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Modeling Continuous Non-point Source Inputs from Rural Watersheds to Lakes and Impoundments: A Review of Tools for Predicting Climate Change Effects

by

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I. INTRODUCTION

A number of scientists have recognized the potential for global climate change due to the so-called greenhouse effect (*e.g.* Bolin and Doos, 1986; Harrington, 1987; Schlesinger, 1991). The measured and expected increase in atmospheric CO_2 has been predicted to raise the average temperature of the Earth's atmosphere, leading to significant changes in the climate of many regions of the world, including the U.S. It is important, then, to determine the impact of these climate changes on the natural environment. Accurate predictions of ecosystem responses at watershed and regional levels would provide guidance for managing and protecting our nation's natural resources prior to and during a potentially radical change in the average climatological conditions in the U.S.

II. BACKGROUND

Predicting the impacts of climate change on aquatic ecosystems requires identification and simulation of the ecological responses to climatological factors (*e.g.,* precipitation, temperature, humidity, wind, and solar radiation) that result in ecological impacts (*e.g.,* temperature stress, oxygen stress, loss of habitat, etc.). Stefan *et al.,* (1992) have identified primary and secondary ecological responses to climate change. The primary responses include: 1) water temperature and thermal stratification of lakes and streams, 2) lake volume, stream flow, and runoff flow, and 3) terrestrial vegetation type and amount. The secondary responses include 1) dissolved oxygen concentrations, 2) nutrient concentrations, and 3) suspended solids concentration.

Researchers at the University of Minnesota's St. Anthony Falls Laboratory (SAFL) are adapting and modifying a model, MINLAKE, for predicting the response of aquatic ecosystems to climate change. This model simulates the responses of the water temperature, thermal stratification, and dissolved oxygen concentrations in lakes to variations in climate (Riley and Stefan, 1988; Hondzo and Stefan, 1993; Stefan and Fang, 1994). This model has been validated with field data and has been used to predict the impact of climate change on fish populations (Stefan *et al.*, 1994, 1995; Eaton *et al.*, 1995).

The research performed thus far has focussed on in-lake processes and how they respond to changes in air temperature, solar radiation, humidity, and wind. It was assumed that the trophic status, the volume, and the turbidity of the lakes did not change. The lake model now must be connected with the processes in the surrounding watershed in order to begin to determine the role of watershed- and regional-scale processes in climate-induced ecosystem responses. For example, a substantial change in suspended solids concentration in runoff waters, runoff water volume, and/or nutrient concentrations in runoff waters could have a substantial influence on the response of a lake ecosystem to climate change.

III. APPROACH

The main goal of this research is to adapt existing runoff water quality models and/or procedures to simulate the change in suspended solid and nutrient concentrations in streamflow entering lakes in response to climate change. Changes in runoff water volume, as they affect nutrient and suspended solids inputs to lakes, also need to be simulated. The resulting simulation methods should be applicable to ungauged rural watersheds so that assessments on the impacts of climate change can be performed for many watersheds within a selected geographic region.

It is important that one builds on the successes of previous research. Therefore, existing models and/or procedures that have been validated were examined to determine if they are appropriate for the proposed task. Once a model or procedure has been chosen, it will be modified to suit the needs of the research project.

The modifications required will most likely be determined when the chosen model is tested against existing conditions in one or two watersheds where precipitation, runoff water volume, and runoff water quality have been measured. One of the watersheds used for testing the model will be the Little Washita watershed in southwest Oklahoma. Another watershed, located in or near Minnesota, will be chosen for testing simulations as well.

The model will then be used first to predict the primary impact of climate change; *i.e.,* the aquatic ecosystem's response to changes in precipitation, temperature, and solar radiation. Once the model is shown to satisfactorily simulate the relationship between aquatic ecosystems and the primary climatic impacts, the model will be used to predict the secondary impact of climate change; *i.e.,* the aquatic ecosystem's response to changes in land cover, vegetation type, etc. The predicted suspended solids and nutrient concentrations will then be used to predict the impact of climate-induced changes in the watershed on the native fish populations.

IV. FOCUS OF CURRENT RESEARCH RESULTS

The research presented here focussed on determining the best model to use for simulating the non-point source inputs to lakes and streams from the surrounding watershed. The goal of the literature research was to find the most streamlined and direct method that will reliably estimate suspended solid and nutrient concentrations in surface runoff without requiring the model to be calibrated using streamflow, nutrient, and/or sediment data from the watershed to be simulated.

The simplest validated methods for estimating suspended solid and nutrient concentrations in surface waters are found in the U.S. EPA Screening Procedure for Toxic and Conventional Pollutants (Mills *et al.,* 1982). These procedures were designed for simple, calculator-based estimates of the concentrations of pollutants. They are based on average concentration values from nation-wide surveys such as the National Eutrophication Study (Omernik, 1977) and provide the approximate magnitudes of waste loads to surface waters. It is anticipated that these estimates will not be accurate enough or flexible enough to predict changes in non-point source inputs to surface waters from rural watersheds due to climate change. They will, however, be evaluated along with the more complex simulation models to determine if this is true.

A survey of the literature revealed a number of validated models that simulate the water, sediment, and nutrient yields from rural watersheds (Leavesley *et al.,* 1990; Ambrose, *et al.,* 1989; Donigian and Huber, 1991). The watershed models that simulate runoff water quantity and quality can be divided into event- vs. continuous-based, field/plot scale vs. basin/watershed scale, and empirical vs. process models (Table 1). Event models simulate the runoff, sediment and nutrient yield from a single storm event. Continuous based models simulate the water budget of a watershed over time, incorporating a number of rainfall events. The spatial scale of a field/plot scale model consists of a tract of land that has relatively uniform features, such as land use, management practice, soil type, etc. Basin and watershed scale models simulate entire watersheds and have some mechanism for incorporating the variability that is typical of rural watersheds. Basin scale models include channel routing techniques for transporting flow, sediments, nutrients, and pesticides through a river basin. Finally, empirical models represent important features of watersheds, such as runoff volume and sediment yield, using empirical relationships based on a large number of field studies. Process models, on the other hand, simulate the mechanics of the important features of a watershed.

It is most likely that a continuous, basin scale, empirical model will best suit the needs of this research project. Such a model will use the general relationships measured in field studies to simulate the inputs from an entire rural watershed to a lake or stream over the time scale needed to investigate the direct and indirect impacts of climate change. The following sections will illustrate why this type of model is the best choice using an example of each of three different types of models: an event, basin-scale, empirical model (AGricultural Non-Point Source pollution model, AGNPS), a continuous, basin-scale, empirical model (Soil and Water Assessment Tool, SWAT), and a continuous, basin-scale, process model (Hydrological Simulation Program-FORTRAN, HSPF).

Table 1 Survey of watershed water quality models that simulate non-point inputs to lakes and streams.

Model	Temporal Scale	Spatial[1] Scale	Approach[2]	Reference
AGNPS	Event	Basin	Empirical	Young *et al.*, 1989
ANSWERS	Event	Field	Process	Beasley & Huggins, 1982
CREAMS	Continuous	Field	Process/ Empirical	Knisel, 1980
EPIC	Continuous	Field	Empirical	Williams, *et al.*, 1984
HSPF	Continuous	Basin	Process	Johanson *et al.*, 1984
Opus	Continuous	Watershed	Process/ Empirical	Smith and Ferreira, 1987
SWAT	Continuous	Basin	Empirical	Arnold *et al.*, 1994
SWRRB	Continuous	Watershed	Empirical	Arnold *et al.*, 1990

[1]Field scale models use uniform hydrologic parameters for the entire area simulated. Watershed scale models subdivide the area simulated into cells or subbasins, each of which have uniform hydrologic parameters. Basin scale models include a channel routing scheme for transporting runoff, sediment, nutrients and pesticides through the river basin.

[2]This column states the approach the model uses to simulate runoff volume, sediment yield, and nutrient yields. If a mix of process and empirical approaches is used, or if the user has a choice between the two, the model's approach is listed as process/empirical.

AGNPS (Young *et al.*, 1989) is an event-driven, cell based model that uses readily available data for input. It was designed to provide basic water quality information that can be used to classify non-point-source pollution problems in agricultural watersheds. SWAT (Arnold *et al.*, 1994) is a continuous, subbasin-based model that uses readily available data for input parameters. It was designed to predict the effect of management decisions on water, nutrient, pesticide, and sediment yields with reasonable accuracy for large ungauged rural basins throughout the U.S. HSPF (Johanson *et al.*, 1984) is a continuous, process-based model of a complete watershed that requires the user to calibrate its parameters using data from a well-measured watershed. It provides an integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions.

All models of non-point source inputs to lakes need to represent the following processes: 1) watershed hydrology, 2) sediment detachment and transport, 3) nutrient dynamics due to hydrologic processes, erosion, and chemical processes and, if desired, 4) pesticide dynamics (Leavesley *et al.,* 1990). How models simulate these processes differentiates them from each other and determines the context in which they can be used.

V. WATERSHED HYDROLOGY MODEL FORMULATIONS

Models of watershed hydrology need to address the following issues: 1) what is the most appropriate method for basin characterization, 2) how best to represent the water balance in the watershed, 3) what are the best methods for calculating runoff, 4) what precipitation data is required or how to simulate precipitation if detailed data are not available, 5) how to calculate the amounts of and the interactions between the surface water and the various subsurface waters (*i.e.,* infiltration, percolation, and groundwater), and 6) what are the best methods for simulating evapotranspiration (Leavesley *et al.,* 1990).

V.1 Basin Characterization

AGNPS

Each of the three models uses a different approach to characterize the simulated watershed. AGNPS divides the watershed into square 40-acre (16 ha) cells. Runoff, sediments, nutrients, and chemical oxygen demand due to a single rainfall event are calculated for each cell and then routed from cell to cell. Each cell has uniform characteristics, one input, and one output. AGNPS also includes a submodel for impoundments. This approach allows for a detailed characterization of the watershed and, by using small cells, improves the accuracy of using uniform characteristics within a cell. It is, however, very data intensive for larger watersheds like the Little Washita watershed (~150,000 acres $\approx$ 3,750 cells).

SWAT

SWAT allows the user to divide the watershed basin into subbasins or cells. The shapes of the subbasins are determined by the characteristics of the watershed. If square cells are used, the size of the cells is determined by the watershed size and by data availability. If a subbasin is highly variable in its soil types and/or land cover, but only the percentages of each type are known, it can be subdivided into hydrologic response units (HRU). The hydrologic response and non-point source constituents in each HRU are calculated individually and the results are weighted for the subbasin. Whether HRU's are used or not, runoff, sediment, nutrient, and pesticide yields are calculated for each subbasin and then routed via channels or overland flow from the subbasin into other subbasins and/or via channels to the basin outlet. SWAT includes submodels for routing flow and water quality constituents through ponds, wetlands, and reservoirs, and a submodel of lake water quality. This approach allows the user to divide the watershed basin into as many subbasins as is feasible based on the available topographic, soil series, crop management and land cover data.

HSPF

HSPF uses a free-form segmentation approach to characterizing a watershed basin. The different features of a watershed, such as the soil profile in a subbasin, a channel reach in a stream, etc., are represented as elements. The fluxes between elements are then described and like elements are grouped together for computation whenever possible. This method provides a high degree of flexibility so that the elements have uniform characteristics and can be computationally efficient. It can, however, be very data intensive for large watersheds.

V.2 Water Balance

AGNPS

Most watershed models use a water balance equation to calculate the amount of water in various components of the watershed. AGNPS, since it traces a single rainfall event, doesn't use a water balance equation. Water storage, evapotranspiration, and percolation are not simulated. The antecedent moisture conditions are represented using the SCS curve number.

SWAT

SWAT, on the other hand, calculates a water balance on soil water:

$$SW_t = SW + \sum_{i=1}^{t}(R_i - Q_i - ET_i - P_i - QR_i)$$

SW = soil water content minus the 15-bar water content
t = time in days
R = precipitation
Q = runoff
ET = evapotranspiration
P = percolation
QR = return flow

(all variables in mm)

Water that percolates out of the root zone enters the shallow aquifer. Water that percolates from the shallow aquifer to the deep aquifer is lost to the watershed, except as a source for irrigation water. The return flow term, QR, includes water that enters a stream from both the root zone and the shallow aquifer.

