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A Field-Scale Model for Nonpoint Source Pollution Evaluation[1/]

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Mathematical models to assess nonpoint source pollution and evaluate the effects of management practices are needed to adequately respond to the Water Quality Legislation of the past 10 years. Action agencies must assess nonpoint source pollution from agricultural areas, identify problem areas, and develop conservation practices to reduce or minimize sediment and chemical losses from fields where potential problems exist. Monitoring every field or farm to measure pollutant movement is impossible, but landowners need to know the benefits before they apply conservation practices. Only through the use of models can pollutant movement be assessed and conservation practices planned.

Models developed for these purposes include the Pesticide Runoff Transport (PRT) model to estimate runoff, erosion, and pesticide losses from field areas (Crawford and Donigian, 1973); the Agricultural Runoff Model (ARM) to estimate runoff, erosion, and pesticide and plant nutrient losses from field areas (Donigian and Crawford, 1976); and the Agricultural Chemical Transport Model (ACTMO) to estimate losses from field or basin size areas (Frere, Onstad and Holtan, 1975). Bruce, et al. (1975) developed an event model to estimate pesticide losses from fields during single runoff-producing storms. These models are expensive when several years of data are simulated, and all require calibration. Beasley, et al. (1977) developed the ANSWERS model to estimate runoff and erosion and sedimentation from basin sized areas. This model has been used to identify sources of erosion and to consider conservation practices for erosion control, but it does not estimate nutrient or pesticide movement.

In 1978, the U.S. Department of Agriculture, Science and Education Administration, Agricultural Research (USDA-SEA-AR), began a national project to develop relatively simple and inexpensive mathematical models for evaluating nonpoint source pollution. A model that does not require calibration was planned, since very little calibration data are available. The initial efforts were concentrated on field scale, since that is where conservation management systems are applied. A field was defined as an area with relatively homogeneous soils under a single management practice that was small enough that rainfall variability was minimal. Requirements for the model were that it be simple and yet represent a complex system, be physically based and not require calibration, be a continuous simulation model, and have the potential to estimate runoff, erosion, and adsorbed and dissolved chemical transport. A field-scale model has been developed and is operational.

The purpose of this paper is to present the concepts and describe application of the field scale model. Details of the model cannot be given because space

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is limited, but each component is described. A manuscript in the process of publication will describe the model in detail and give instructions for its use.[3]

CREAMS MODEL STRUCTURE

The model reported in this paper consists of three major components: hydrology, erosion/sedimentation, and chemistry. The hydrology component estimates runoff volume and peak rates, evapotranspiration, soil water content, and percolation, all on a daily basis. The erosion component estimates erosion and sediment yield including particle size distribution at the edge of the field. The chemistry component includes a plant nutrient element and a pesticide element. Stormloads and average concentrations of adsorbed and dissolved chemicals are estimated in the runoff, sediment, and percolation fractions.

The Hydrology Component

This component consists of two options, depending upon availability of rainfall data. If the user is limited to daily rainfall data, Option 1 provides a means of estimating storm runoff. If hourly or breakpoint (time-intensity) rainfall data are available, Option 2 offers the user an infiltration-based method of estimating storm runoff.

Option 1: Williams and La Seur (1976) adapted the Soil Conservation Service (1972) curve number method for simulation of daily runoff. The method relates direct runoff to daily rainfall as a function of curve number (Fig. 1). Curve

