LARGE AREA HYDROLOGIC MODELING AND ASSESSMENT
PART I: MODEL DEVELOPMENT

J. G. Arnold, R. Srinivasan, R. S. Mutiah, and J. R. Williams

ABSTRACT: A conceptual, continuous time model called SWAT (Soil and Water Assessment Tool) was developed to assist water resource managers in assessing the impact of management on water supplies and nonpoint source pollutants in watershed and large river basins. The model is currently being utilized in several large area projects by EPA, USDA, NRCS and others to estimate the effects of climate change on water resources, nonpoint source loads, and pesticide contamination. Model development, operation, limitations, and assumptions are discussed and components of the model are described. In Part II a GIS input-output surface is presented along with model validation on three areas within the Upper Trinity basin in Texas. (TDAM: simulation; surface water hydrology; erosion; sediment; nonpoint source pollution; large area modeling; plant growth; agricultural land management.)

INTRODUCTION

Large area water resources development and management require an understanding of basins and estimation of water supplies and nonpoint source pollution. Large scale flooding, and offsite impacts of land management. Recent advances in water hardware and software increasing increased storage, advanced software debugging and GIS/spatial analysis software have allowed area development to become feasible. The challenge is to develop a basin-scale model that: computationally efficient; (2) allows consideration of spatial detail; (3) requires readily available input; (4) is continuous in time; (5) is capable of simulating management scenarios; and (6) gives reasonable results. The model must correctly reflect changes in land use and agricultural management on stream flow and sediment yield. Available models with these capabilities are generally limited by spatial scale. Available river-basin models generally do not link outputs to land use and management adequately to evaluate management strategies. Also, most are single-event models. We chose good agricultural management models to link with simple efficient, yet realistic routing components for the purpose of capturing management effects on large river basins through long-term simulations.

The objective of this overview is to briefly describe an overview of model operation, model applications, and a description of model components of a river basin scale model called SWAT (Soil and Water Assessment Tool).

LITERATURE REVIEW

Integrated water management of large areas should be accomplished within a spatial unit (the watershed) through modeling. Integrated water management can be viewed as a three or more dimension process centered around the need for water, the policy to meet the needs, and the management to implement the policy. Watershed modeling is fundamental to integrated management. Watershed models abound in the hydrological literature (Sohug, 1989) and state-of-the-art of watershed modeling is reasonably advanced. However, these models have yet to become common planning or decision making tools. A
majority of watershed models simulate watershed response without or with inadequate consideration of water quality. If these models are to be used for environmental or ecological modeling, they must consider water quality (Singh, 1985).

A number of developments of the Stanford Watershed Model (Crawford and Linsey, 1986) numerous operational, lumped or "conceptual" models have been developed. These include: SOARX (Rockwood et al., 1972), the Sacramento model (Burnash et al., 1973), the task model (Sugawara et al., 1976); HEC-1 (Hydroligic Engineering Center, 1981), HYMO (Williams and Henn, 1973), and ROBB (Laurenson and Mein, 1982). In these models, some processes are described by differential equations based on simplified hydraulic laws, and other processes are expressed by empirical algebraic equations. More recent conceptual models have incorporated soil moisture replenishment, depletion and redistribution for the dynamic variation in areas contributing to direct runoff. Several models have been developed from this concept which use a probability distribution of soil moisture including the ARNO model (Tokini, 1980; Zhu, 1984; Moore and Clarke, 1981) or the use of a topographic index, as in ZOMPOMEL (Beven and Kirkby, 1978; Beven et al., 1984). Jayachitra et al. (1988) recently developed a variable source conceptual model that shows promise for incorporation into comprehensive models.

Another class of hydrological models is a differential model based on conservation of mass, energy, and momentum. Examples of differential models include SHE (Abbot et al., 1986a, 1986b), IDRIM (Beven et al., 1987), and Bieley et al. (1989). The SHE model simulates water movement in a basin with the finite difference solution of the partial differential equations describing the processes of overland and channel flow, unsaturated and saturated subsurface flow, interception, ET, and snowmelt. The spatial distribution of catchment parameters is achieved by representing the basin on an orthogonal grid network. Jain et al. (1992) successfully applied the SHE model to an 850 km² catchment in central India. However, they note that the data requirements are substantial. Jain et al. (1992) also concluded that the strength of differential models like SHE "lies beyond the field of pure rainfall-runoff modeling, for which purpose traditional and simpler hydrologic models often perform equally well."