HSPF

HSPF also calculates a water balance, but on all the water in the watershed (Viessman *et al.,* 1989):

$$P = E + R + \Delta S$$

P = precipitation
E = evapotranspiration
R = runoff
ΔS = total change of storage in upper, lower, and groundwater storage zones.

The hydrology of HSPF is based on the Stanford Watershed Model (Crawford and Linsley, 1966). Of the three models, this is by far the most complete accounting of the water balance, but requires the user to calibrate the parameters governing water flow.

V.3 Runoff

AGNPS & SWAT

Runoff can be simulated using empirical or process equations. AGNPS and SWAT use the SCS Curve Number Method, an empirical approach developed with many plot years of data, to simulate runoff volume. This method calculates runoff based on a retention parameter (S):

$$Q = \frac{(R - 0.2S)^2}{R - 0.8S}$$

Q = Runoff volume (mm)
R = Rainfall (mm)
S = Retention parameter (mm)

The retention parameter is calculated using the curve number (CN):

$$S = 254\left(\frac{100}{CN} - 1\right)$$

The curve number for a particular subbasin or cell is determined by its vegetative cover, land use, and soil types. The resulting rainfall runoff relationships for various types of soils and land cover are shown in Fig. 1. Once the curve numbers are assigned for all of the cells or subbasins, they are modified to represent the soil moisture conditions. If the soil is dry, as in times of drought, the curve number is decreased. If the soil is wet, the curve number is increased. These adjustments result in an increase in runoff volume under high soil moisture conditions and a decrease in runoff volume under low soil moisture conditions. In AGNPS, the user must modify the curve number to represent the antecedent moisture conditions. SWAT calculates the change in the curve number required to simulate the current soil moisture conditions at each time step.

AGNPS

Since the SCS Curve Number Method only calculates runoff volume, AGNPS and SWAT must use additional techniques for estimating the other features of a runoff event such as peak runoff rate, runoff duration, snowmelt contribution, transmission losses and channel routing. AGNPS uses an expression relating watershed area (A), channel slope (S_c) and length (L_c), and runoff volume (Q) to simulate peak runoff rate (Q_p in cfs):

$$Q_p = 8.484 \cdot A^{0.7} \cdot S_c^{0.159} \cdot Q^{(0.824 \cdot A^{0.0166})} \left(\frac{L_c^2}{A \cdot 43560}\right)^{-0.187}$$

It simulates runoff duration (OFT, in seconds) as slope length (L_s) divided by velocity (V_o), with velocity calculated via land slope (S_1) and an overland surface condition constant (SCC):

$$OFT = \frac{L_s}{V_o},$$

where $V_o = 10^{0.5 \cdot \log(S_1 \cdot 100) - SCC}$

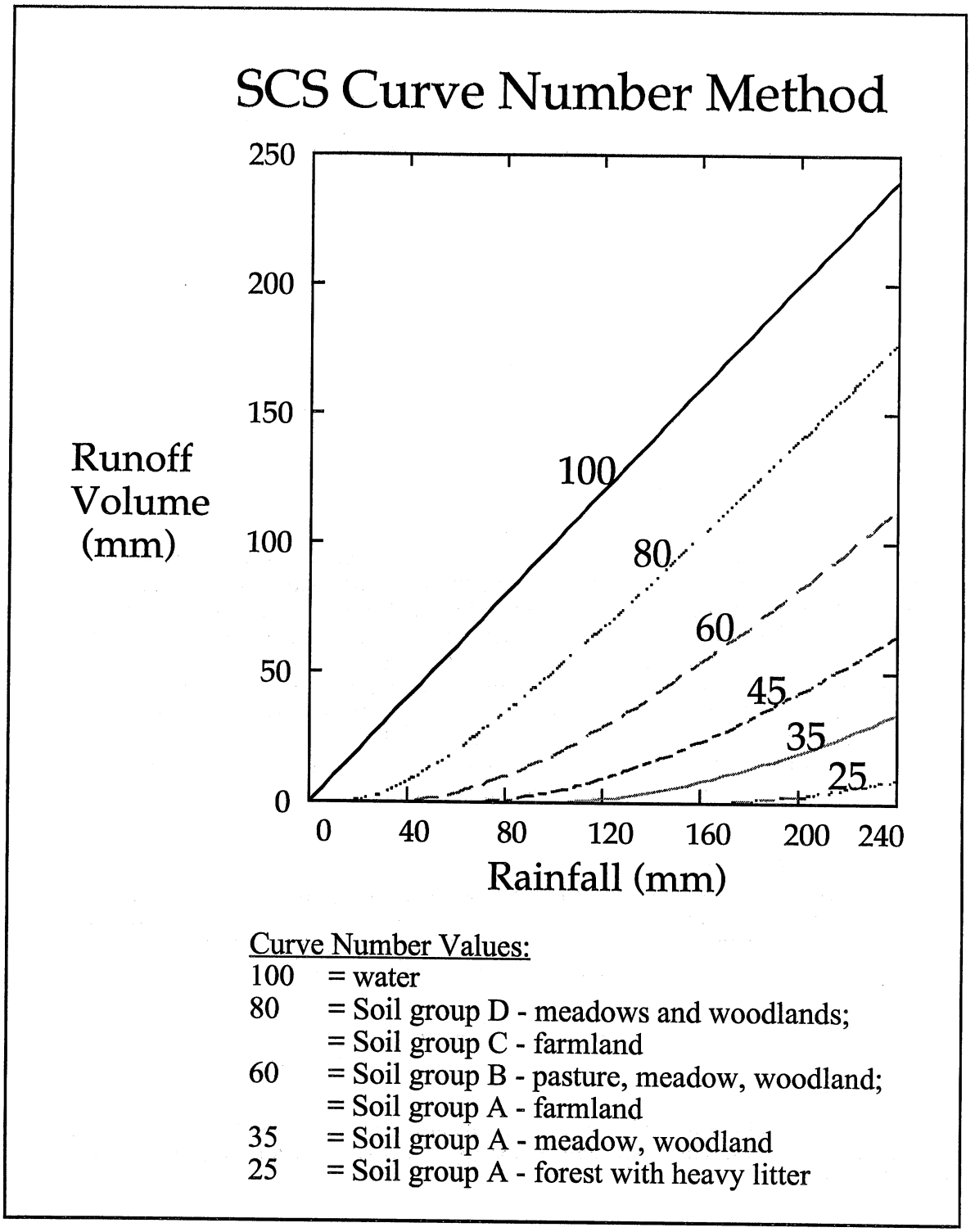

Figure 1: Rainfall-runoff volume relationships for various soil types and land covers using the SCS Curve Number Method.

SWAT

SWAT uses the Rational Equation Method or the SCS TR-55 Method to calculate peak runoff rate. The Rational Equation Method relates peak runoff to an infiltration coefficient, the rainfall intensity, and the watershed area:

$$q_p = \frac{\rho r A}{360}$$

q_p = peak runoff rate in m^3/s

ρ = infiltration coefficient

$= \frac{Q}{R}$, R = precip. and Q = runoff volume

r = rainfall intensity in mm/h

$$r = \frac{R_{tc}}{t_c}$$

R_{tc} = The amount of rainfall during the time of concentration, t_c. The value of R_{tc} is estimated stochastically from weather data. The value of t_c is the sum of surface and channel flow times calculated using Manning's equation and the average channel flow length.

A = drainage area in ha

The SCS TR-55 Method relates the peak runoff rate to the rainfall distribution and amount, the runoff curve number, and the time of concentrations:

$$Q_p = q_p \cdot R$$

R = storm rainfall amount (mm)

q_p = peak rate per unit of rainfall, calculated using rainfall distribution, curve number, and the time of concentration, t_c

t_c = sum of times for channel flow, surface flow, and shallow channel flow, calculated with Manning's equation for channel flows, slope length and steepness for surface flow.

SWAT assumes that the runoff duration is less than or equal to one day, so all surface runoff reaches the subbasin channel on the day of the rainfall event. SWAT calculates the amount of snowmelt using air and soil temperature. It simulates transmission losses via a regression based on channel length, width, and hydraulic conductivity. It also includes submodels for estimating the effect of ponds and reservoirs on water yield. SWAT's channel routing algorithm is as follows. Flow rate and average velocity are calculated using Manning's equation. Travel time is computed by dividing channel length by velocity. These calculations are done for full channel depth and for one tenth of full channel depth. Travel time is then related to flow using the non-linear relationship:

$$TT = \chi_1 q^{\chi_2}$$

TT = travel time (h)
q = flow rate (m^3/h)
χ_1, χ_2 = parameters determined for each reach when flow is within the channel.

This procedure is repeated for a depth of 1.5 times the full depth of the channel, yielding parameters for each reach for when flow exceeds full channel flow. Storage for each reach is then calculated as:

$$S_i = S_{i-1} + I_i - O_i - TS - EV + dv + rt$$

S_i = storage in reach on current day
S_{i-1} = storage in reach on previous day
I_i = inflow (m^3)
O_i = outflow (m^3)
TS = channel transmission losses (m^3)
EV = evaporation (m^3)
dv = diversions (m^3)
rt = return flow (m^3)

$$O_i = SC\,(I_i + S_{i-1})$$

$$SC = \frac{48}{2TT + 24}$$

HSPF

HSPF uses a kinematic wave unsteady flow analysis to simulate overland flow of water (Viessman *et al.*, 1989). It simplifies the full dynamic equations for surface-water flow to a depth-discharge relation (Manning's equation) and a continuity of mass equation:

depth-discharge relation:

$$q = \frac{1.486}{n} S^{1/2} \left(\frac{D}{L}\right)^{5/3} \left[1.0 + 0.6\left(\frac{D}{D_e}\right)^{3}\right]^{5/3}$$

q = overland flow discharge rate (cfs/ft of width)
D = average detention storage during the time interval (ft^3/ft)
S = slope (ft/ft)
L = length of overland flow (ft)
D_e = surface detention at equilibrium (ft^3/ft)

$$D_e = \frac{0.000818\ i^{0.6}\ n^{0.6}\ L^{1.6}}{S^{0.3}}$$

i = rain rate (in./hr)
n = Manning's roughness coefficient

$$D = \frac{D_1 + D_2}{2}$$

D_1 = surface detention at the beginning of time interval (ft^3/ft)
D_2 = surface detention at the end of time interval (ft^3/ft)

continuity of mass equation:

$$D_2 = D_1 + \Delta D - q \cdot \Delta t$$

D_2 = surface detention at the end of time interval (ft^3/ft)
D_1 = surface detention at the beginning of time interval (ft^3/ft)
ΔD = change in surface detention; calculated via rainfall, infiltration, evapotranspiration, etc. (ft^3/ft)
q = discharge rate from depth-discharge relation (cfs/ft of width)
Δt = length of time interval

The depth discharge relation and the continuity of mass equation are solved simultaneously at each time step to obtain the overland discharge rate, q, and the surface detention at the end of the time step, D_2. These equations allow complete determination of overland flow using easily-obtained data that describe the watershed.

HSPF also includes a river submodel for simulating stream flows and channel flood routing. The formulations will not be presented here.

V.4 Precipitation

The main forcing function for watershed models is precipitation. AGNPS requires the user to input the rainfall amount and the energy intensity of the rainfall for the simulated event. SWAT simulates daily rainfall values using monthly minimum and maximum temperature, monthly temperature variability, mean monthly solar radiation, monthly maximum 0.5 h rainfall, and either monthly rainfall probabilities (*i.e.,* the probability that tomorrow is a wet day given today is a wet day and the probability that tomorrow is a wet day given today is a dry day) or the mean, standard deviation, and skew of the number of days of precipitation in each month. These data can be automatically entered from SWAT's database by supplying the name of the nearest weather station (the model documentation lists the weather stations included in the database). HSPF, on the other hand, requires the user to input continuous (preferably hourly, but at least daily) rainfall data.

V.5 Subsurface Water

AGNPS

AGNPS, SWAT, and HSPF take different approaches to simulating the water under the surface of the watershed. AGNPS uses infiltration only to calculate the amount of soluble nitrogen leached from the surface layer and ignores all other subsurface water. Infiltration is equal to the rainfall minus the runoff volume (Runoff volume is calculated using the SCS curve number method).