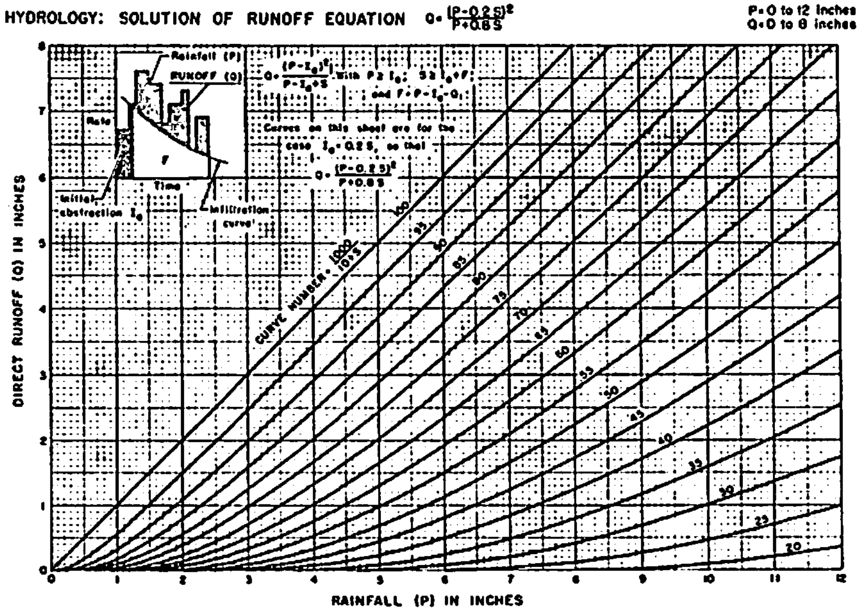

Figure 1. Soil Conservation Service Curve number method of storm runoff estimation (USDA, Soil Conservation Service, 1972).

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[3] U.S. Dept. of Agri., Science and Education Administration. CREAMS: a field scale model for estimating Chemicals, Runoff, and Erosion from Agricultural Management Systems. To be published as a USDA-SEA Conservation Research Report.

number is a function of soil type, cover, management practice, and antecedent rainfall. The relationship of runoff, Q, to rainfall, P, is

$$Q = \frac{(P\ 0.2S)^2}{P + 0.8S} \tag{1}$$

where S is a retention parameter related to soil moisture. A water balance is calculated by

$$SM_t = SM + P - Q - ET - O \tag{2}$$

where SM is initial soil moisture, SM_t is soil moisture at day t, P is precipitation, Q is runoff, ET is evapotranspiration, and O is percolation below the root zone. Eq.(2) estimates the soil water for determining the retention parameter, S, in Eq. (1).

The percolation component uses a storage routing technique to estimate flow through the root zone. The root zone is divided into 7 layers -- the first layer is 1/36 of the total root zone depth, the second layer 5/36 of the total, and the remaining layers, all equal in thickness, are 1/6 of the root zone depth. The top layer is approximately equivalent to the chemically active surface layer and the layer where interrill erosion is active. The soil water capacity for each layer is defined as the field capacity, and percolation cannot occur until the field capacity is exceeded. Percolation through each layer is based on the saturated hydraulic conductivity for the layer.

The peak rate of runoff, q_p, (required in the erosion model) is estimated by the empirical relationship (Williams and LaSeur, 1976)

$$q_p = 200D^{\left(0.7 + 0.23e^{-4.7D}\right)} C^{0.159} Q^{\left(0.917D^{0.0166}\right)} L^{-0.187} \tag{3}$$

where D is drainage area, C is mainstem channel slope, Q is daily runoff volume, L is the watershed length-width ratio, and e is the base of natural logarithms. Although Eq. (3) was developed and tested for basin-sized areas, it has been found applicable to field-sized areas as well.

Option 2: The infiltration model is based on the Green and Ampt (1911) equa- equation (Smith and Parlange, 1978). A defining diagram of the infiltration model is given in Fig. 2. The concept assumes that the soil contains some

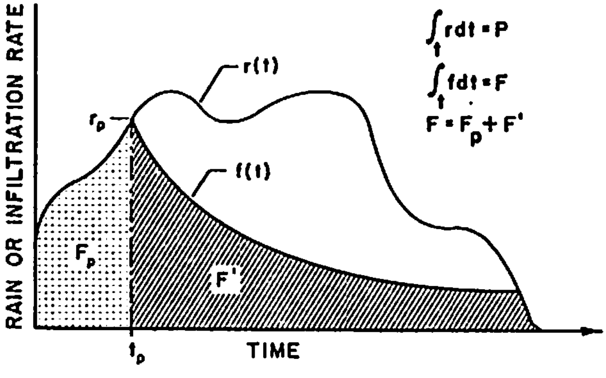

Figure 2. Schematic representation of runoff model using infiltration approach (Smith and Parlange, 1978).

