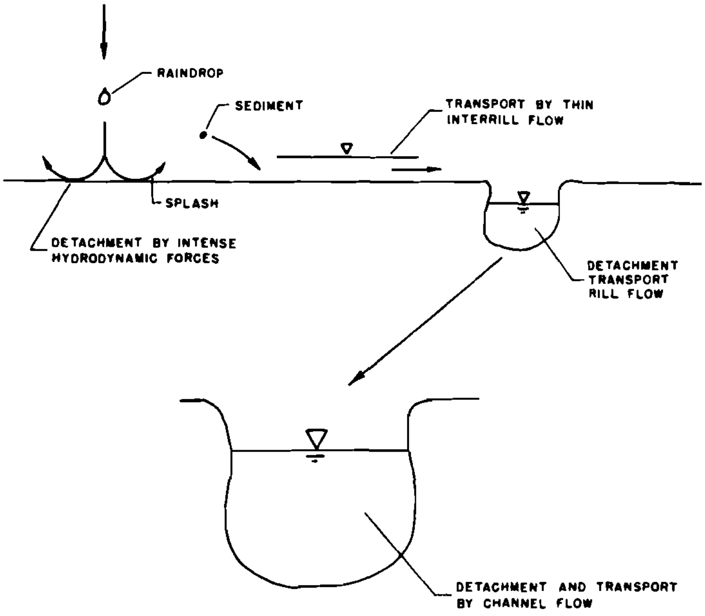


Figure 6. Schematic representation of erosion and sediment transport processes.

Source: [7].

The Universal Soil Loss Equation (USLE) was developed to predict average annual soil loss for different soils, climate, slope, cover, and practices [8]. The well-known USLE is expressed as:

$$A = RKLSCP \qquad (1)$$

where A is average annual soil loss, R is rainfall energy, K is the soil erodibility, L is slope length, S is slope percent, C is cover, and P is the management practice. The USLE was not developed to predict storm erosion, which is necessary for predicting chemical transport. However, it contains terms that consider management practices, which are essential for the systems being developed. Foster et al. [9] and Williams [10] have modified the USLE for application on a storm event basis. Foster's modification is given as

$$E = (aR + bQq^{c})KLSCP \tag{2}$$

where E is storm erosion; Q is runoff volume; q is peak rate of runoff; a, b, and c are coefficients; and the other terms are the same as in Equation (1). Foster's modification contains the rainfall detachment potential, aR, and a transport potential, bQq^{c}. Williams' modification is expressed as

$$E = a(Qq)^{b}KLSCP \tag{3}$$

where a and b are coefficients and the remaining terms are the same as above. In Equation (3), the detachment and transport capacity is expressed by the product of runoff volume and peak runoff rate. These two modifications are being assessed against watershed data to determine their relative accuracy.

In estimating average annual erosion, as with the USLE, the system is considerably smoothed. However, a number of problems must be considered when estimating storm erosion, particularly in relation to adsorbed chemicals. For example, equivalent slope length and steepness for complex slopes is sufficient for estimating annual erosion, but erosion/deposition is important on a storm event basis for estimating chemical transport. Slope shape has a pronounced effect, as shown in Figure 7. Relative sediment yields for the various slope shapes indicate the compounding nature of complex slopes. Sediment yield for a concave slope decreases for slope lengths greater than about 80 m because of deposition in the flatter portions, as shown in the upper part of Figure 7. These effects must be considered in the erosion/sedimentation model.

Interterrace erosion, with deposition in the terrace channel, is another problem that must be treated with the erosion/sedimentation model. Terraces effectively control erosion by breaking the slope length. There is erosion between the terraces, and varying amounts of material are deposited from the channel flow, depending upon particle size, terrace gradient, and flow retardation of the channel cover. A similar problem that needs evaluation is the further transport of sediment into and through the grassed terrace outlet. Grassed waterways are sometimes recommended for stabilizing concentrated watercourses in fields where natural overland drainage is a problem. Sediment deposition in the grassed waterway must be treated with the erosion model. Not only is there concern about the deposition of sediment in transit, but consideration must be given to grassed waterway maintenance, overflow, and meandering.