SWAT

Infiltration/Percolation

SWAT also uses the SCS curve number method to calculate infiltration. In addition, it simulates the percolation of soil water through up to 10 soil layers, lateral subsurface flow, and groundwater flow in the shallow aquifer. Percolation is simulated using a storage routing technique plus a crack-flow model. To improve accuracy, soil water is routed through the soil layers as a series of 4 mm slugs. The storage routing technique employs these equations:

$$O_i = SW_i\left[1 - \exp\left(\frac{-\Delta t}{TT_i}\right)\right]$$

O_i = percolation rate from layer i (mm/d)
SW_i = soil water content in layer i at the beginning of the day (mm)
Δt = time interval (24 h)
TT_i = travel time through layer i (h)

$$TT_i = \frac{SW_i - FC_i}{H_i}$$

FC_i = field capacity of layer i minus wilting point water content (mm)
H_i = hydraulic conductivity of layer i (mm/h)

$$H_i = SC_i\left(\frac{SW_i}{UL_i}\right)^{\beta_i}$$

SC_i = saturated conductivity for layer i (mm/h)
UL_i = upper limit of soil water storage (porosity minus 15-bar water content, mm)

$$\beta_i = \frac{-2.655}{\log\left(\frac{FC_i}{UL_i}\right)}$$

The percolation rate from layer i, O_i, is then adjusted for the water content of the layer beneath it (layer i+1):

$$O_{ci} = O_i\sqrt{1 - \frac{SW_{i+1}}{UL_{i+1}}}$$

O_{ci} = corrected percolation rate for layer i (mm)
SW_{i+1} = soil water content for layer i+1 (mm)
UL_{i+1} = upper limit of soil water storage for layer i+1 (mm)

No percolation occurs from a soil layer if the layer beneath it is saturated nor if the temperature of the layer is $\leq 0°C$. Water can, however, percolate into a frozen layer and it is allowed to flow upward from a saturated layer to the layer above it. Upward flow is calculated with the following equation:

$$q_{sat} = \frac{24K_sL_s}{L}$$

q_{sat} = upward flow (mm/d)
K_s = saturated conductivity
L_s = saturated slope length (m)
L = hillslope length (m)

The crack flow model estimates the amount of percolation due to crack flow using equations similar to the storage routing technique:

$$O_i = O_{i-1}\exp\left(\frac{-\Delta t}{TT_{ci}}\right)$$

O_{i-1} = percolation from layer above layer i (mm)
TT_{ci} = travel time due to crack flow (mm/h)

$$TT_{ci} = \frac{O_{i-1}}{\zeta_i}$$

ζ_i = dimensionless soil parameter (0-1) that expresses the degree of cracking and is a function of soil water and clay content.

$$\zeta_i = 0.01(CLA_i)\left(1 - \frac{SW_i}{SW_i + \exp(7.0 - 0.11\ SW_i)}\right)$$

CLA_i = clay content of soil layer i (0-1)

SWAT simulates lateral subsurface flow (one part of return flow, QR in the water budget equation) with the following equation:

$$q_{lat} = 0.024\frac{2SK_s\sin(\alpha)}{\Theta_d L}$$

S = drainable volume of water in layer (m/m)
= max(0, SW_i - FC_i)
K_s = saturated conductivity of layer
α = slope of hill (m/m)
Θ_d = drainable porosity of the soil
L = hillslope length (m)

Groundwater

The submodel for estimating groundwater flow in the shallow aquifer was designed for application to ungauged basins, so the parameters can be estimated without extensive calibration. The water that percolates from the root zone recharges the shallow aquifer. Water that percolates from the shallow to the deep aquifer is lost from the simulated system. The water balance for the shallow aquifer is:

$$V_{sa_i} = V_{sa_{i-1}} + Rc - rvp - q_{rf} - p_{gw} - WU_{SA}$$

V_{sa} = shallow aquifer storage
Rc = recharge
rvp = water flow from the shallow aquifer back to the root zone via ET
q_{rf} = return flow
p_{gw} = percolate to the deep aquifer
WU_{SA} = water withdrawn from the shallow aquifer for irrigation, etc.
i = day

$$q_i = q_{i-1}\, e^{-\alpha \Delta t} + Rc(1.0 - e^{-\alpha \Delta t})$$

α = reaction factor

$$Rc = (1.0 - e^{(-1.0/\delta)})\, Rc_i + e^{(-1.0/\delta)}\, Rc_{i-1}$$

δ = delay time or drainage time of the aquifer (days)

$rvp = \beta_r\, ET_{act}$ if $rvp > rvp_{st}$
$= 0.0$ if $rvp \leq rvp_{st}$

rvp_{st} = rvp storage
ET_{act} = actual evapotranspiration occurring in the soil profile
β_r = rvp coefficient

$$p_{gw} = \beta_p\, Rc$$

β_p = percolation coefficient.

The parameters β_p, β_r, δ, and α must be estimated from what is known about the groundwater flow in the watershed basin. The height of the water table is also calculated:

$$h_i = h_{i-1}\, e^{-\alpha Dt} + \frac{Rc}{0.8\, \mu\, \alpha}\left(1.0 - e^{-\alpha \Delta t}\right)$$

μ = specific yield

The water balance for the deep aquifer is

$$V_{da_i} = V_{da_{i-1}} + p_{gw} - WU_{DA}$$

V_{da_i} = deep aquifer storage
p_{gw} = water percolate to the deep aquifer
WU_{DA} = water use (withdrawal) from the deep aquifer.

HSPF

HSPF's method for simulating infiltration comes from the Stanford Watershed Model (see Viessman *et al.*, 1989). It assumes that the infiltration capacity of a watershed follows a linear cumulative distribution function (Fig. 2). The maximum infiltration capacity of a watershed, b, and the maximum interflow capacity, cb-b, are determined by calibrating to hydrologic data from the watershed to be simulated. Then, for a given amount of moisture supply, x, the change in surface detention, ΔD, is the area above the line through cb. The change in interflow detention (the interflow water is equivalent to the lateral subsurface flow calculated in SWAT) is the area between the lines through cb and b. The amount of infiltration in the watershed is the area under the line through b.

This approach is quite the opposite of the approach used by AGNPS and SWAT. Those two models first calculate runoff and then subtract it from the rainfall to determine

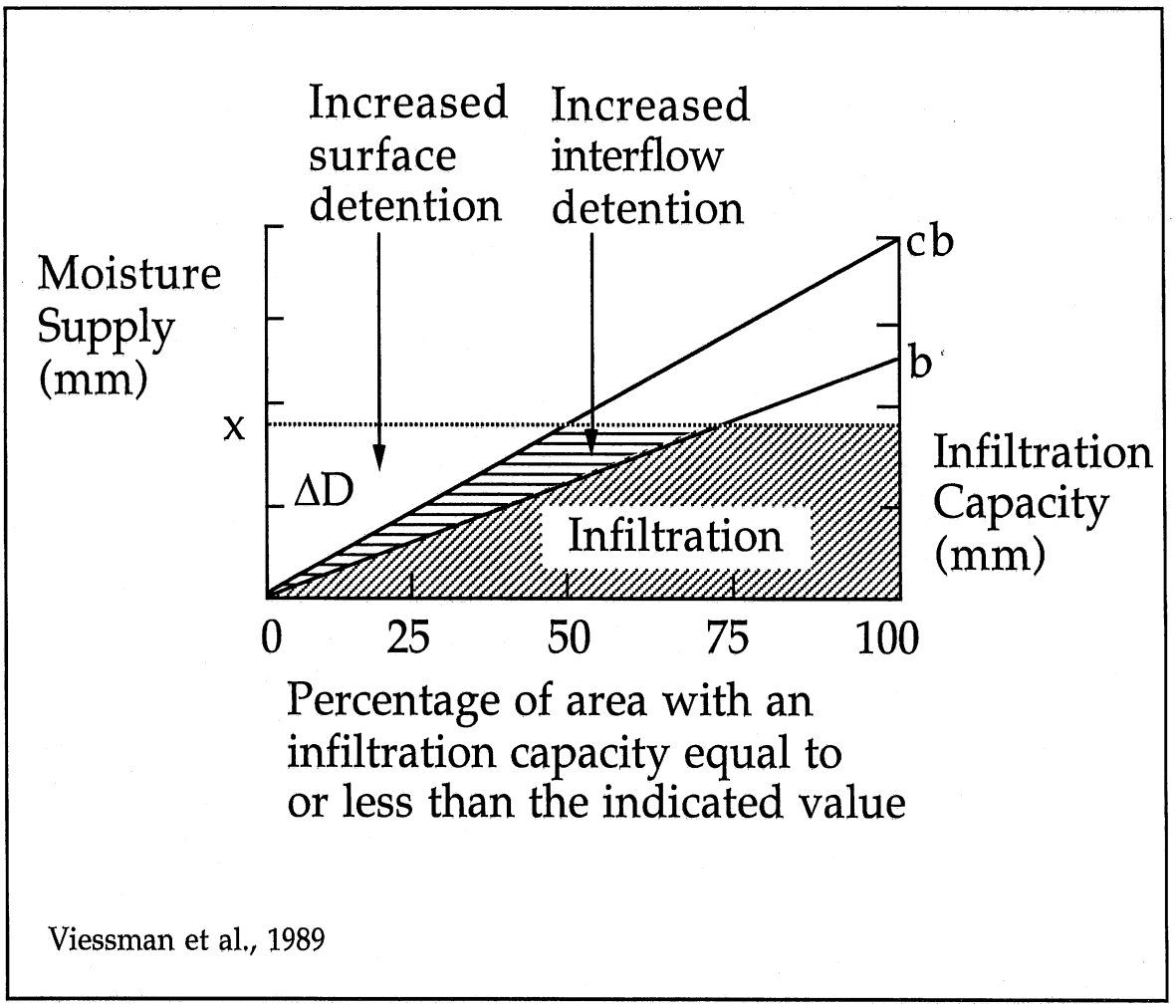

Figure 2: HSPF's method for calculating infiltration, interflow detention, and surface detention.

infiltration. HSPF first calculates infiltration and interflow detention and then subtracts them from the rainfall to get the change in surface detention, which is then used to calculate runoff.

Once infiltration, interflow detention and surface detention are calculated, the following equations are used to calculate interflow, upper and lower storage zones, and groundwater outflow.

interflow

$$IFWO = IFWK1 \cdot INFLO + IFWK2 \cdot IFWS$$

IFWO = interflow outflow (in/time interval)
INFLO = inflow into interflow detention (in/interval)
IFWS = interflow detention at the start of the interval (in)

$$IFWK1 = 1.0 - \frac{IFWK2}{KIFW}$$

$$IFWK2 = 1.0 - \exp(-KIFW)$$

$$KIFW = -\ln(IRC) \cdot \frac{DELT60}{24.0}$$

IRC = interflow recession parameter (1/day), the ratio of the present rate of interflow outflow to the value 24 hours earlier, if there was no inflow. Can be input on a monthly basis.
DELT60 = number of hr/interval
24.0 = number of hours per day

upper storage zone

$$PERC = 0.003 \cdot cb \cdot UZSN \left(\frac{UZS}{UZSN} - \frac{LZS}{LZSN} \right)^3$$

PERC = percolation rate out of upper storage zone (in/hr)
cb = index that controls the rate of infiltration (see Fig. 2)
UZS = current soil moisture storage in the upper zone (in)
UZSN = nominal soil moisture storage amount in the upper zone (in), approximately a function of watershed topography and cover, much smaller than LSZN
LZS = current soil moisture storage in the lower zone (in)
LZSN = nominal storage level in the lower zone (in), normally set equal to the median value of the lower zone storage

lower zone storage

$$P_g = 100 \left[\frac{LZS}{LZSN} \left(\frac{1.0}{1.0 + LZI} \right)^{LZI} \right] \qquad \frac{LZS}{LZSN} < 1.0$$

$$P_g = 100\left[1.0 - \left(\frac{1.0}{1.0 + LZI}\right)^{LZI}\right] \qquad \frac{LZS}{LZSN} > 1.0$$

P_g = percentage of net infiltration that reaches groundwater storage

$$LZI = 1.5\left|\frac{LZS}{LZSN} - 1.0\right| + 1.0$$

groundwater storage

$$GWF = (1.0 - KK24^{1/96})(1.0 + KV \cdot GWS) \cdot SGW$$

GWF = outflow from groundwater storage (in/day)
KK24 = minimum of all the observed daily recession constants, where each constant is the ratio of the groundwater discharge rate to the groundwater discharge rate 24 hr. earlier
GWS = influence of long term inflows to groundwater, value for day i is: $GWS_i = 0.97(GWS_{i-1}$ + inflow to groundwater storage during day i)
SGW = groundwater storage parameter that reflects the fluctuations in the volume of water stored, ranges from 0.10 to 3.90 in.
KV = allows for changes that are known to exist in the groundwater recession rates as time passes.