In the early 1970s work also began on non-point source modeling in response to the Clean Water Act. The CREAMS model (Krisel, 1986) was developed to simulate the impact of land management on water, sediment, and agricultural chemical yields. Several field scale models evolved from the

SCALING ISSUES

Scaling and its impacts are directly related to the areal extent which can be traced to two major sources. The principal sources of heterogeneities are differences in climate, topography, soil, and geology which govern the hydrologic response. The other source is the discontinuities or boundaries separating soil types, geologic formations, or land covers (upstream range). This leads to defining a scale as a size of a cell or subwatershed within which the hydrologic process can be treated as homogeneous (Singh, 1980). Spatial variability of precipitation can dominate the water balance of large watersheds, particularly in dry and mountainous areas. Barros and Lettenmaier (1993) developed, implemented, and applied a logistical to simulate geographic indexed precipitation. The model was designed to reproduce the properties of individual storms and (to estimate the long term hydroclimatolgy of large regions. Coupling with a spatially distributed surface-energy model improved the assessment of the hydrological balance throughout the spatial domain (Barros and Lettenmaier, 1993).

MODEL OPERATION

SWAT is an operational or conceptual model that operates on a daily time step. The objective of model development was to predict the impact of management on water, sediment, and agricultural chemical yields in large ungauged basins. To satisfy the objective, the model (a) does not require calibration (calibration is not possible on ungauged basins), (b) uses readily available inputs for large areas, (c) computationally efficient to operate on large basins.
A reasonable time, and (d) is continuous time and capable of simulating long periods for computing the effects of management changes.

A command structure is used for routing runoff and chemicals through a watershed similar to the structure of HYMO (Williams and Hann, 1973). Commands are included for routing flows through streams and reservoirs, adding flows, and inputting measured data on point sources (Figure 1). Using the routing command language, the model can simulate a basin subdivided into grid cells or subwatersheds. Additional commands have been developed to allow measured and point source data to be input to the model and routed with simulated flows.

Although the model operates on a daily time step and is efficient enough to run for many years, it is intended as a long-term yield model and is not capable of detailed, single-event flood routing.

**MODEL COMPONENTS**

The subbasin components can be placed into eight major divisions—hydrology, weather, sedimentation, temperature, crop growth, nutrients, pesticides, and agricultural management.

The hydrology model is based on the water balance equation (Figure 2).

\[
SW = \sum_{i=1}^{n} (R_i - Q_i - ET_i - P_i - QR_i)
\]

(1)

SW is the soil water content minus the 15-hour content, is in days, and R, Q, ET, P, and QR are the daily amounts of precipitation, runoff, evaporation, and return flow; all are in mm. The model maintains a continuous water balance by subdividing basins to reflect different ET for various crops, soils, etc. Thus, runoff, evaporation, and return flow are calculated separately for each subarea (Figure 2) to obtain the total runoff for the basin. The model uses accuracy and gives a better physical basis for the water balance.

**Runoff Volume.** Surface runoff is predicted by using the SCS curve number (USDA-SCS, 1972).

\[
Q = \frac{(R - 0.2 s)^2}{R + 0.8 s} \quad R > 0.2 s
\]

(2)

\[
Q = 0.0, \quad R \leq 0.2 s
\]

where Q is the daily surface runoff (mm), R is the daily rainfall (mm), and s is a retention parameter. The retention parameter, s, varies a) among watersheds because soils, land use, management, and slope all vary and b) with time because of changes in soil water content. The parameter s is related to curve number (CN) by the SCS equation (USDA-SCS, 1972).

\[
s = 254 \left( \frac{100}{CN} - 1 \right)
\]

(3)