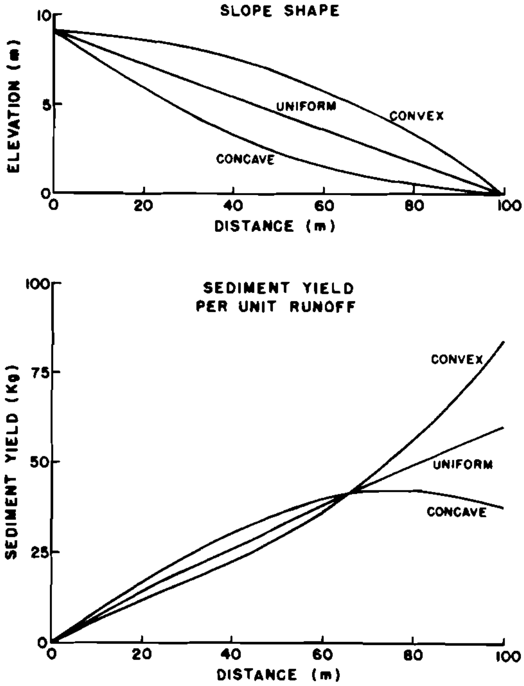


Figure 7. Relation between slope shape and sediment yield for overland flow. After: [11].

Gully erosion and head-cut migration require special treatment. Gullies are often the critical source of sediment, both in cropland and in rangeland where abandoned or retired cropland has been planted with grass. Eroded material from the gullies is the principal pollutant, since plant nutrients and pesticides are not generally applied. For the purpose of estimating nonpoint-source pollution some type of sediment "accounting" may be necessary to distinguish between sources. In short-term field-scale modeling, attention is not being given to gullies, but they must be included in longer-term more comprehensive models.

Sediment particle size is important in adsorbed chemical transport. Even if a relatively large amount of material were eroded from a field, if most of the particles were silt- and sand-grain-sized, the potential for adsorbed chemical transport would be low. Conversely, if most of the eroded material were clay-sized, the potential chemical movement would be relatively high. An equally important consideration is aggregate transport. Aggregates are made up of individual soil particles, but do not move or settle as equivalent single-grain particles. This is a problem for two reasons: sample collection, and sample processing in laboratories. Only total load samplers and/or bedload samplers can include aggregates in the sample. Pump samplers and integrating samplers generally do not have intakes large enough to collect aggregates. Even when samples containing aggregates are collected, the normal laboratory procedure completely destroys the aggregates, and particle-size analysis reflects only the single-grain material that makes up the aggregates. The potential for adsorbed chemical transport is relatively high for aggregates. Particle-size routing routines are being incorporated into the erosion model. Relative success in particle-size routing in river basins has been attained by Li et al. [12]. However, the smoothing effect of basin scale may be a simpler process to model than that of field-scale areas. Particle-size distributions for four Cornbelt soils are shown in Figure 8. The relative importance of the sediment for chemical transport can be seen be the relative percentages of clay for each soil.

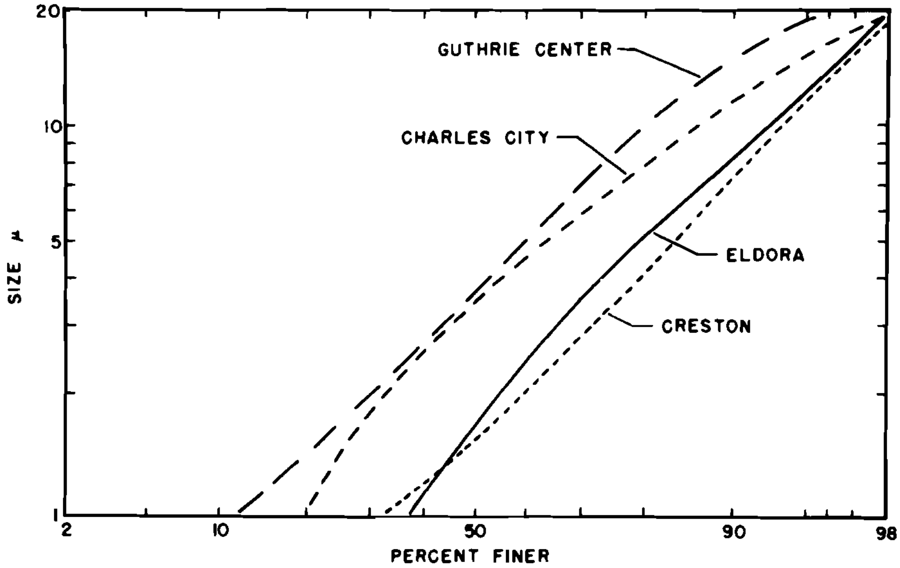


Figure 8. Sediment particle-size distribution for four soils in Iowa (courtesy of J.M. Laflen, USDA-SEA-AR, Ames, Iowa).