V.6 Evapotranspiration

Evapotranspiration (ET) involves the interaction between the water, soil, and plant cover of a watershed. In most cases, the ET contribution to the water budget is only significant between rainfall events. Therefore, AGNPS does not simulate ET.

SWAT

SWAT, on the other hand, includes ET and an accompanying crop growth submodel in its simulation of the water budget in a watershed. SWAT first calculates potential ET based on air temperature and solar radiation using one of three methods:

Method 1 -- Priestley-Taylor

$$E_o = 1.28\left(\frac{h_o}{HV}\right)\left(\frac{\delta}{\delta + \gamma}\right)$$

E_o = potential ET (mm)
HV = latent heat of vaporization (MJ/kg), calculated using temperature
δ = slope of saturation pressure curve (kPa/°C), calculated using temperature

γ = psychrometer constant (kPa/°C), calculated using elevation

h_o = net radiation (MJ/s^2), calculated using day of year, latitude, soil albedo, and crop biomass/residue.

Method 2 -- Hargreaves and Samani

$$E_o = 0.0032 \left(\frac{RA_{mx}}{HV}\right)(T + 17.8)\,(T_{mx} - T_{mn})^{0.6}$$

E_o = potential ET (mm)
RA_{mx} = maximum possible solar radiation at the earth's surface (langleys), calculated using day of the year and latitude
HV = latent heat of vaporization (MJ/kg), calculated using mean temperature
T_{mx} = daily maximum air temperature (°C)
T_{mn} = daily minimum air temperature (°C)

Method 3 -- Penman-Montieth

$$E_o = \frac{\dfrac{\delta(h_o - G) + 86.7\ AD\ (e_a - e_d)}{AR}}{HV\ (\delta + \gamma)}$$

$$E_p = \frac{\dfrac{\delta(h_o - G) + 86.7\ AD\ (e_a - e_d)}{AR}}{HV\left(\delta + \gamma\left[1 + \dfrac{CR}{AR}\right]\right)}$$

E_o = potential ET (mm)
E_p = plant water evaporation (mm)
AD = air density (g/m^3)
AR = aerodynamic resistance for heat and vapor transfer (s/m)
CR = canopy resistance for vapor

$$AD = \frac{0.01276\ PB}{1 + 0.0367\ T}$$

$$AR = \frac{6.25\left(\ln\left(\dfrac{10 - ZD}{ZO}\right)\right)^2}{V_w}$$ when crop growing

$$AR = \frac{350}{V_w}$$ when no crop growing

ZD = displacement height of the crop (m)
ZO = surface roughness parameter (m)
V_w = daily mean wind speed (m/s)

$$ZO = 0.131\ CHT^{0.997}$$
$$ZD = 0.702\ CHT^{0.979}$$

CHT = crop height (m)

$$CR = \frac{p_1}{LAI\ (g_o^*)(1.4 - 0.00121\ CO_2)}$$

p_1 = parameter ranging from 1.0 to 2.0
LAI = leaf area index of the crop
g_o^* = leaf conductance (m/s)
CO_2 = carbon dioxide level in atmosphere (ppm)

$$g_o^* = g_o\ (FV)$$

g_o = crop leaf resistance when VPD < threshold VPD
FV = VPD correction factor

$$FV = 1 - b_v\ (VPD - VPD_t) \geq 0.1$$

b_v = crop coefficient
VPD_t = threshold VPD for the crop

SWAT then uses the potential ET and the leaf area index to calculate the actual plant ET (methods 1 and 2):

$$E_p = \frac{E_o\ LAI}{3.0}, \qquad 0 \leq LAI \leq 3.0$$
$$E_p = E_o, \qquad LAI \geq 3.0$$

E_p = predicted plant water evaporation rate (mm/d), reduced if soil water is limited
E_o = potential evaporation (mm)
LAI = leaf area index, calculated using the crop growth submodel.

Potential soil evaporation is calculated using potential ET, a soil cover index, and the actual plant ET.

$$E_{so} = \min\left[E_o EA, \frac{E_o^2\ EA}{E_o EA + E_p}\right]$$

E_{so} = potential soil water evaporation rate (mm/d)
E_o = potential ET (mm)
EA = soil cover index, calculated using crop residue/above ground biomass from the crop growth submodel
E_p = actual plant ET, included so that potential soil evaporation is reduced during periods of high plant water use.

Actual soil evaporation is governed by soil depth and potential soil water evaporation. Any snow pack is evaporated first. Then, using the following equation,

$$EV_Z = E_{so}\left[\frac{Z}{Z + \exp(2.374 - 0.00713\,Z)}\right]$$

EV_Z = total soil water evaporation (mm) from soil of depth Z mm,

soil evaporation is calculated for each layer and adjusted for limited soil water:

$$E_{si} = (EV_{Z(U)} - EV_{Z(L)})\exp\left(\frac{2.5\,(SW_i - FC_i)}{FC_i - WP_i}\right) \qquad SW_i < FC_i$$

$$E_{si} = (EV_{Z(U)} - EV_{Z(L)}), \qquad SW_i \geq FC_i$$

E_{si} = soil water evaporation from layer i (mm)
$Z(U,L)$ = depth at upper and lower limits of layer, respectively (mm)
SW_i = soil water content of layer i (mm)
FC_i = field capacity of layer i (mm)
WP_i = wilting point of layer i (mm).

Finally, soil evaporation is adjusted to assure that soil water supply is greater than or equal to the demand:

$$E_{si} = \min(E_{si}, SW_i - b_w WP_i)$$

b_w = 0.0 - 1.0 in top 0.5 m of soil
= 1.0 below 0.5 m,
allows top 0.5 m of soil to dry down to the specified fraction, b_w, of the wilting point.

HSPF

HSPF simulates ET with an approach similar to its method for calculating infiltration. It assumes that the ET opportunity in a watershed (*i.e.,* the maximum ET possible from a given plot of land given unlimited potential ET) is distributed according to a linear cumulative distribution function (Fig. 3). The maximum ET opportunity in the watershed, r, is determined via calibration. For a given potential ET, E_p, then, the ET is the area under the line through r and the horizontal line through E_p.

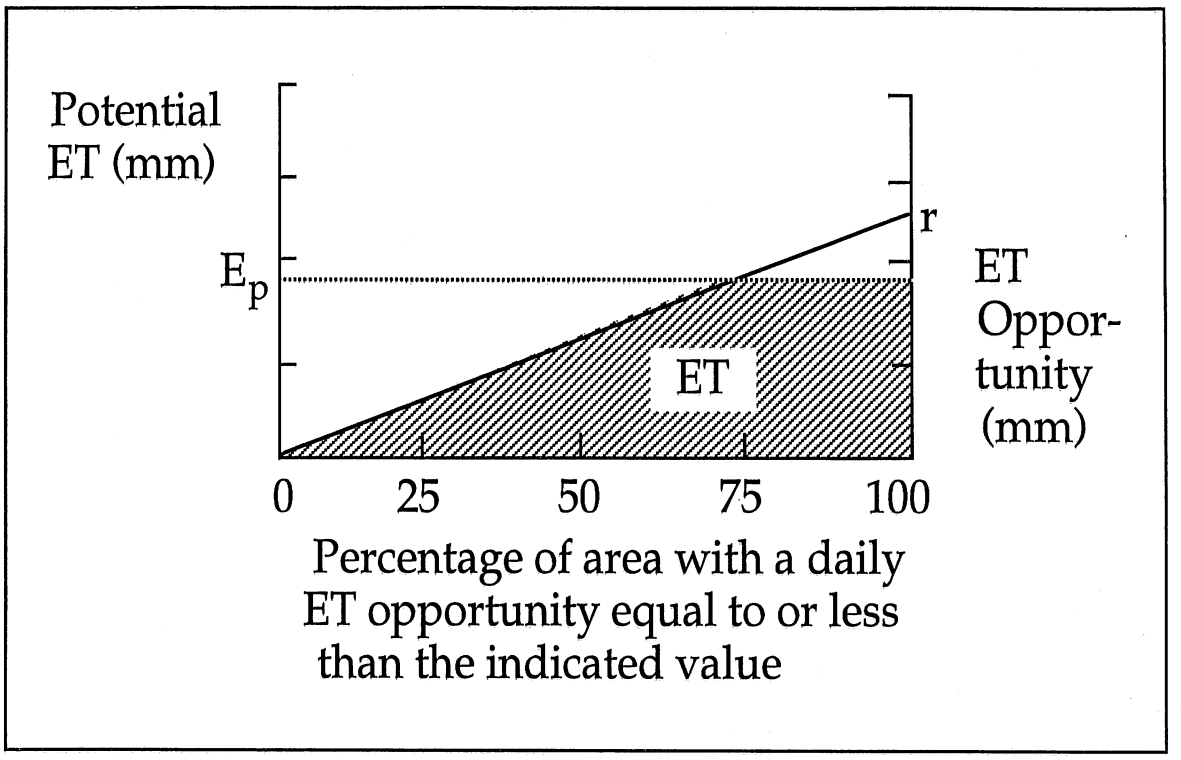

Figure 3: HSPF's method for calculating evapotranspiration.

VI. SEDIMENT MODEL FORMULATIONS

The sediment yield from a watershed is determined by detachment processes and transport processes at work in the basin. AGNPS and SWAT take similar approaches to simulating sediment detachment and transport, separating the calculations for detachment from those for transport, while in HSPF, both types of processes are simulated with the same set of equations.

VI.1 Sediment Detachment

AGNPS

AGNPS uses a modified universal soil loss equation (MUSLE) to estimate sediment erosion:

$$E = EI \cdot K_s \cdot L_f \cdot S_f \cdot C_f \cdot P_f \cdot SSF$$

E	= soil loss (tons/acre)
EI	= rainfall energy-intensity (100 ft-ton in/acre hr)
K_s	= soil erodibility factor (ton-acre hr/100-acre foot-ton in)
L_f	= slope-length factor
S_f	= slope-steepness factor
C_f	= cover and management factor
P_f	= support practice factor
SSF	= slope shape factor

The various factors (except for SSF) are calculated using the methods in Wischmeier and Smith (1978). The slope shape factor was included to account for the increased deposition (and the resulting decrease in soil loss) at the bottom of concave slopes (and vice versa for convex slopes).

The universal soil loss equation, and its modified forms, take into account geographic and temporal information (EI), local topography (L_f and S_f), the relative erodibility of the soil (K_s), and various soil and farming management practices (C_f and P_f). Using this information, it produces an estimate of the average soil loss over the slope length for the time period. AGNPS uses the form that has been modified to produce single-event predictions. The USLE does have some limitations: 1) deposition is not calculated and thus the net sediment yield must be calculated separately, 2) yield from larger scale multifield areas or changing slopes requires empirical techniques, and 3) it does not simulate concentrated flow phenomena such as channel or gully erosion. Its main advantage is that it requires little or no calibration (Leavesley *et al.*, 1990).