The constant, 254, in Equation (3) gives s in mm. Fluctuations in soil water content cause the retention parameter to change according to the equation

\[
s = s_i \left( 1 - \frac{FCC}{FCC + \exp[w_1 - w_2(FCC)]} \right)
\]

(4)

where s is the value of s associated with CN, FCC is the fraction of field capacity, and w and w are shape parameters. FCC is computed with the equation

\[
FCC = \frac{SW - WP}{FC - WP}
\]

(5)

where SW is the soil water content in the root zone (mm), WP is the wilting point water content (1,500 kPa for many soils), and FC is the field capacity water content (mm) (33 kPa for many soils). Values for w and w are obtained from a simultaneous solution of Equation (4) according to the assumptions that s = s when FCC = 0.6 and s = s when (SW-FC)/FC = 0.5.

There are two options for estimating the peak runoff rate—the modified Rational formula and the SCS TR-55 method (USDA-SCS, 1986). A stochastic element is included in the Rational equation to allow realistic simulation of peak runoff rates, given only daily rainfall and monthly rainfall intensity.

**Percolation.** The percolation component uses a storage routing technique combined with a crack-flow model to predict flow through each soil layer. Once water percolates below the rootzone, it is lost from the watershed (becomes ground water or appears as return flow in downstream basins). The storage routing technique is based on the equation
\[ SW_i = \frac{SW_{0i}}{TT_i} \exp \left( -\frac{M}{TT_i} \right) \]  

where \( SW_0 \) and \( SW \) are the soil water contents (mn) at the beginning and end of the day, respectively; \( \Delta t \) is the time interval (24 h); and \( TT \) is the travel time (h) through layer \( i \). Thus, the percolation can be computed by subtracting \( SW \) from \( SW_0 \).

\[ O_i = SW_{0i} \left[ 1 - \exp \left( -\frac{\Delta t}{TT_i} \right) \right] \]  

where \( O \) is the percolation rate (mm-d\(^{-1}\)).

The travel time, \( TT_i \), is computed for each soil layer with the linear storage equation

\[ TT_i = \frac{(SW_i - FC_i)}{H_i} \]

where \( H_i \) is the hydraulic conductivity (mm-h\(^{-1}\)) and \( FC \) is the field capacity minus wilting point water content for layer \( i \) in mm. The hydraulic conductivity is varied from the saturated conductivity value at saturation to near zero at field capacity.

\[ H_i = SC_i \left( \frac{SW_i}{UL_i} \right) ^\beta \]

where \( SC_i \) is the saturated conductivity for layer \( i \) (mm-h\(^{-1}\)) and \( \beta \) is a parameter that causes \( H_i \) to approach zero as \( SW_i \) approaches \( FC_i \).

The equation for estimating \( \beta \) is

\[ \beta_i = \frac{-2.655}{\log_{10} \left( \frac{UL_i}{UL_4} \right)} \]

The constant (-2.655) in Equation (10) was set to assure \( H_1 = 0.002SC_i \) at field capacity.
Figure 3. Hydrologic Flow Chart of SWAT Subbasin Model.
may occur when a lower layer exceeds field capacity. Movement from a lower layer to an adjoining upper layer is regulated by the soil water to field capacity ratios of the two layers. Percolation is also affected by soil temperature. If the temperature in a particular layer is 0°C or below, no percolation is allowed from that layer.

**Lateral Subsurface Flow.** Lateral subsurface flow in the soil profile (0-2 m) is calculated simultaneously with percolation. A kinematic storage model (Sloan et al., 1983) is used to predict lateral flow in each soil layer.

\[
q_{lat} = 0.204 \frac{(2S \text{ SC \sin(a)})}{\Theta_d L}
\]

where \(q_{lat}\) is lateral flow (mm d\(^{-1}\)), \(S\) is drainable volume of soil water (mm h\(^{-1}\)), \(a\) is slope (mm m\(^{-1}\)), \(\Theta_d\) is drainable porosity (mm\(^{-3}\)), and \(L\) is flow length (m). If the saturated zone rises above the soil layer, water is allowed to flow to the layer above (back to the surface for the upper soil layer). To account for multiple layers, the model is applied to each soil layer independently, starting at the upper layer.