water initially in a surface infiltration-control layer at the time rainfall occurs. When rainfall begins, the soil water content in the control layer approaches saturation and surface ponding occurs at some time, t_p (Fig. 2). The amount of rain that has already infiltrated at time of ponding, designated F_p in Fig. 2, is analogous to the initial abstraction in the SCS curve number model (Option 1), but it is a function of rainfall rate in this option. After the time of ponding, the Green and Ampt (1911) equation assumes that water moves as a sharply defined wetting front with a characteristic capillary suction, H_c, as the principle driving force. At any time, the potential gradient is

$$g = \frac{H_c + L}{L} \tag{4}$$

where L is the depth of wetting. The flow, f, is the product of effective saturated conductivity, K_s, and the gradient, or

$$f = K_s\left(\frac{H_c + L}{L}\right). \tag{5}$$

The infiltrated depth, F, (Fig. 2) is

$$F = L(\theta_s - \theta_i) \tag{6}$$

where θ_s is the water content at saturation and θ_i is the initial water content. The infiltration capacity, f_c, becomes

$$f_c = K_s \frac{H_c\phi(\theta_s - \theta_i) + F}{F} \tag{7}$$

where θ_s approaches the soil porosity, ϕ, and, letting $G = \phi H_c$ the infiltrated depth at t_p is

$$F_p = \frac{G(\theta_s - \theta_i)\, K_s}{r - K_s} \tag{8}$$

where r is rainfall rate. If $D = (\theta_s - \theta_i)$, and approximating the infiltration curve of Fig. 2 by a series expression for the natural logarithm, the infiltrated depth in a time interval, ΔF, is

$$\Delta F = \sqrt{4A(GD + F) + (F - A)^2} + A - F, \tag{9}$$

where $A = \frac{K_{si}\Delta t}{2}$. The average infiltration rate for any interval i, $\bar{f}_i$, is

$$\bar{f}_i = \frac{\Delta F_i}{\Delta t_i} \tag{10}$$

and runoff during the interval, q_i, is rainfall rate for the interval minus the infiltration rate, $r_i - \bar{f}_i$. Total runoff is the sum of all q_i for the storm. Thus, the infiltration-based model has three parameters: G, D, and K_s.

The percolation estimated is similar to that used in Option 1, except that a single layer below the infiltration control layer represents the root zone. Percolation is calculated using average profile soil water content above field capacity and the saturated hydraulic conductivity, K_s.

Peak rate of runoff is estimated in Option 2 by attenuating the rainfall excess using the kinematic wave model for flow over a simple plane (Wu, 1978). The plane is approximated by the field slope and flow length.

Evapotranspiration: The evapotranspsiration (ET) element of the hydrology component is the same for both options. The ET model, developed by Ritchie (1972), calculates soil evaporation and plant evaporation separately. Evaporation is based on heat flux and is a function of daily net solar radiation and mean daily temperature. Daily radiation and temperature are interpolated by fitting a Fourier series to mean monthly radiation and temperature (Kothandaraman and Evans, 1972). Evaporation is calculated in two stages: the first is potential soil evaporation to modify the moisture flux based upon plant canopy or leaf area index, and the second stage is a function of time and an evaporation constant. Plant evaporation is computed as a function of soil evaporative flux and leaf area index. If soil water is limiting, plant evaporation is reduced by a fraction of the available soil water. Evapotranspiration is the sum of plant and soil evaporation but cannot exceed potential soil evaporation.

Erosion

The erosion component of the CREAMS model considers the basic processes of soil detachment, transport, and deposition. The concepts of the model are that sediment load is controlled by either transport capacity or the amount of sediment available for transport, whichever is less. If sediment load is less than transport capacity, detachment may occur; deposition occurs if sediment load is greater than transport capacity. The model represents a field comprehensively by considering complex slopes for overland flow, concentrated channel flow, and impoundments or ponds. The model can estimate particle size transport for the primary particles -- sand, silt, and clay -- and large and small aggregates. Detachment and deposition do not occur simultaneously. In deposition, the model calculates sediment sorting. Temporary ponding can result in transport of only the finer particles.