SWAT

SWAT uses a slightly different form of the MUSLE. This version calculates the rainfall energy intensity from the runoff volume and peak rate and uses the crop biomass estimate from the crop growth submodel to calculate the crop management factor:

$$Y = 11.8\,(V \cdot q_p)^{0.56} \cdot K \cdot C \cdot PE \cdot LS$$

Y	= sediment yield from the subbasin (metric tons)
V	= surface runoff column for the subbasin (m^3)
q_p	= peak flow rate for the subbasin (m^3/s)
K	= erodibility factor
C	= crop management factor
PE	= erosion control practice factor
LS	= slope length and steepness factor

$$LS = \left(\frac{l}{22.1}\right)^{\xi} \left(65.41\,S^2 + 4.565\,S + 0.065\right),$$

ξ	= 0.6 [1 - exp(-35.835◊ S)]
S	= slope steepness
l	= slope length

$$C = \exp[(-0.2231 - CVM)\exp(-0.00115◊◊CV) + CVM]$$

CV	= soil cover = above ground biomass + residue (kg/ha), from crop growth submodel
CVM	= minimum value of C (kg/ha) = 1.463 ln(CVA) + 0.1034

Values from tables in Wischmeier and Smith (1978):

CVA:	based on crop type
K:	based on soil types
PE:	based on the erosion prevention practices

VI.2 Sediment Transport

AGNPS

In AGNPS, the routing of sediment is done for each cell and each particle size, starting at the headwaters of the basin and proceeding to the outlet. The model represents each watershed cell as shown in Fig. 4. The sediment discharge equation for each of five pre-defined particle sizes, i, is as follows. It incorporates the flow rates, the physical dimensions of the channel, and the particle transport capacity of the channel.

$$Q_{si}(x) = \left[\frac{2q(x)}{2q(x)+DxV_{ssi}}\right] \cdot \left[Q_{si}(0) + Q_{sli} - \frac{\overline{W}Dx}{2} \cdot \left[\frac{V_{ssi}}{q(0)}[q_{si}(0)-g_{si}(0)] - \frac{V_{ssi}}{q(x)g_{si}(x)}\right]\right]$$

$Q_{si}(x)$	= particle discharge at the cell outlet (lbs/s)
q(x)	= discharge per unit width exiting the cell (cfs-ft)
Δx	= channel length across cell (ft)
V_{ssi}	= particle fall velocity (ft/s)

$Q_{si}(0)$ = particle discharge into the cell (lbs/s)

$\overline{W}$ = average channel width (ft)
$q(0)$ = discharge per unit of width into the cell (cfs-ft)
$q_{si}(0)$ = particle discharge per unit of width into the cell (lbs/s-ft)
$g_{si}(0)$ = particle transport capacity into the cell (lbs/s-ft)
$g_{si}(x)$ = particle transport capacity out of the cell (lbs/s-ft)
Q_{sli} = lateral particle inflow rate (lbs/s)

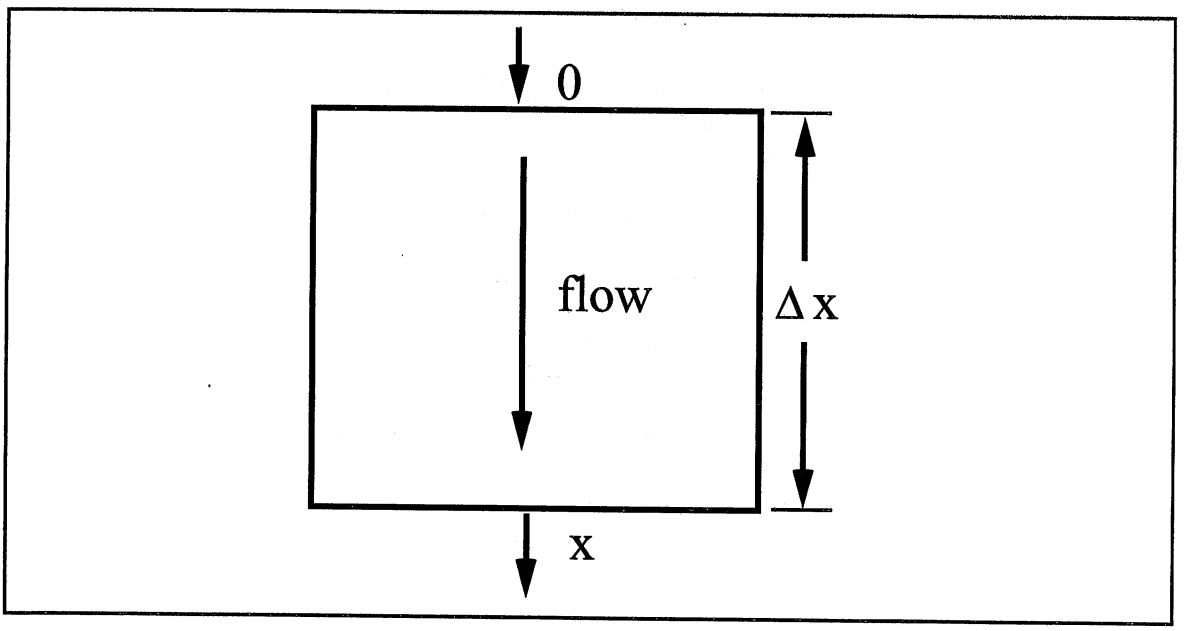

Figure 4: Representative watershed cell.

Sediment discharge is calculated in two periods: while eroded sediment from the upland portions of the cell enters the channel and after erosion has stopped but channel flow continues. Sediment flow at point 0 of a cell, which is the discharge from all upstream cells, remains constant. The flow rates, q(0) and q(x), are equal to $\frac{QP}{W}$, where

W = appropriate channel width (ft)
QP = peak channel flow rate (cfs)

$$QP = 8.484 \cdot A^{0.7} \cdot S_c^{0.159} \cdot RF^{(0.824A^{0.0166})} \cdot \left(\frac{L_c^2}{43560 \cdot A}\right)^{-0.187}$$

A = drainage area (acres)
S_c = channel slope (ft/ft)
RF = runoff volume (in)
L_c = channel length (ft)

The particle transport capacity, g_{si} is calculated as follows:

$$g_{si} = \eta * \kappa * \tau * \frac{V_c^2}{V_{ss}}$$

η = an effective transport factor, based on:
- •specific weight of particles
- •the diameter of particles
- •shear stress
- •specific weight of water

κ = the transport capacity factor, based on:
- •efficiency constant
- •specific weight of particles
- •specific weight of water

τ = shear stress (lbs/ft^2)

V_c = average channel velocity (ft/s)

$$V_c = \frac{1.49}{n} * S_c^{0.5} * R_h^{0.667}$$

n = Manning's roughness coefficient for the channel

S_c = channel slope (ft/ft)

R_h = hydraulic radius (ft)

$$\tau = \gamma_w R_h S_c$$

γ_w = specific weight of water (lbs/ft^3)

Finally, the channelized flow duration, D, is calculated and multiplied by the sediment discharge rate, $Q_{si}(x)$, to get the total mass of sediment discharged to the next cell.

$$D = RF * 3{,}630 * \frac{A}{QP}$$

D = flow duration (s)

QP = peak discharge (cfs)

RF = runoff volume (in)

A = drainage area (acre)

AGNPS also simulates the deposition of sediments in impoundments.

SWAT

SWAT uses a more simplified approach for simulating sediment transport. AGNPS simulates the sediment transport through each cell in the watershed. SWAT simulates the sediment transport by routing the sediment yield from each subbasin through the main channel of the downstream subbasins to the basin outlet. If the subbasins in the simulated watershed are small enough, this method provides a clear

representation of stream transport throughout most of the watershed. The amount of sediment reaching the basin outlet is:

$$SED_{out} = SED_{in} - DEP + DEG$$

SED_{out} = sediment reaching the basin outlet from a subbasin (t)
SED_{in} = sediment entering channel reach (t), the yield from upstream subbasins (calculated via MUSLE and channel routing algorithm)
DEP = sediment deposition (t)
DEG = sediment degradation (t)

Deposition is simulated as follows:

$$DEP = SED_{in}(1 - DR)$$

DR = sediment delivery ratio

$$DR = \frac{1 - 0.5y_f}{d_q} \qquad y_f < d_q$$

$$DR = \frac{0.5d_q}{y_f} \qquad y_f > d_q$$

d_q = depth of flow (m)
y_f = depth (m) that sediment of particle size d will fall during time TT

$$y_f = 411 \cdot d^2 \cdot TT$$ (From Stokes' Law for fall velocity)

d = particle diameter
TT = travel time (h)

$$TT = \frac{L_c}{3.6V_c}$$

L_c = channel length (km)
V_c = velocity in the channel (m/s)

$$V_c = \frac{q_p}{w\, d_q}$$

q_p = peak runoff rate (m^3/s), calculated earlier
w = channel width
d_q = channel flow depth

$$d_q = \left(\frac{q_p n}{w\, S_c^{0.5}}\right)^{0.6}$$

n = Manning's coefficient
S_c = channel slope (m/m)

Degradation is calculated as follows:

$$DEG = (DEG_R + DEG_B)(1 - DR)$$

DEG_R = sediment reintrained (t)
DEG_B = degradation of stream bed material (t)
DR = delivery ratio (same as for deposition)

$$DEG_R = \alpha_{sp}\, \gamma^{1.5}\, DU\, w\, (d_q\, S_W\, V_c)^{1.5}$$

α_{sp} = parameter related to maximum stream power for the reach
γ = density of water
DU = streamflow duration (h)
w = average channel width (m)
d_q = depth of flow (m)
S_W = water surface slope (m/m)
V_c = velocity in the channel (m/h)

$$\alpha_{sp} = (69.44\, \gamma\, DA\, S_c)^{-0.5}$$

γ = density of water
DA = drainage area (ha)
S_c = channel slope (m/m)

$$DU = \frac{QA}{1.8\, q_p}$$

Q = surface runoff volume (mm), calculated earlier
A = drainage area (ha)
q_p = peak runoff rate (m^3/s), calculated earlier

SWAT includes submodels for predicting sediment transport and deposition in and/or through ponds, wetlands, and reservoirs.

VI.3 Detachment and Transport Processes

HSPF

The equations in HSPF for simulating sediment detachment and transport (Fig. 5) distinguish between erosion caused by raindrop impact (interrill) and by shear stress from surface flow (rill) using a transport capacity-deficit relation. HSPF uses a fundamentally-based technique rather than the empirically-based techniques used by AGNPS and SWAT. The advantages of this approach are that it is more physically based, can be more accurately extrapolated, is better at representing spatial diversity, can account for deposition processes directly, and can account for channel erosion and deposition. The

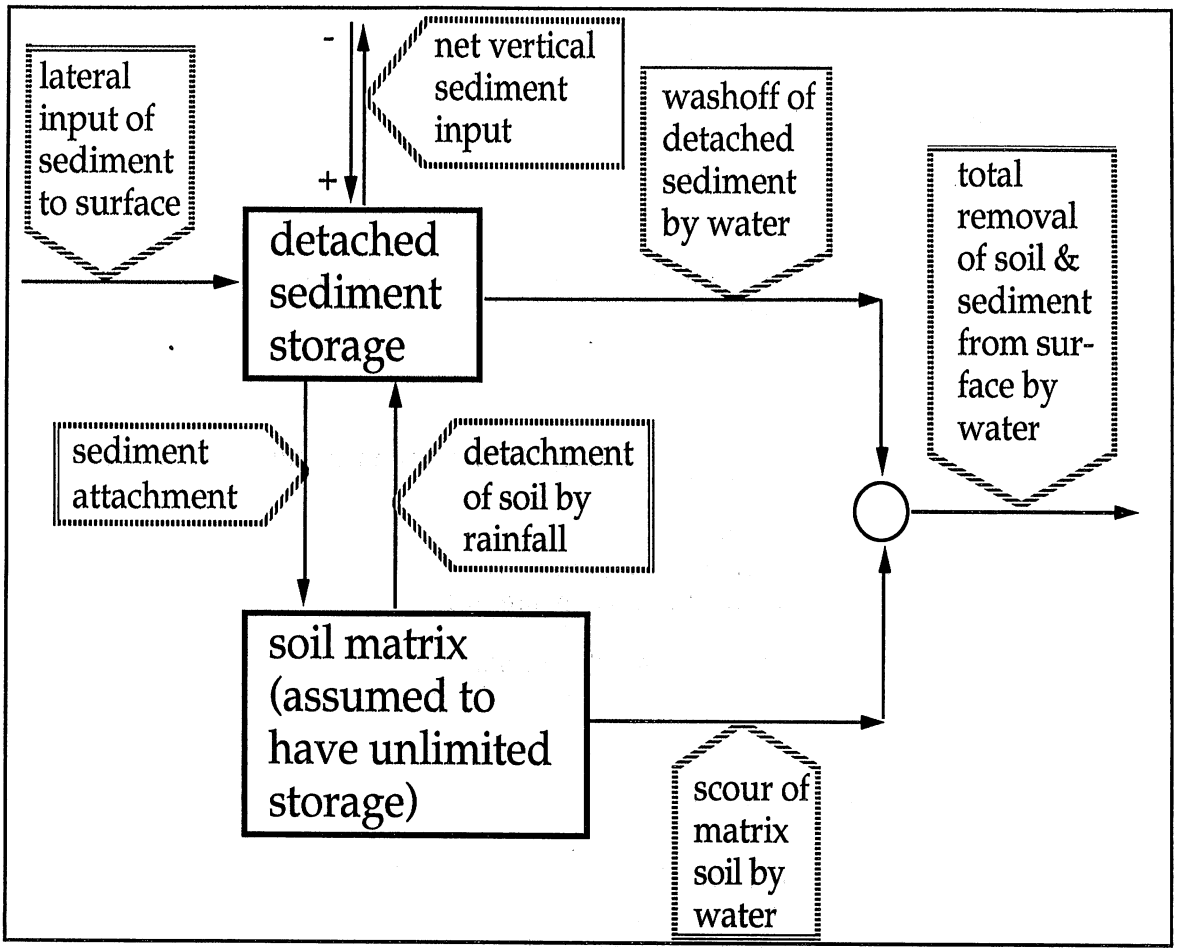

Figure 5: Schematic of the HSPF simulation of erosion by water.

main disadvantage is that the user needs to calibrate the model. The required parameters are not measurable *a priori* (Leavesley *et al.*, 1990).