**Ground Water Flow.** Ground water flow contribution to total streamflow is simulated by creating a shallow aquifer storage. The water balance for the shallow aquifer is

\[
V_{sa4} = V_{sa3} + Re - rewap - rf \cdot perc_{ew} \cdot WU_{SA}
\]

where \(V_{sa}\) is the shallow aquifer storage (mm), \(Re\) is recharge (percolate from the bottom of the soil profile) (mm), \(rewap\) is root uptake from the shallow aquifer (mm), \(rf\) is the return flow (mm), \(perc_{ew}\) is the percolate to the deep aquifer (mm), and \(WU_{SA}\) is the water use (withdrawal) from the shallow aquifer (mm), and \(i\) is the day.

Return flow from the shallow aquifer to the stream is estimated with the equation (Arnold et al., 1993):

\[
rf = rf_i \cdot e^{-\alpha i} + Re \cdot (1.0 - e^{-\alpha i})
\]

where \(\alpha\) is the constant of proportionality or the reaction factor.

The relationship for water table height is (Arnold et al., 1993)

\[
h_i = h_{i-1} \cdot e^{-\alpha i} + \frac{Re}{0.8 \mu} \cdot (1.0 - e^{-\alpha i})
\]

where \(h\) is the water table height, (m above stream bottom), and \(\mu\) is the specific yield.

**Evapotranspiration.** The model offers three options for estimating potential ET – Hargreaves (Hargreaves and Samani, 1985), Priestley-Taylor (Priestley and Taylor, 1972), and Penman-Monteith (Monteith, 1965). The Penman-Monteith method requires solar radiation, air temperature, wind speed, and relative humidity as input. If wind speed, relative humidity, and solar radiation data are not available (daily values can be generated from average monthly values), the Hargreaves or Priestley-Taylor methods provide options that give realistic results in most cases.

\[
E_o = \frac{\delta (ho + S) + p_\alpha C_p r_s (r_e - r_o) / r_o}{HV (\delta + \gamma)}
\]

where \(E_o\) is evaporation (g m\(^{-2}\)), \(HV\) is latent heat of vaporization (J g\(^{-1}\)), \(ho\) is net radiation (J m\(^{-2}\)), \(S\) is slope of the saturation vapor density function (g m\(^{-3}\)), \(r_s\) is air density (g m\(^{-3}\)), \(C_p\) is specific heat of air (J g\(^{-1}\)), \(r_e\) is saturation vapor density (g m\(^{-3}\)), \(r_o\) is air vapor density (g m\(^{-3}\)), and \(\delta\) is aerodynamic resistance for heat and vapor transfer (s m\(^{-1}\)), and \(\gamma\) is canopy resistance for vapor transfer (s m\(^{-1}\)).

The Priestley-Taylor (1972) method provides estimated potential evaporation based only on temperature and radiation

\[
E_o = 1.26 \left( \frac{h_o}{HV} \right) \left( \frac{\delta}{\delta + \delta} \right)
\]

The latent heat of vaporization, saturation vapor pressure, and slope of the saturation vapor pressure curve are all estimated with the temperature function (Arnold et al., 1993)

The Hargreaves and Samani (1985) method estimates potential evapotranspiration as a function of extraterrestrial radiation and air temperature. Hargreaves’ method was modified for use in SWAT by increasing the temperature difference exponent from 0.5 to 0.6. Also, extraterrestrial radiation is replaced by RAMX (maximum possible solar radiation at the earth’s surface) and the coefficient is adjusted from 0.0023 to 0.0002 for proper conversion. The modified equation is

\[
E_o = \frac{0.0002 \cdot \left( \frac{\text{RAMX}}{HV} \right) (T + 17.8) (T_{max} - T_{min})^{0.6}}{}
\]

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION 79
where \( T_{\text{max}} \) and \( T_{\text{min}} \) are the daily maximum and minimum air temperatures in °C.

The model computes evaporation from soils and plants separately as described in Ritchie (1972). Potential soil water evaporation is estimated as a function of potential ET and leaf area index (area of plant leaves relative to the soil surface area). Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential ET and leaf area index.

