United States
Environmental Protection
Agency

Research and Development

Environmental Research
Laboratory
Athens GA 30613

EPA-600/S3-84-028 March 1984

EPA

Project Summary

Simulation Model for Watershed Management Planning

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Evaluation of nonpoint source pollution problems requires an understanding of the behavioral response of an ecosystem to the impacts of land use activities on individual components of that ecosystem. By analyzing basic ecosystem processes and impacts of land use activities on specific factors governing production and transport of nonpoint source pollution, it is possible to predict cause-effect relationships between these activities and water quality. To facilitate these predictions, a simulation model for evaluating alternative agricultural and silvicultural practices as a function of both environmental and management parameters was developed.

The generalized planning model may be used to predict watershed response to land use including both planned management practices and unplanned activities associated with catastrophic events. Nonpoint source pollution from these activities and events may include loading of streams by: 1) sediment from surface erosion, mass wasting, and channel bottom and bank erosion; 2) thermal energy; 3) biological oxygen demanding contaminants; 4) organic debris; 5) nutrients and dissolved solids; 6) pesticides; and 7) other waste materials either in solution or adsorbed to sediments. The model consists of a soil-plant-atmospheric water component for adjusting soil moisture as a function of evaporation, evapotranspiration, soil water hydraulics, and snowmelt; a kinematic wave surface water routing component; a hydraulically based sediment yield component; a subsurface flow component; a temperature and dissolved oxygen component; a pollutant routing routine; and streambank erosion and forest litter routing routines. The model is presented in two volumes — one describing the model theory and formulation and the second providing a user's manual with an example application.

This Project Summary was developed by EPA's Environmental Research Laboratory, Athens, GA, to announce key findings of the research project that is fully documented in two separate reports (see Project Report ordering information at back).

Introduction

Analysis of nonpoint source pollutant loads from forest management activities can be enhanced by the mathematical modeling process. Development of successful modeling approaches, however, must meet criteria related to watershed management goals and the specific context of forest management. Temporal resolution should be both short- and long-term. Forest management for timber production is usually related to tree life. Consequently, any analysis having a time horizon of less than one rotation is inadequate for proper long-range timber management planning, and the temporal resolution for long-range plans should be 20 to 40 years.

Specific management plans and activities are very often limited to small watersheds. Many watersheds subject to water quality management planning, however, are quite large and often encompass complete river basins or sub-basins. As a consequence, spatial resolution should accommodate small watersheds within river systems as a whole. The model should be widely applicable, i.e., regional specificity should be reflected in model parameters, not in the model itself. The only feasible way to develop such a model is to consider the physical significance of the governing processes. Only such a physically based model can provide an appropriately general cause-effect relationship between forest activities and water quality.

In addition to the above criteria, some additional guidelines were adapted for model subcomponent development: 1) models should use the simplest approximations of physical processes that provide accurate representation without sacrificing necessary sensitivity to management criteria; and 2) implementation of theory should provide routines that are efficient in computer time and computer memory requirements. To satisfy these guidelines whenever possible, formulations were used that lead to equations having analytical solutions. Usually an analytical solution to a system of equations or a particular differential equation results in a more efficient algorithm than a numerical approach. In some cases, however, boundary condition requirements dictate the circumstances under which an analytical solution may be applied.

Management activities modeled include both planned management practices — such as road construction, watershed management, stream improvement, low head impoundments, fertilizer applications, foliage production and grazing, mechanical site preparation, and disposal of wastes by land treatment — and unplanned activities associated with catastrophic events such as heavy runoff after rain storms.

The basic model components are: (1) soil-water balance, (2) erosion water and sediment routing, (3) pollutant routing, (4) heat and dissolved oxygen routing, (5) streambank erosion, and (6) vegetative litter routing. A flow chart for the model showing the interaction of these components is presented in Figure 1.

Soil-Water Balance

Since infiltration exerts a fundamental control on the storm water runoff hydrograph, any long-term hydrologic simulation must have a component for calculating the changes in soil moisture content as a function of time. The primary processes affecting the amount of soil moisture are infiltration, percolation, evaporation, evapotranspiration and drainage. These interrelated processes involve hydrologic, biologic, atmospheric and soil-specific aspects. Therefore, a physically based water balance model must simulate all of these aspects and properly account for their interrelation. PROSPER, a widely tested water balance model, was modified for use in this application. It was possible to adapt model subroutines to a particular watershed environment by modifying the methods used to calculate the resistances to water flux through the soil and plant components.