The main equations used to simulate water erosion in HSPF are as follows. The equations for lateral and net vertical input and for sediment attachment have been omitted here.

detachment of sediment due to rainfall

$$DET = DELT60(1.0 - CR) \cdot SMPF \cdot KRER \cdot \left(\frac{RAIN}{DELT60}\right)^{JRER}$$

DET	= sediment detached from the soil matrix by rainfall (tons/acre/interval)
DELT60	= number of hours per interval
CR	= fraction of the land covered by snow and other cover
SMPF	= supporting management practice factor (based on P factor from USLE)

KRER	= detachment coefficient dependent on soil properties
RAIN	= rainfall (in/interval)
JRER	= detachment exponent dependent on soil properties

washoff of detached sediment

$$STCAP = DELT60 \cdot KSER \cdot \left(\frac{SURS + SURO}{DELT60}\right)^{JSER}$$

STCAP	= capacity for removing detached sediment (tons/acre/interval)
DELT60	= hr/interval
KSER	= coefficient for transport of detached sediment
SURS	= surface water storage (in) = D_e in runoff equations
SURO	= surface outflow of water (in/interval)
JSER	= exponent for transport of detached sediment

When STCAP is greater than the amount of detached sediment in storage, washoff is calculated by:

$$WSSD = DETS \cdot \frac{SURO}{SURS + SURO}$$

If the storage is sufficient to fulfill the transport capacity, then the following relationship is used:

$$WSSD = STCAP \cdot \frac{SURO}{SURS + SURO}$$

WSSD	= washoff of detached sediment (tons/acre/interval)
DETS	= detached sediment storage (tons/acre)

WSSD is then subtracted from DETS.

transport and detachment of soil particles from the soil matrix

$$SCRSD = \frac{SURO}{SURS + SURO} \cdot DELT60 \cdot KGER \cdot \left(\frac{SURS + SURO}{DELT60}\right)^{JGER}$$

SCRSD	= scour of matrix soil (tons/acre/interval)
KGER	= coefficient for scour of the matrix soil
JGER	= exponent for scour of the matrix soil

The sum of the two fluxes, WSSD and SCRSD, represents the total sediment outflow from the land segment.

VII. NUTRIENT MODEL FORMULATIONS

The behavior of phosphorous and nitrogen in watersheds is determined by hydrologic and erosion processes and by chemical processes (Leavesley *et al.,* 1990). Hydrologic and erosion processes determine the extraction, entrainment, transport, and dilution of nutrients. Chemical processes and their interaction determine the types, forms, and amounts of nutrients available for transport and they determine the partitioning between the water- and sediment-transport phases. AGNPS, SWAT, and HSPF take different approaches to simulating these processes. Some advantages and limitations of each modeling approach are listed in Table 2.

Table 2: Advantages and limitations of the three approaches to simulating nutrients in rural watersheds.

Model	Advantages	Limitations
AGNPS	•Uses data that is readily available •Simple approach speeds computation	•Can only simulate single events •Contribution of lower soil layers ignored
SWAT	•Uses data that is readily available •Can simulate watershed response to multiple events •Simulates nutrients in lower soil layers	•Does not simulate transformations between nutrient species within streams and lakes
HSPF	•Simulates all of the relevant forms of N and P and their interaction	•Parameters must be determined by calibration •Can only simulate a well-studied watershed

AGNPS

AGNPS (Fig. 6) simulates nutrients as soluble N, soluble P, sorbed N, and sorbed P in the top 1 cm of the soil. Soluble N and soluble P are added to the soil through fertilizers and soluble N is added from rainfall. The concentrations of soluble N and soluble P in runoff waters and the amount of soluble N leached into lower soil layers are calculated via extraction coefficients. These coefficients are calculated using soil bulk density values, which are easily measured in the field. The concentrations of sorbed N and P in runoff waters are calculated using enrichment ratios. These ratios are calculated using soil texture factors, which can be found in a table in the user's manual, and assume constant sorbed N and sorbed P concentrations in the soil. More specifically, the concentration of soluble N in runoff waters is calculated as follows:

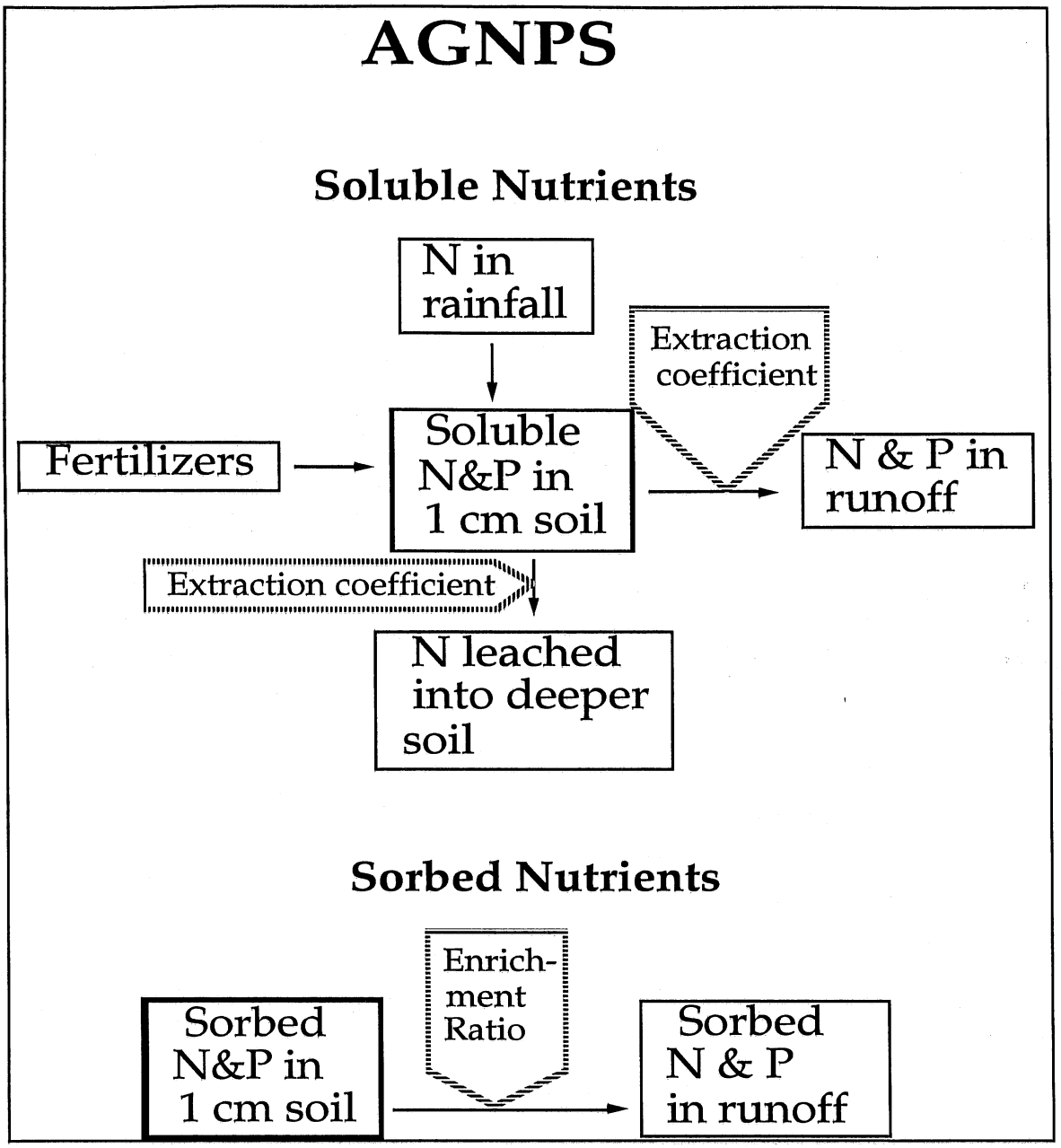

Figure 6: Schematic of AGNPS methods for simulating nutrients.

$$RON = 0.892 * \frac{C^N_{*e}{}^{-k1} - C^N_{*e}{}^{(-k1-k2*RO)}}{COEFF} + \frac{RN*RO}{EFRAIN}$$

RON = soluble N in the runoff

C^N = $C^N_0 - C^N_R$, the difference between the available soluble N in the soil, C^N_0, and the available N due to the

rainfall, C_R^N

k1 = XKFN1*EFI, the product of a rate constant for downward movement of N into the soil, XKFN1, and the total infiltration for the storm, EFI

k2 = a rate constant for N movement into the runoff, assumed to be 0.050

RO = total storm runoff

COEFF= a porosity factor

RN = N contribution due to the rain

EFRAIN = effective rainfall

$$C_0^N = (SOLN + FN(x)*FA(x)) * COEFF$$

SOLN = soluble N in the surface centimeter of the original soil

FN(x) = N fertilizer application in cell x

FA(x) = fraction of this application remaining in the top centimeter of the soil

$$SOLN = 0.10 * CSN * POR$$

CSN = concentration of N in the pore water of the surface centimeter of soil (assumed to be 5 ppm)

POR = soil porosity = $1 - \frac{\text{bulk density}}{2.65}$

$$COEFF = \frac{0.00001}{POR}$$

$$C_R^N = RCN * 10^{-6}$$

RCN = N concentration in the rainfall, assumed to be 0.8 mg/L.

$$XKFN1 = \frac{0.25}{10*POR}$$

$$EFI = EFRAIN - RO$$

EFRAIN = effective rainfall
= R - 10*POR

R = storm rainfall

RO = total storm runoff

$$XKFN2 = \frac{0.050}{10*POR}$$

$$RN = RCN * R * 0.01$$

AGNPS's equations for soluble P are similar to the equations for soluble N, but contributions from rainfall are omitted.

$$ROP = 0.892 * \frac{C^P * e^{-k1} - C^P * e^{(-k1-k2*RO)}}{COEFF} + \frac{C_S^P * RO}{COEFF}$$

ROP = soluble P in the runoff

$C^P = C_0^P - C_S^P$, the difference between the available soluble P due to natural and fertilizer nutrient level, C_0^P, and the available P due to the initial soil, C_S^P

k1 = XKFP1*EFI, the product of a rate constant for downward movement of P into the soil, XKFP1, and the total infiltration for the storm, EFI

k2 = a rate constant for P movement into the runoff

RO = total storm runoff

COEFF= a porosity factor

$$C_0^P = (SOLP + FP(x)*FA(x)) * COEFF$$

SOLP = soluble P in the top cm of the original soil

FP(x) = P fertilizer application in cell x

COEFF & POR are the same as in soluble N eqn.

$$SOLP = 0.10*CSP*POR$$

CSP = concentration of P in the pore water of the surface centimeter, assumed to be 2 ppm

$$C_S^P = SOLP * COEFF$$

$$XKFP1 = \frac{0.25}{10*POR}$$

$$XKFP2 = \frac{0.025}{10*POR}$$

The sorbed nutrient yield is calculated in AGNPS as follows:

$$SED- = SOIL * SED * ER * 0.892$$

SED- = N or P transported by the sediment

SOIL = sediment yield
= 0.001 lb N/lb soil and
= 0.0005 lb P/lb soil

ER = enrichment ratio
$= 7.4SED^{-0.20} * T_f$

T_f = correction factor for soil texture, values available in user documentation

SWAT

SWAT simulates nutrients as nitrate-N, organic N, soluble P, and sorbed P. It represents the movement of these nutrients through soil, runoff, streams and pond (Fig. 7) and the chemical transformation between species in the soil (Fig. 8).