The detachment process is described by a modification of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) for a single storm event. This interrill detachment, D_{IR}, in the overland flow element is expressed as

$$D_{IR} = 4.57EI\ (S_{of} + 0.014)\ KCP/(q_p/Q), \qquad (11)$$

where EI is storm rainfall energy, S_{of} is the slope of the overland flow, q_p is runoff peak rate, Q is runoff volume, K is the soil erodibility factor, C is the cover factor, and P is the management practice factor. The rill detachment process, D_R is expressed as

$$D_R = (6.84 \times 10^6)\ n_x Q q_p^{1/3} (x/22.1)^{n_x - 1}\ S_{of}^2 KCP(q_p/Q) \qquad (12)$$

where x is the distance down slope, n_x is slope-length exponent, and Q, q_p, K, C, and P are defined as above. As shown in Eq. (11), interrill erosion is a function of rainfall detachment and transport, and from Eq. (12) rill erosion is a function of transport capacity denoted by the runoff volume and peak rate. Both equations contain the K, C, and P factors of the USLE (Wischmeier and Smith, 1978). Sediment transport for the overland flow element is estimated by the Yalin transport equation (Yalin, 1963) modified for mixtures of sediment having varying sizes and densities.

The concentrated flow or channel element of the erosion model assumes that the peak rate of runoff is the characteristic discharge for the channel, and detachment or deposition is based on that discharge. Detachment can occur when the shear stress developed by the characteristic discharge is greater than the critical shear stress for the channel. Bare channels, grassed waterways, and combinations of bare and grass channels can be considered by the model for as many as 10 channel segments. Discharge is assumed to be steady state, but spatially varied, increasing downstream with lateral inflow. Friction slope and shear stress are estimated from solution of the spatially varied flow equations. The solutions consider drawdown or backwater effects in the channel as a result of channel outlet control.

Water is often impounded in field situations, either as normal ponding, where a channel flows through a restriction at a fence line or a road culvert, or as outflow from an impoundment-type terrace. Any such restriction reduces the flow velocity and coarse-grained sediments and aggregates can settle out of the flow. Deposition in impoundments is a function of the fall velocity of the particles and particle travel time through the impoundment. The fraction of particles passing through the impoundment, FP, of a given size, i, is given by the exponential relation

$$FP_i = A_i e^{B_i d_i} \tag{13}$$

where d_i is the equivalent sand-grain diameter and A and B are coefficients dependent upon impoundment surface area and depth, and settling velocity of the particles.

In addition to calculating the sediment transport fraction for each of the five particle size classes, the model computes the sediment enrichment ratio, which is based on the specific surface area of the sediment and organic matter and the specific surface area for the residual soil. As sediment is deposited in transport, the organic matter, clay, and silt are the principle particles transported, and this results in high enrichment ratios. The enrichment ratios are important in adsorbed chemical transport.

Chemical Component

Plant Nutrients: The basic concepts of the nutrient component are that nitrogen and phosphorus are adsorbed to soil particles and are lost as sediment is transported, that soluble nitrogen and phosphorus are lost with surface runoff, and that soil nitrate can be leached by percolation, denitrified, or taken up by plants.

Nitrogen and phosphorus are mixed with the soil, and the amounts lost with sediment are a function of sediment yield and enrichment ratio. A logarithmic function is used to relate nitrogen and phosphorus losses to enrichment ratios.

The chemical model component assumes that an arbitrary surface layer 1 cm deep is effective in chemical transfer to sediment and runoff. Soluble nitrogen and phosphorus are assumed to be thoroughly mixed with the water in the top centimeter. This includes soluble forms from the soil, surface-applied fertilizers, and plant residues. These soluble nutrients are imperfectly extracted by overland flow. The extraction from this active layer is expressed by an empirical extraction coefficient. All broadcast fertilizer is added to the surface active layer, whereas only a fraction would be added by fertilizer incorporated with the soil.

When infiltrated rainfall saturates the surface active layer, soluble nitrogen moves into the root zone below the layer from which chemicals are extractable. Nitrate in the rainfall contributes to the total in both this layer and the root zone.