PROSPER is a plant-atmosphere-soil water flux simulation that implements an energy balance and an aerodynamic calculation of evapotranspiration using the Penman method with a multilayer Darcian soil model. The model simulates the fluxes of water through the soil and plants in response to atmospheric and solar conditions. The simulation uses a time increment of one day. All hydrologic, plant and atmospheric processes are averaged daily. The model as implemented uses an electrical circuit analogue for the soil and plant system. The current in the circuit loop represents the water flux through the respective soil, plant, or atmospheric component.

Since PROSPER was written for predicting daily variations in water flux, its formulation was found to be inadequate for the prediction of infiltration and interception on a storm-by-storm basis. Further, since the time history of infiltration during a storm is particularly critical when determining water and sediment runoff, the effects of watershed management on infiltration parameters could not be properly simulated without modification to PROSPER. Therefore, the water balance was adjusted to include a modified Green-Ampt infiltration component for layered soils for more precise determination of storm water runoff and a storm water interception routine. Both infiltration and interception components provide greater sensitivity to management activities in the watershed than the original PROSPER, and the infiltration routine provides for the interfacing of the water balance component with the water and sediment routing and water quality subprograms.

Resistances in the current analogue are formulated in terms of physically defined watershed moisture parameters. These parameters include soil layer hydraulic conductivities, root resistance, and empirically measured, species-specific stomatal resistances. By varying the values of these parameters to fit the physical setting of the watershed, it is possible to achieve a more precise representation of physical processes than provided by previous simulations of similar scope.

In many watersheds the most significant contribution to runoff is from snowmelt. Often the most severe erosion and sedimentation events occur as combinations of high intensity spring rainfall and snowmelt runoff. This aspect of the hydrologic cycle is particularly important in high altitude watersheds of the western United States and in northern latitudes. After examining available snowmelt models, it was believed that a simulation model originally developed for snowmelt prediction in Colorado subalpine watersheds was best suited for this application. It is a mechanistic approach with data requirements consistent with previously described planning model components, in particular, evapotranspiration and water balance components. The snowmelt model as formulated is designed to provide daily runoff water yields, and therefore, it requires modification to interface with the other water balance routines.

The snowmelt model is a combination of the fundamental laws of conservation of mass (water balance) and conservation of energy. The thermal state of the snowpack is described by the calorie deficit of the pack on any given day. The calorie deficit is defined to be the number of calories (per unit area) required to bring the pack to an isothermal state at 0 °C. It is assumed that no melt can occur until the pack has reached this state. The general scheme of computing snowpack accumulation, temperature change, and melt begins with an assessment of the effects of the day's precipitation, if any, on the pack. This includes the effect of the snow or rain introduced to the pack at the average air temperature, as well as the addition of water to the pack as snow or as rainfall. After the effect of rainfall has been assessed, an energy balance calculation is begun with a determination of the net radiation input (or loss) to the snow pack. Depending on the thickness of the snowpack and the amount of free water existing in the pack, a thermal diffusion model is used instead of a radiation balance. The new pack temperature is calculated using either the thermal diffusion model or the radiation balance directly. Based on the new temperature, a new calorie deficit or melt is calculated, and the simulation proceeds to the next day's precipitation and radiation data. Water balance relations are adjusted daily based on the above outcome.

The original snowmelt model was designed to produce daily runoff water yields. As in the previously discussed case, this type of runoff description is inadequate for prediction of the water hydrographs required for simulation of nonpoint source pollution transport. A means for transforming the melt water volume into a snowmelt hyetograph is required. Since the melt occurs in response to the input of solar energy, it seems reasonable to approximate the snowmelt hyetograph by distributing the melt over the sunshine period using the hourly insolation divided by the total daily insolation as a weighting function. Since hourly measurements of insolation at the snowpack are not usually available, it is assumed that the corresponding ratio of hourly extraterrestrial to total extraterrestrial radiation will suffice. This insolation-weighted meltwater runoff function is subjected to infiltration at a rate equal to the saturated hydraulic conductivity, and the resulting excess runoff is treated by the routing models in the same manner as the excess rainfall.

Water, Erosion and Sediment Routing

The water, erosion and sediment routing model is designed to route storm water and sediment runoff from watersheds of complex geometry. To accomplish this task, the complex watershed geometry must be simplified into a representation suitable for computer simulation. The geometric approximation used in this component is an arbitrary number of two plane, one-channel "open book" subwatersheds and planes linked together by channels.