Fertilizers provide the input of nutrients to the top 1 cm of soil (Fig. 7). The extraction rates for nitrate-N are calculated via the water flow rate, the mass of nitrate-N in the soil layer, and the soil porosity. The extraction rate for soluble P is calculated via the soil-water partitioning coefficient for phosphorous. The concentrations of sorbed N and P in runoff waters are calculated using enrichment ratios. These ratios are calculated using the sediment concentration and the sediment delivery ratio, which in turn is calculated using rates determined in the hydrology portion of the model. More specifically, the nitrate-N (soluble N) loss to surface runoff from the top 1 cm soil layer is calculated as follows:

$$VNO3 = WNO3\left(1 - \exp\left[\frac{-QT}{PO_1 - WP_1}\right]\right)$$

VNO3 = amount of NO_3-N lost from the first layer of soil
WNO3 = weight of NO_3-N at end of day
QT = total flow leaving soil layer
PO_1 = porosity of first soil layer
WP_1 = wilting point in first soil layer (mm)

$$QT = Q + O_1 + QR_1$$

Q = runoff volume
O_1 = percolation volume from layer 1
QR_1 = lateral subsurface flow from layer 1

The average concentration of nitrate-N, C_{NO3}, in the total flow, QT, for each day is:

$$C_{NO3} = \frac{VNO3}{QT}$$

Leaching and lateral subsurface flow of nitrate-N from the lower soil layers (up to 10) is calculated in the same manner, except surface runoff is not included.

Organic-N (sorbed N) is simulated using the following equations:

$$YON = 0.001 \cdot Y \cdot CON \cdot ER$$

YON = organic N runoff loss at the subbasin outlet (kg/ha)
Y = sediment yield (t/ha), calculated earlier
CON = concentration of organic N in the top soil layer (g/t), constant value input by user
ER = enrichment ratio

$$ER = x_1 c_a^{x2}$$

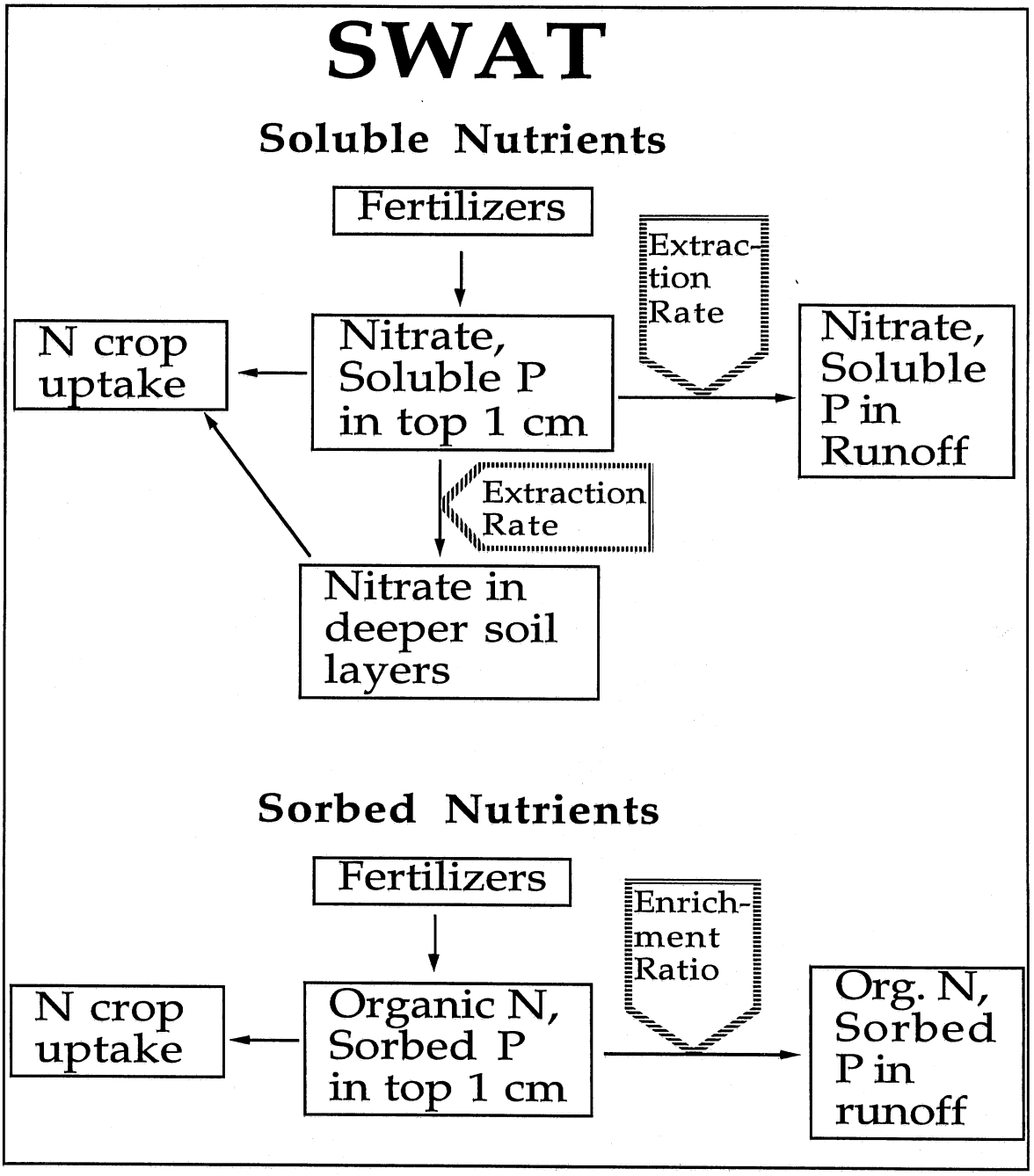

Figure 7: Schematic of SWAT methods for simulating nutrients.

$$x_1 = \frac{1}{0.25^{x_2}}$$

$$x_2 = \frac{-\log(DR)}{2.699}$$

DR = delivery ratio

$$DR = \left(\frac{q_p}{r_p - f}\right)^{0.56}$$

q_p = peak runoff rate (mm/h)
r_p = peak rainfall rate (mm/h)
f = average infiltration rate (mm/h)

$$f = R - \frac{Q}{4.605 \cdot R/r_p}$$

R = rainfall (mm)
Q = runoff volume (mm)

Crop use of N is estimated for each day, i, using a supply and demand approach:

$$UND_i = (C_{NB})_i \cdot B_i - (C_{NB})_{i-1} \cdot B_{i-1}$$

UND = N demand of the crop (kg/ha)
C_{NB} = optimal N concentration in the crop
B = N accumulated by crop (kg/ha)
i = current day
i-1 = previous day

$$C_{NB} = 4.0\ bn + 1.54\ bn \exp(-bn\ B_1)$$

bn = crop parameter expressing N concentration
B_1 = fraction of the growing season

$$B_{1,i} = \sum_{k=1}^{i} \frac{HU_k}{PHU}$$

HU_k = daily heat units above the crop's base temperature (°C)
PHU = potential heat units to mature the crop (°C)

The crop is allowed to take N from any soil layer that has roots. Uptake starts at the upper layer and proceeds downward until the daily demand is met or until all N has been depleted. If the soil cannot supply the daily N demand for legumes, the deficit is attributed to N fixation.

Since it is a small fraction of the total P transported in a watershed, soluble P lost to surface runoff is simulated in SWAT using a simple partitioning coefficient:

$$YSP = \frac{0.01 \cdot C_{LP} \cdot Q}{k_d}$$

YSP = soluble P lost to runoff (kg/ha)

C_{LP} = concentration of available P in top soil layer (kg/ha), constant value input by user
Q = runoff volume (mm)
k_d = partitioning coefficient (concentration in sediment divided by concentration in water) = 175

The sediment transport of P is simulated with a function similar to that used for simulating organic N:

$$YP = 0.01 \cdot Y \cdot C_p \cdot ER$$

YP = sorbed P lost to runoff (kg/ha)
Y = sediment yield (t/ha)
C_p = concentration of P in top soil layer (g/t)
ER = enrichment ratio, same as for organic N

Fertilizer application rates and dates for N and P are input by the user. The entire amount of N and P is added to the first soil layer and is considered available for water and sediment transport, leaching and crop uptake.

After the movements of N and P in and through the subbasins have been calculated, SWAT simulates the routing of N and P from the subbasin outlets through the main channels in downstream subbasins to the basin outlet using an enrichment ratio approach:

$$Y_x = \sum_{j=1}^{nsb} 0.01 \cdot Y_{Bj} \cdot C_{Bxj} \cdot ER_{Rj}$$

Y_x = organic N or sorbed P yield at the basin outlet (kg/ha)
nsb = number of subbasins
Y_{Bj} = sediment yield reaching the basin outlet from subbasin j (t/ha)
C_{Bxj} = concentration of organic N or sorbed P in the sediment reaching the subbasin j outlet (g/t)
ER_{Rj} = enrichment ratio for the channel routing from subbasin j to the channel outlet.

The enrichment ratio is calculated using the same equations as the ER for nutrient routing within the subbasins, but with the following delivery ratio:

$$DR = \frac{Y_{SBj}}{Y_{Bj}}$$

Y_{SBj} = sediment yield at the outlet of subbasin j (t/ha)
Y_{Bj} = sediment yield from subbasin j after it has been routed to the basin outlet (t/ha)

The chemical transformations simulated by SWAT (Fig. 8) are the denitrification, mineralization and immobilization of N in the soil and the mineralization and immobilization of P in the soil. SWAT uses temperature, water content, and some assumptions concerning C:N:P ratios and microbial assimilation rates to simulate these transformations.

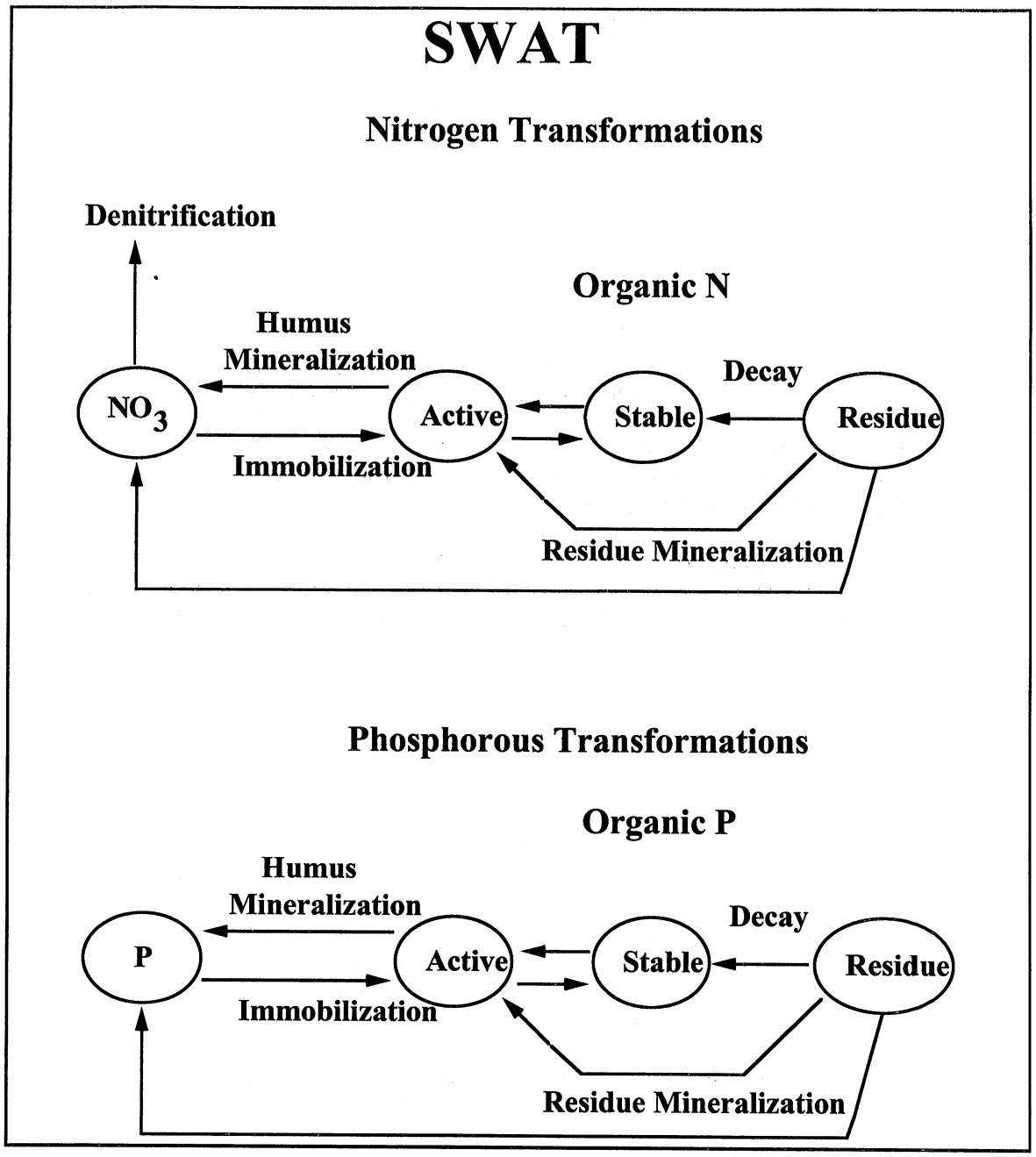

Figure 8 Nutrient transformations simulated by SWAT.