Fertilizer addition and mineralization of organic matter both increase soil nitrate. Mineralization is calculated by a first-order rate equation from the amount of potential mineralizable nitrogen and is modified by soil water content and temperature. Optimum mineralization rates occur at soil temperatures of 35°C. Soil temperature is approximated by air temperature, as calculated in the hydrology component of the model.

The model assumes that plant uptake of nitrogen under ideal conditions is described by a normal probability distribution curve. The potential uptake is reduced to the actual by a ratio of actual plant evaporation to potential plant evaporation. A second option for estimating nitrogen uptake is based on plant growth and the plant's nitrogen content.

Soil nitrate is available to plants for uptake. It can also be leached out of the root zone, or denitrification can reduce it. The description of nitrate leaching in the model assumes uniform mixing of the draining water and the nitrate remaining in the soil water. The amount of nitrate leached is a function of the amount of water percolated out of the root zone, as estimated by the hydrology component of the model.

Denitrification of soil nitrate in the root zone occurs when the soil water content exceeds field capacity, i.e., when percolation occurs. The amount of denitrification is based upon soil temperature and the organic carbon content of the soil. The model estimates organic carbon from the organic matter content in the root zone. The rate constant for denitrification at 35°C is calculated from the amount of organic carbon and is adjusted for temperature assuming a twofold reduction for each 10-degree decrease in temperature.

Thus, the plant nutrient component of the chemical model estimates nitrogen and phosphorus losses in sediment, soluble nitrogen and phosphorus in the runoff, mineralization, uptake by the crop, nitrate leached by percolate through the root zone, and denitrification in the root zone. The model computes loads of each component, accumulates over the year, and calculates average concentrations of nitrogen and phosphorus in runoff.

Pesticides: The pesticide model was developed to estimate concentrations of pesticides in runoff (water and sediment) and total mass for each storm during the period of interest. The model can accomodate up to 10 pesticides simultaneously in a single run. It is structured to consider foliar application of pesticides separately from soil-applied pesticides, because dissipation from foliage is more rapid than that from soil. The model can also consider multiple applications of the same chemical, as is done with insecticides.

As in the plant nutrient component, a surface active layer that is 1 cm deep is assumed. Movement of pesticides from the surface is a function of infiltrating water and pesticide mobility parameters. Pesticide in runoff is partitioned between the solution, or water, phase and the sediment phase by the following relationships:

$$(C_w Q) + (C_s M) = a C_p \tag{14}$$

and

$$C_s = K_d C_w \tag{15}$$

where C_w is pesticide concentration in water, Q is volume of water per unit volume of stirred runoff interface or surface active layer, C_s is pesticide concentration in sediment, M is the mass of soil per unit volume of interface, a is an extraction ratio of the amount of soil extracted per unit volume in the stirred runoff interface, C_p is the concentration of pesticide residue in the soil, and K_d is the coefficient for partitioning the pesticide between sediment and water phases. The concentration C_w is assumed to be the average concentration in solution that reaches the field edge but is determined by extraction of the pesticide into the runoff from the soil interface in the field. The term C_s is the pesticide concentration in the soil material at the runoff-soil interface after extraction. Only a small part of this mass extraction actually reaches the edge of the field and is calculated as a product of concentration, sediment mass, and the enrichment ratio. The sediment mass and enrichment ratios are calculated by the erosion component of the model.

Pesticide washed off of foliage by rain changes the concentration in the soil. The amount calculated as available for washoff is updated between storms by a foliar degradation process. Pesticide residue in the runoff interface layer is adjusted for downward movement and washoff from foliage.

SUMMARY

A physically based daily simulation model has been developed by SEA-AR scientists to evaluate nonpoint source pollution from agricultural fields. The model simulates processes in hydrology, erosion, and plant nutrient and pesticide losses as affected by management practices. It does not require calibration, and the computer program is computationally efficient -- it costs only a few dollars per year of computations. The hydrology component has been tested in 30 watersheds in 13 land resource areas of the U.S.; the erosion component has been tested in five land resource areas; the chemistry component has been tested in three land resource areas. A comprehensive publication of CREAMS is in progress which includes model concepts and a user manual that aids in parameter and coefficient estimation.

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