For simplicity, a numerical solution to the kinematic wave problem could have been used for both the subwatershed units and the linking channels. An analytical solution such as the method of characteristics approach, however, allows more efficient use of computer storage and usually more rapid calculation of the runoff hydrograph. Therefore, whenever possible, analytical solutions are employed. To be consistent, in the portions of the watershed where the analytical methods are used to route the water, the sediment yield is also computed by an analytical method. Likewise, in the portions where water is routed numerically, sediment yield and transport are computed by a numerical routing scheme.

Overland Flow and Primary Channels

The two tasks performed by this program are the determination of sediment yield by size fractions and the routing of water for all plane and upstream watershed units that form the entire watershed. The water routing is performed analytically by applying the method of characteristics to the kinematic wave approximation to the momentum and continuity equations. The sediment yield is calculated by comparing the supply due to detachment by both rainfall and runoff, and the potential transporting capacity. The transport capacity is determined by size fraction. The suspended sediment transport capacity and the bed load are calculated for both the overland flow and primary channel flow routines.

Main Channel Water Routing

The main channel routing program uses a numerical scheme to route the water in the downstream main channels. It uses the discharges calculated in the overland flow and primary channel routines as upstream and lateral inflows into the channel units. In addition, an infiltration routing calculates the amount of water that infiltrates in the channel units and subtracts it from the lateral inflow.

Sediment Routing

The sediment routing in the main channel routine uses a principle similar to the sediment yield calculations in the overland flow and primary channel model — the process of balancing supply and capacity for each sediment size. In addition, the main channel includes the effect of armoring on the sediment transport rate. The process of armoring occurs because of the difference in sediment transport capacity between the different sizes, resulting in a layer of large size fraction formed on the surface. If the erosion processes continue, this layer of larger size fraction will protect the small one from detaching or dislodging.

The sediment calculations in the main channel are also different in that the numerical method used allows for the sediment to be routed through the channels at each time increment and then integrated over the time increments to arrive at a total yield for each size fraction. The method used in overland flow and primary channel model can only provide a total yield for each size fraction, but cannot truly route the sediment through the channel. The main channel model is able to route the sediment because the balance of transporting capacity and supply can be compared at each time and space increment along the channel due to the use of the numerical scheme. The method used in the overland flow and primary channel does not allow for this, since only average conditions are determined.

Since the main channel model uses the numerical method, which requires sediment transport rates at each time increment, and needs to use the yields calculated in the overland flow and primary channel model as upstream and lateral inflows, the yields in the latter must be transformed into sediment hydrographs. This is accomplished by distributing the yields from overland flow and primary channel models in proportion to the water discharge at each time increment.

This water and sediment routing method has been successfully employed on a variety of watersheds. Results have shown that it provides very accurate characterization of watershed hydraulics. A considerable degree of emphasis has been placed on the previously described water balance and the water and sediment routing components. Pollutants are chiefly transported by surface and subsurface flow components. Therefore, the characterization of the hydraulics of infiltration, overland flow, and channel flow, and the mechanics of sediment yield and transport are critical to accurately estimating pollutant migration. The described hydraulic components provide the level of accuracy necessary to represent these processes and through the model structure remain practical for implementation on most computing hardware.

Pollutant Routing

As originally formulated, the pollutant routing module addressed the routing of nutrients. Nutrient compounds are a source of nonpoint pollutants affecting water quality. Nutrients, such as nitrogen and phosphorus, are of concern because of their role in eutrophication processes. A physical process simulation model was developed for predicting nutrient losses from forest and agricultural watersheds associated with surface runoff and sediment transport. Mass balance and loading function concepts were the basic principles used in formulating this model. The model was developed to predict loadings of organic nutrients, nitrate, ammonium, and inorganic ortho-phosphorus to streams and rivers.

Natural nutrient input to the ecosystem comes mainly from precipitation, litter fall, and geological weathering. Precipitation and litter fall were considered the primary external inputs of nutrients from the atmosphere. These average inputs were routed into the litter layer where microbial degradation occurred. The products of degradation were then routed to the stream and into the soil layer. Within the soil layer, these products were again evaluated along with plant uptake and soil adsorption. The products of these processes occurring within the soil were then routed to the stream. Generally, nutrient constituents cannot move unless transported by sediment and water and therefore, water and sediment are the major carriers of nutrients through the ecosystem. Evaluation of these carrier amounts is necessary for predicting nutrient losses from the watershed.