CHEMICAL COMPONENT

Chemical transport is highly complicated because large numbers of different compounds which have different degradation characteristics, adsorption characteristics, solution components, methods of application, mechanism of transport, volatilization, and frequency of application are used. The nitrogen and phosphorus cycles in agriculture are very complex [6]. The continuous nitrification/denitrification process constantly changes the form of nitrogen. Nitrogen leaves the field in surface runoff with organic matter. Also, if subsurface flow and percolation are significant, considerable amounts of nitrate can be leached. Most of the nitrogen input is in the form of commercial fertilizers and animal waste, but natural input from rainfall may be significant and must be considered in evaluating non-point-source pollution. The largest portion of nitrogen is taken up by plants and removed from the field by harvest, or partially removed by harvest and partially returned to the soil as crop residue. Accounting for the various forms and compartments is important in simulation of nitrogen loss. The present modeling efforts will attempt to simplify the nitrogen cycle. Uptake by plants will be related to evapotranspiration. Mineralization will be approximated by an exponential function of time, soil water, and temperature. Accounting procedures will be used to estimate nitrate available in the root zone, and percolation estimated in the hydrology component will be used to estimate nitrate leached. Nitrogen lost from a field in surface runoff will be estimated as a product of the soluble nitrogen and an extraction coefficient. Also, an accounting will be necessary to estimate the nitrogen transmitted to the soil profile by infiltration.

Phosphorus is transported primarily as material adsorbed on soil particles in erosion and sediment transport. Soluble phosphorus in runoff is estimated by an extraction coefficient. Considerable amounts of orthophosphate phosphorus have been observed in watersheds with high concentrations of dairy animals [13]. In some instances, this may approach point-source pollution.

The complex nutrient cycles must be simplified to provide workable models that users will accept. A simplified nutrient pollution flowchart is shown in Figure 9. The various segments

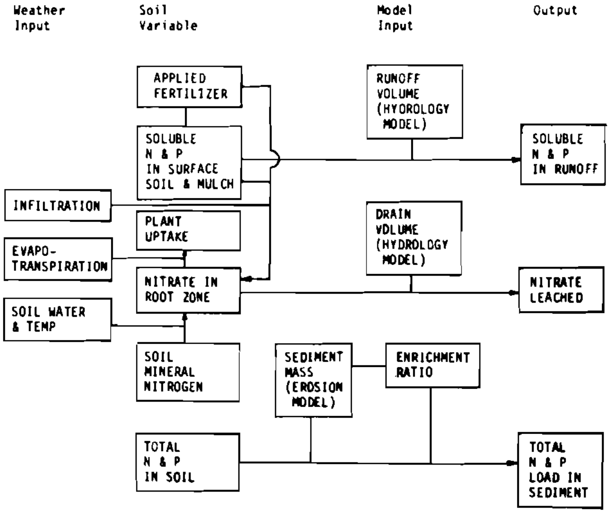


Figure 9. Nutrient pollution flow chart.

Source: [14].

will require estimates of partitioning coefficients and enrichment ratios. Several difficulties arise in model verification. For example, some research locations analyze runoff water samples for nitrate only; others look at total nitrogen; soil nitrogen concentrations are not determined. Such fragmented information makes it difficult to obtain sufficient total data for testing model concepts.

Non-point-source pollution from pesticides is very complex because there are thousands of different chemical compounds used and thousands of formulations. Each compound has a different half-life, persistence in soil, chemical types, and mode of transport. Stewart et al. classified herbicides into thirteen different chemical types, and insecticides and miticides into seven [15]. However, the chemical type does not determine the principal means of transport, i.e., soil or water fraction, and thus the partitioning coefficients are different for each pesticide. Figure 10 suggests some of the problems encountered and coefficients needed in modeling pesticide transport.

The method of application is also an important consideration. Pesticides may be applied as spray on bare soil or on a crop canopy. When applied to the canopy, some fraction of the pesticide is intercepted by the foliage or by residue on the soil surface, and some fraction reaches the soil surface. The degradation of the chemical on the soil will be different from that on the foliage. When it rains, a portion of the foliar material will be washed off the plants onto the soil, which changes the concentration at the soil surface when runoff begins. Some pesticides are incorporated into a finite depth of soil with various equipment, resulting in different mixing conditions. Incorporated pesticides are not photodegraded, but high soil-water content and high surface temperatures may result in large volatilization losses. Chemicals applied by spray are subject to drift and volatilization, especially if applied from aircraft, and that portion reaching the target is difficult to estimate.