Snow Melt. If snow is present, it may be melted on days when the second soil layer temperature exceeds 0°C. Snow is melted as a function of the snow pack temperature using the equation:

\[
SML = T \times (1.52 + 0.54 \times SPT) - 0.5 \times SML \times SNO
\]

where SML is the snowmelt rate in mm·d⁻¹, SNO is the snow present in mm of water, T is the mean daily air temperature in °C, and SPT is the snow pack temperature in °C. The snowpack temperature is estimated with the equation:

\[
SPT = \min (T_g, T(2))
\]

where \( T_g \) is the temperature at the top of the snow pack and \( T(2) \) is the temperature at the center of soil layer 2. Melted snow is treated the same as rainfall for estimating runoff volume and percolation, but rainfall energy is set to 0.0 and peak runoff rate is estimated by assuming uniformly distributed rainfall for a 24-hour duration.

Transmission Losses. Many semiarid watersheds have alluvial channels that abstract a considerable portion of streamflow (Lane, 1982). The abstractions, or transmission losses, reduce runoff volumes as the flood wave travels downstream. Lane’s method described in USDA (1980) is used to estimate transmission losses. Channel losses are a function of channel width and length and flow duration. Both runoff and peak rate are adjusted when transmission losses occur.

Ponds. Farm ponds are small structures that occur within a subbasin. Pond storage is simulated as a function of pond capacity, daily inflows and outflows, seepage, and evaporation. Ponds are assumed to have only emergency spillways. Required inputs are capacity and surface area. Surface area below capacity is estimated as a non-linear function of storage.

**Weather**

The weather variables for driving the hydrologic balance are precipitation, air temperature, solar radiation, wind speed, and relative humidity. If daily precipitation and maximum/minimum temperature data are available, they can be input directly. If not, the weather generator can simulate daily rainfall and temperature. Solar radiation, wind speed, and relative humidity are always simulated. One set of weather variables may be simulated for the entire basin, or different weather may be simulated for each subbasin.

**Precipitation**. The precipitation model developed by Nicks (1974) is a first-order Markov chain model. Thus, input to the model must include monthly probabilities of receiving precipitation if the previous day was dry and if the previous day was wet. Given the wet-dry state, the model determines stochastically if precipitation occurs or not. When a precipitation event occurs, the amount is determined by generating from a skewed normal daily precipitation distribution. The amount of daily precipitation is partitioned between rainfall and snowfall using average daily air temperature.

**Air Temperature and Solar Radiation**. Daily maximum and minimum air temperature and solar radiation are generated from a normal distribution corrected for wet-dry probability state. The correction factor is used to provide more deviation in temperatures and radiation when weather changes and for rainy days. Conversely, drying is smaller in dry days. The correction factors are calculated to insure that long-term standard deviations of daily variables are maintained.

**Wind Speed and Relative Humidity**. Daily wind speed is simulated using a modified exponential equation given the mean monthly wind speed as input. The relative humidity model simulates daily average relative humidity from the monthly average by using a triangular distribution. As with temperature and radiation, the mean daily relative humidity is adjusted to account for wet- and dry-day effects.

**Sedimentation**

**Sediment Yield**. Sediment yield is computed for each subbasin with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1977).

\[
Y = 11.8 \times (V_{soil})^{0.54} \times (K)^{0.5} \times (C)^{0.5} \times (P)^{0.5} \times (L)^{0.5}
\]

**JWRA**

**Journal of the American Water Resources Association**
where \( Y \) is the sediment yield from the subbasin in \( t \), \( V \) is the surface runoff column for the subbasin in \( m^3 \), \( q_p \) is the peak flow rate for the subbasin in \( m^3/s \), \( K \) is the soil erodibility factor, \( C \) is the crop management factor, \( PE \) is the erosion control practice factor, and \( LS \) is the slope length and steepness factor. The LS factor is computed with the equation (Wischmeier and Smith, 1978)

\[
LS = \left( \frac{\lambda}{(22.1)^{0.5}} \right) (55.41 S^2 + 4.565 S + 0.65) \tag{21}
\]