The nutrient simulator proposed here is basically a nutrient budget model. All of the processes mentioned above except the immobilization process were taken into account when simulating average nutrient concentrations in the soil. The quantities of nutrient losses to streams during storms were predicted by the incorporation of the loading function concept.

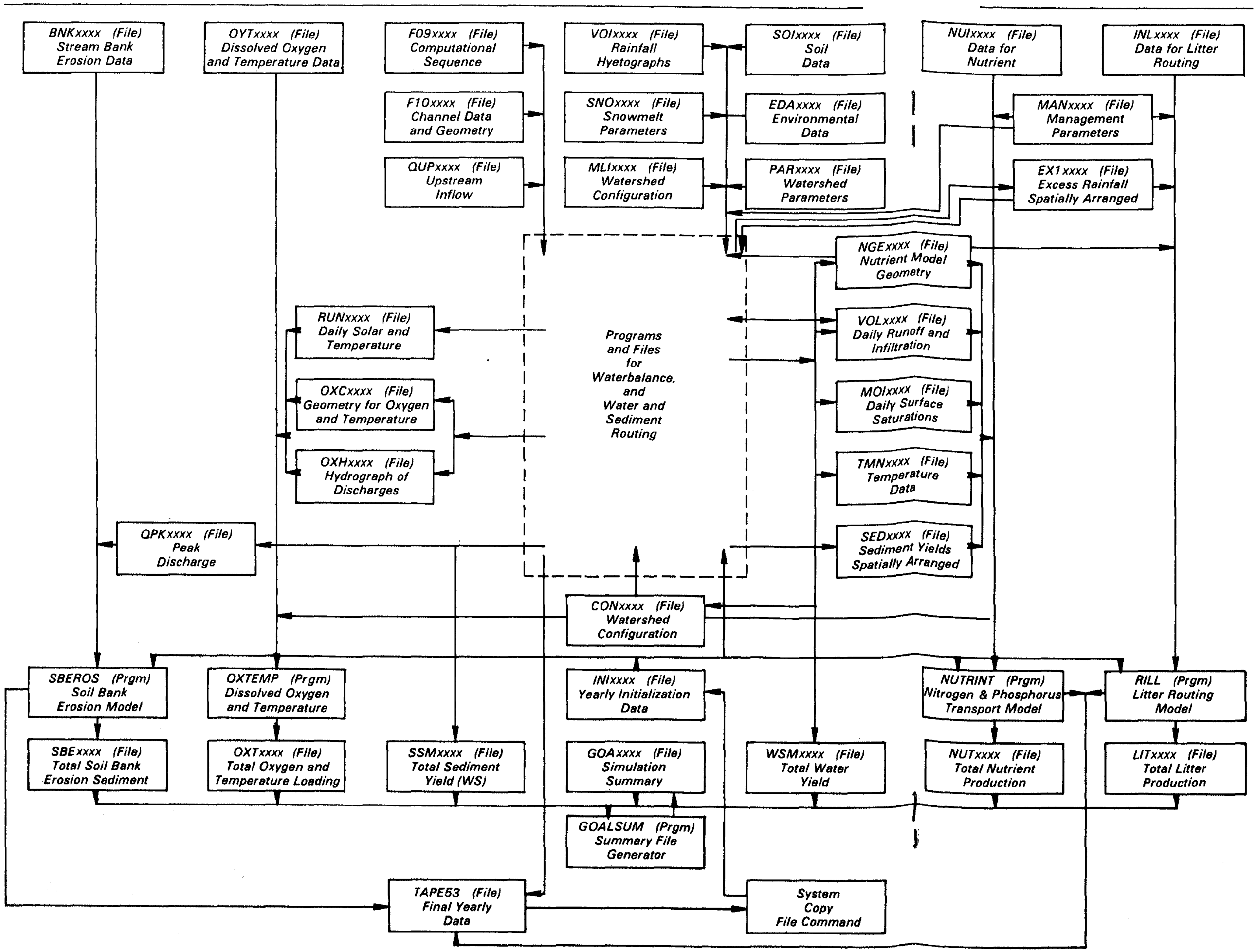

Figure 1. *Generalized Planning Model.*

Temperature and Dissolved Oxygen Routing

Thermal energy content, dissolved oxygen (DO), and biological oxygen demand (BOD) of runoff water can directly or indirectly affect the temperature and oxygen content in the stream. Based on mass and energy balance, the temperature and dissolved oxygen model is included in this simulation. This model is useful in evaluating the thermal and dissolved oxygen loading to the stream through surface runoff.