Finally, SWAT includes a submodel for predicting lake water quality. The lake water quality submodel simulates the lake toxic balance, the soil-liquid partitioning of toxic chemicals, and the lake phosphorous mass balance.

HSPF

HSPF (Figs. 9 & 10) simulates nutrients as ammonium in solution, sorbed ammonium, nitrate (plus nitrite), organic N, plant N, plant P, organic P, phosphate in solution, and sorbed phosphate. The kinetics of these species are represented with temperature-corrected first order rate constants. HSPF also provides the option of using a Freundlich isotherm for calculating adsorption/desorption kinetics. The rate constants are not easily measured. They are typically determined by calibrating to detailed nutrient

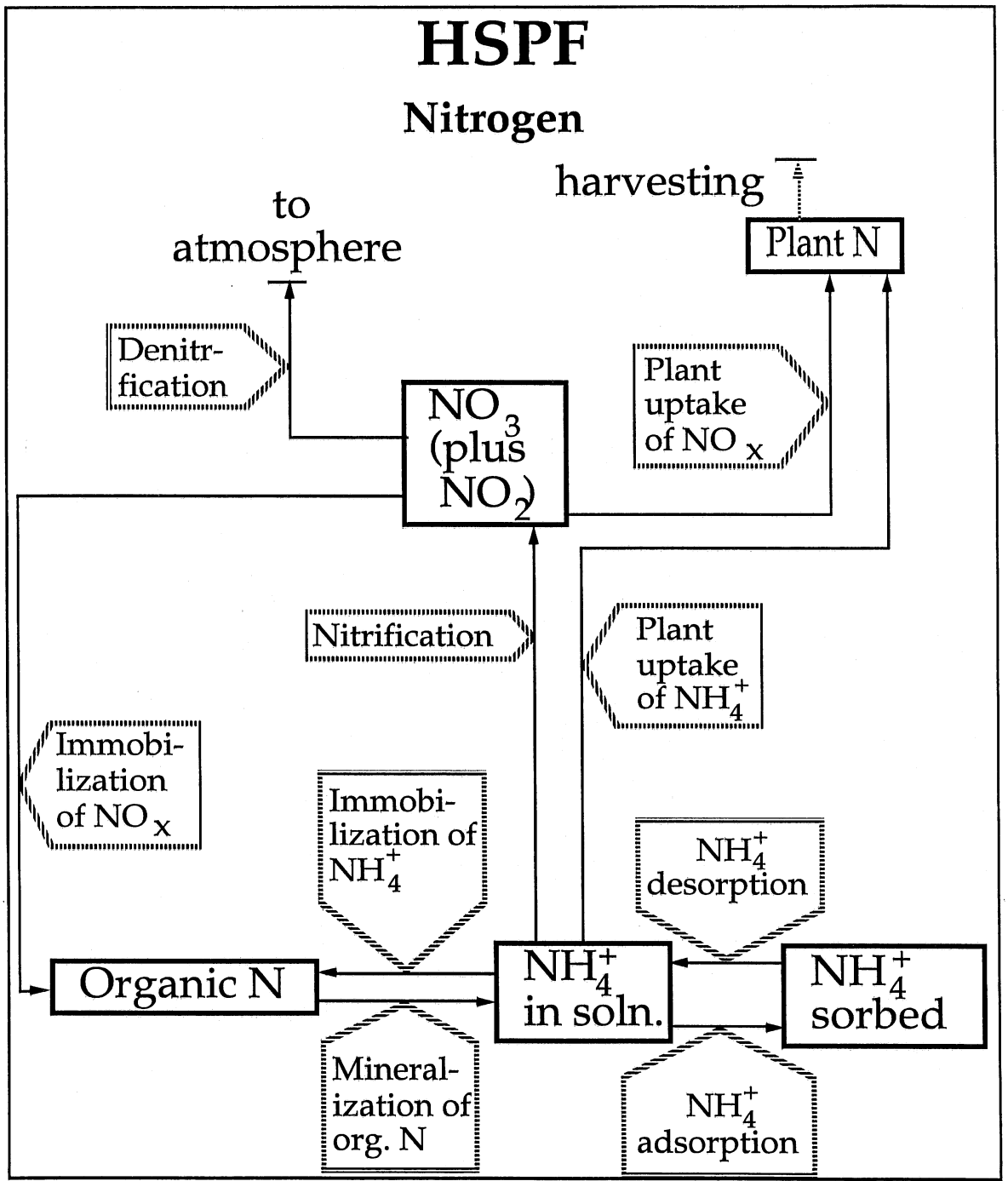

Figure 9: Schematic of HSPF methods for simulating nitrogen.

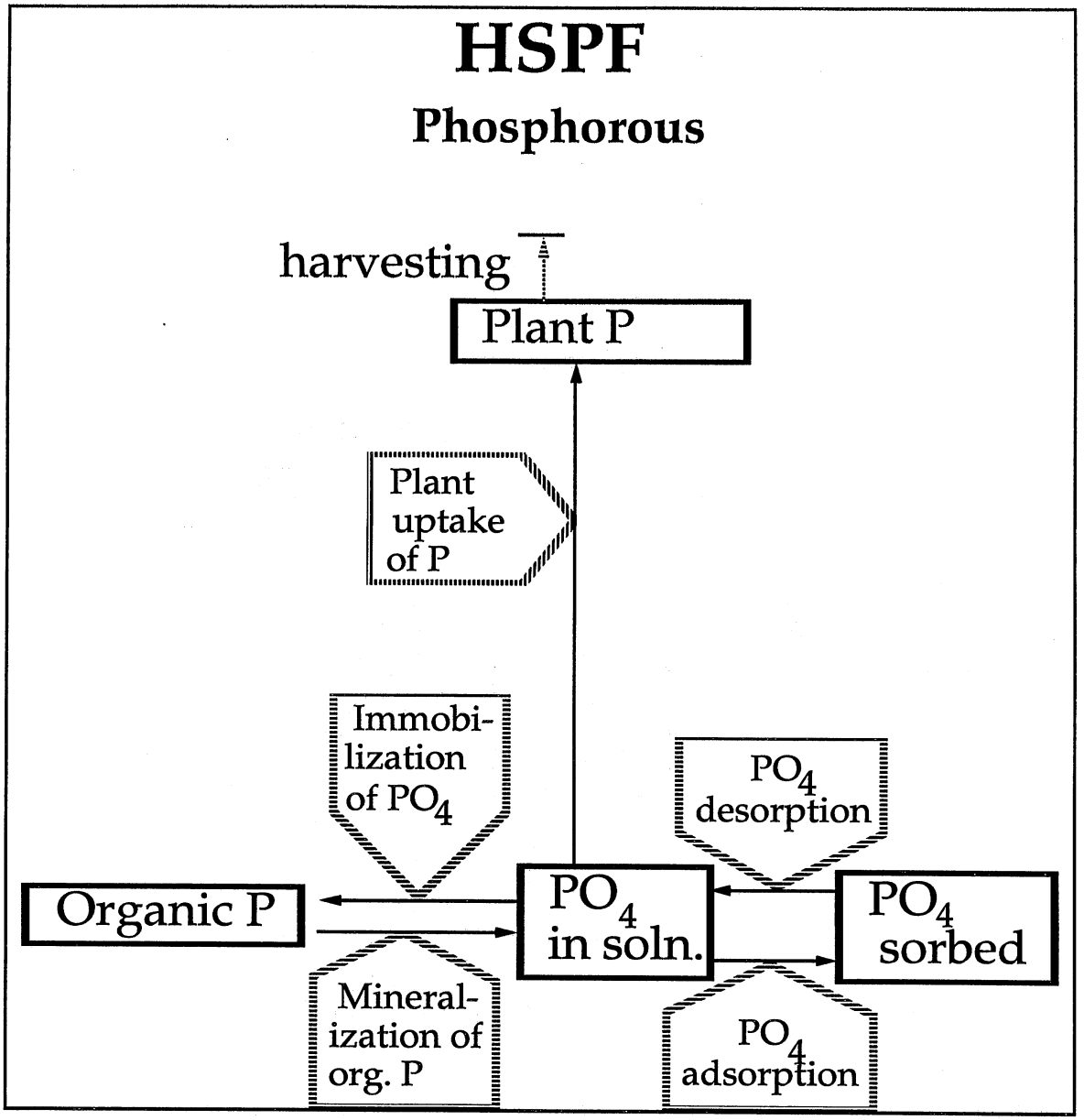

Figure 10: Schematic of HSPF methods for simulating phosphorous.

data from the watershed the model will be used to simulate. Once the concentrations of the nutrients due to transformations have been determined the transport of nutrients is calculated as follows:

sediment associated nutrients

$$WASHQS = WSSD \cdot POTFW$$

WASHQS = flux of nutrient associated with detached sediment washoff (mass/acre)

WSSD = washoff of detached sediment (tons/acre/interval)
POTFW = washoff potency factor (mass/ton)

$$SCRQS = SCRSD \cdot POTFS$$

SCRQS = flux of nutrient associated with scouring of the matrix soil (mass/acre)
SCRSD = scour of matrix soil (tons/acre/interval)
POTFS = scour potency factor (mass/ton)

WASHQS and SCRQS are combined to give the total sediment associated flux of the constituent from the land segment.

soluble nutrients

$$SOQO = SQO \cdot (1.0 - \exp(-SURO \cdot WSFAC))$$

SOQO = washoff of the nutrient from the land surface (mass/acre/interval)
SQO = storage of available nutrient on the surface (mass/acre)
SURO = surface outflow of water (in/interval)
WSFAC = susceptibility of the nutrient to washoff (1/in)

$$SQO = ACQOP + SQOS(1.0 - REMQOP)$$

ACQPO = accumulation rate of the nutrient (mass/acre/day)
SQOS = SQO at the start of the interval
REMQOP = unit removal rate of the stored nutrient (1/day)

$$REMQOP = \frac{ACQOP}{SQOLIM}$$

SQOLIM = asymptotic limit for SQO as time approaches infinity if no washoff occurs (mass/acre)

$$WSFAC = \frac{2.30}{WSQOP}$$

WSQOP = rate of surface runoff which results in a 90% washoff in one hour (in/hr)

HSPF also simulates, in some detail, the hydrology, sediment transport and deposition, and nutrient kinetics within streams and well-mixed reservoirs.

VIII. CONCLUSIONS

The overall goal of the research project, of which this report is a part, is to estimate the change in the non-point source inputs to lakes from rural watersheds. A model that can be applied to ungauged watersheds and will simulate the watershed over time is required. Therefore, a continuous basin model would be the best choice for this work. The event-based, empirical models, such as the Agricultural Non-Point Source Pollution Model (AGNPS; Young *et al.,* 1994), do not have the capability to simulate the watershed response over time. The field-scale models, such as the Erosion Prediction Impact Calculator (EPIC; Williams *et al.,* 1984), do not incorporate a large enough geographic scale. The continuous-based process models, such as the Hydrologic Simulation Program - FORTRAN (HSPF; Johanson *et al.,* 1984), typically require calibration to measurements of rainfall depth, runoff and flow volume, and suspended solid and nutrient concentrations in the watershed of interest. This amount of data is only available for experimental watersheds, so it would be very difficult to apply HSPF to a number of watersheds in a geographic region. A continuous, empirically based model that is a good candidate for this project is the Soil and Water Assessment Tool (SWAT; Arnold *et al.,* 1994). This model simulates, over time, the runoff volumes, peak flow volumes, nutrient concentrations and suspended solid concentrations in a watershed using input data that can be obtained via topographic and land cover maps, site visits, and/or remote sensing. Since it requires little or no calibration, SWAT can be applied to ungauged watersheds.

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