The partitioning of chemicals into dissolved and adsorbed portions is also a problem in modeling. In the earlier discussion of erosion/sedimentation, it was mentioned that sediment particle size is important. Particle size tells only part of the story; mineralogy of the clay fraction must also be known to estimate chemical adsorption. Soil surface condition at the time of chemical application and rainfall is very significant in movement of the chemicals into the soil profile and in estimating chemical concentration in the soil at the active water/erosion interface. Bulk density varies with soil type and with water content for the same soil. Tillage changes bulk density radically and suddenly. It is virtually impossible to identify and accurately describe all the conditions and parameters affecting chemical transport. The processes must be simplified considerably to achieve a useful model for chemical transport.

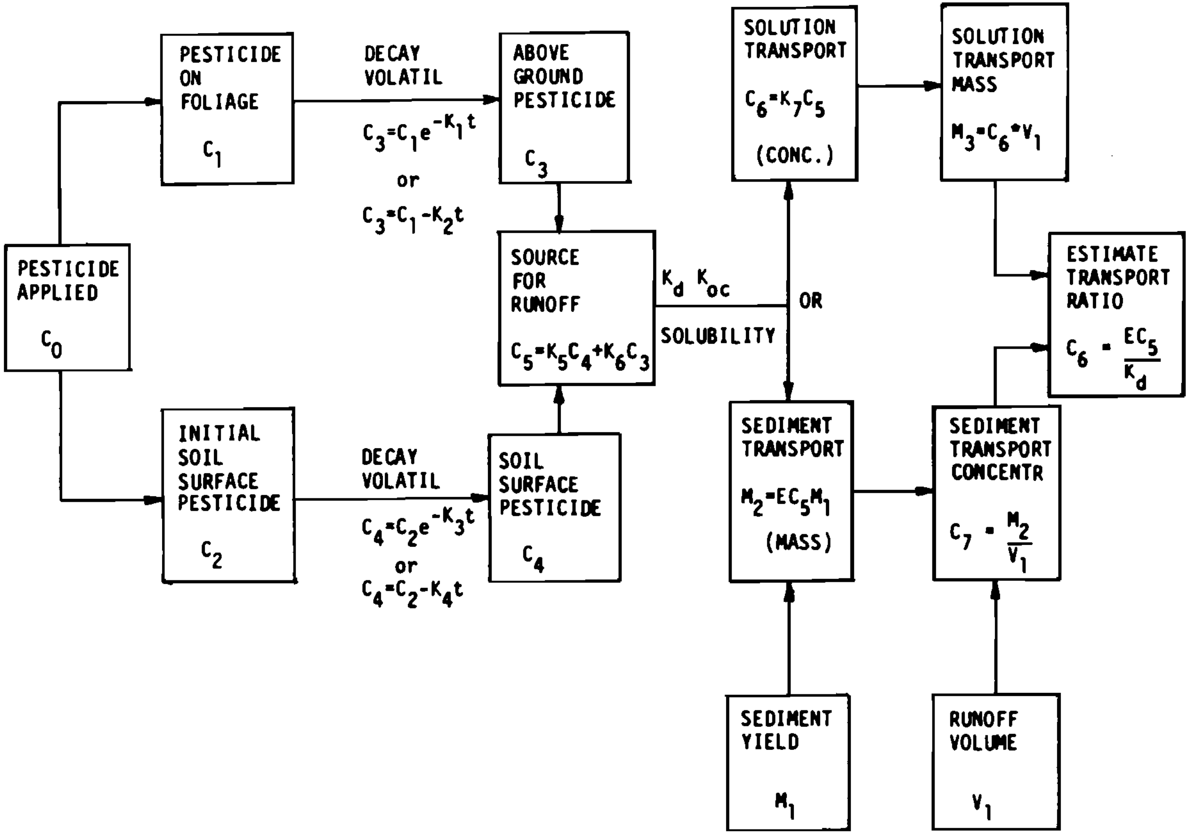


Figure 10. Flow chart for estimating pesticide runoff as storm totals or average storm concentrations.

Source: [16].

FUTURE CONSIDERATIONS

The systems being developed for evaluating non-point-source pollution are not to be considered as an end in themselves, but rather as a first step towards the development of user-oriented comprehensive models. Data are not sufficient for testing all facets of the models, especially for the chemicals. The initial models will help identify areas in which research is needed, and some well-planned data collection programs must be developed to adequately test model concepts. These initial efforts provide a common focal point for a sound water (quantity and quality) management program and for resource conservation.

Future efforts will consider more comprehensive models for field-size areas and will give more attention to watersheds and basins. The more comprehensive field-scale models may be entirely different from, or may be improvements of, the initial models, depending upon levels of technology and development at the time. Comprehensiveness will not be measured by numbers of variables or complexity. Simplicity and user acceptance will continue to be the criteria for model improvements and refinement.

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