Overland flows transmit thermal and DO loading from land surfaces to the stream. Temperature and DO loading of the stream result from high temperature, high biochemical oxygen demand, and low dissolved oxygen in runoff water. Temperature and DO effects of subsurface flow are not included in this model.

The three mechanisms of heat transfer — radiation, conduction, and convection — are included in this model. Each mechanism plays a role in the heat transfer process. Conduction is the predominant mechanisms for heat transfer between soil layers and heat transmission between soil and surface flow. Convective heat transfer occurs because of relative motion between various parts of the heated body or fluid. Convection plays an important role in heat transfer from water surfaces, particularly in evaporative processes. In this model, these heat transfer mechanisms are used to formulate equations for (1) atmospheric processes, (2) canopy-ground cover processes, and (3) surface runoff processes.

The oxygen concentration in the stream water at any given time is determined by the solubility of oxygen in the water, the rate at which this oxygen is consumed by various biological processes (represented by BOD) and the rate at which this depletion is replenished. Deoxygenation of the water due to the bacterial decomposition of carbonaceous organic material and reaeration caused by the oxygen deficit and turbulence are the most fundamental processes occurring in natural water. The rate at which the BOD is exerted was presumed to be identical to that observed while using the laboratory BOD test. A proportionality is assumed to exist between the reaeration rate and certain hydraulic parameters of flow. The DO effects include concentration reductions due to purging action of gases rising from the benthal layer, plant aspiration, diffusion into the benthic layer, and DO additions through photosynthesis.

Streambank Erosion

Much of the sediment production of watersheds and channel systems arises from streambank erosion. Therefore, a mathematical model of the process of streambank erosion by channel widening is included in this simulation. The predictive capability of the model is enhanced by its phenomenological structure, although empirical data are needed in the stream morphology component. The model estimates the total amount of streambank erosion and the fraction of it that goes into suspension. Threshold channel conditions, bank characteristics, and the hydrologic events are input to the model.

As formulated, the streambank erosion model estimates the total amount of erosion that is likely to occur in the transition from a condition of geomorphic equilibrium to another condition of equilibrium. As such, it does not provide information on the rate of streambank erosion; rather, it gives a total value assuming the new equilibrium condition is eventually reached. In practice, however, the rate of streambank erosion is a function of the time history of hydrologic events, which are not explicitly considered in the present model. Therefore, the calculated values are to be regarded as estimates of the total amount of streambank erosion that is associated with a certain level of hydrologic excitation. Further refinements must be implemented if the model is to provide information on the rate of streambank erosion.

Forest Litter

A first approximation to rill formation and the loading of forest litter is included in this simulation. The model is based on the assumption that the amount of forest litter loading is directly proportional to the demonstrated effectiveness of concentrated flow in transporting sediment and debris through upland watershed drainage networks. This approach allows the conversion of the forest litter loading problem into that of determining the areal extent of rilling (rilling density), given a set of topographic, hydrologic, and morphologic conditions.

The quantity of forest litter delivered to a stream is a direct function of the areal extent of rilling and the amount of forest litter production. The areal extent of rilling, in general, will be determined by large events. Smaller subsequent events will not entirely fill the established rill network. Therefore, the litter washed out of the rill network will be detached from the area defined by the top width of the flowing water.

Potential Applications

Potential applications of the simulation are initially intended to aid in the evaluation of watershed management alternatives. Management activities that could be considered initially were vegetation growth (over story and under story), timber harvest, foliage utilization (grazing), site preparation, waste disposal and prescribed nutrient and pesticide applications. The linkage of the management activity models, the process models and the multiple objective programming model form the preliminary generalized planning model. This preliminary planning model would be useful in evaluating selected alternatives as a function of environmental goals. Environmental goals relate to control of sediment, nutrients, pesticides, hazardous waste, thermal, and dissolved oxygen pollution. Also, resource management goals can be identified that maximize income and/or implement the best management practices. The changes caused by management activities are reflected in changes in input model parameters. The effects of these changes may be simulated by adjusting soil and vegetative and chemical parameters. Chronological simulation allows those parameters to be varied either instantaneously or as functions of time. By interfacing with the planning model, these parameter values may be adjusted in order to select the best management alternatives and schedules.

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The complete report consists of two volumes, entitled "Simulation Model for Watershed Management Planning:"
"Volume I. Model Theory and Formulation," (Order No. PB 84-158 153; Cost: $19.00)
"Volume II. Model User Manual," (Order No. PB 84-158 161; Cost: $31.00)
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