The exponent \( \lambda \) varies with slope and is computed using the equation

\[
\lambda = 0.6 (1 - \exp(-35.835 S)) \tag{22}
\]

The crop management factor, \( C \), is evaluated for all days when \( r_{\text{runoff}} \) occurs using the equation

\[
C = \exp(-0.2231 \cdot CVM) \exp(-0.60115 CVM) + CVM \tag{23}
\]

where \( CM \) is the soil cover above ground biomass + residue in \( kg/ha^{-1} \) and \( CVM \) is the minimum value of \( C \). The value of \( CVM \) is estimated from the average annual \( C \) factor using the equation

\[
CVM = 1.465 In (CVA) + 0.1034 \tag{24}
\]

The value of CVA for each crop is determined from tables prepared by Wischmeier and Smith (1978). Values of \( K \) are contained in the SCS Soils-5 database, and \( PE \) factors can be estimated for each subbasin using information contained in Wischmeier and Smith (1978).

**Soil Temperature**

Daily average soil temperature is simulated at the center of each soil layer for use in hydrology and residue decay. The temperature of the soil surface is estimated using daily maximum and minimum air temperature and snow, plant, and residue cover for the day of interest plus the four days immediately preceding. Soil temperature is simulated for each layer using a function of damping depth, surface temperature, and mean annual air temperature. Damping depth is dependent upon bulk density and soil water.

**Crop Growth Model**

The crop model is a simplification of the EPIC crop model (Williams et al., 1984). SWAT uses EPIC concepts of phenological crop development based on daily accumulated heat units, harvest index for partitioning grain yield, Moncith’s approach (Monteith, 1977) for potential biomass, and water and temperature stress adjustments. A single model is used for simulating all the crops considered and SWAT is capable of simulating crop growth for both annual and perennial plants. Annual crops grow from planting date to harvest date or until the accumulated heat units equal the potential heat units for the crop. Perennial crops maintain their root systems throughout the year, although the plant may become dormant after frost.

Phenological development of the crop is based on daily heat unit accumulation. It is computed using the equation

\[
HU_i = \left( \frac{T_{\text{max}} - T_{\text{min}} - T_0}{2} \right) - T_0, \quad HU_i > 0 \tag{25}
\]

where \( HU \), \( T_{\text{max}} \) and \( T_{\text{min}} \) are the values of heat units, maximum temperature, and minimum temperature in °C on day \( i \) and \( T_0 \) is the crop-specific base temperature in °C (no growth occurs at or below \( T_0 \) of crop). A heat unit index (HUI) ranging from 0 at planting to 1 at physiological maturity is computed as follows.

\[
HUI_i = \frac{\sum_{j=1}^{i} HU_j}{PHU} \tag{26}
\]

where \( HUI \) is the heat unit index for day \( i \) and \( PHU \) is the potential heat units required for maturity of crop \( j \). The value of \( PHU \) is calculated by the model from normal planting and harvest dates.

**Potential Growth**

Interception of solar radiation is estimated with Beer’s law equation (Montes and Saeki, 1953)

\[
PAR_i = 0.02092 \left[ RA_i \left( 1 - \exp(-0.65 LAI_i) \right) \right] \tag{27}
\]

where \( PAR \) is photosynthetic active radiation in MJ \( m^{-2} \), \( RA \) is solar radiation in \( L \), \( LAI \) is the leaf area index, and subscript \( i \) is the day of the year.
Using Monteith’s approach (Monteith, 1977), potential increase in biomass for a day can be estimated with the equation

$$\Delta B_{AI} = \left(\frac{BEI}{PAR}\right)$$

where $\Delta B_{AI}$ is the daily potential increase in total biomass in kg ha$^{-1}$ and BEI is the crop parameter for converting energy to biomass in kg m$^{-2}$ ha$^{-1}$ MJ$^{-1}$. Potential biomass is adjusted daily due to stresses caused by water, nutrients, and temperature.

LAI is simulated as a function of heat units and biomass. LAI is estimated with the equations

$$LAI_i = \frac{LAI_{max}}{B_{AG}} \left(1 - \frac{HIU_i}{DI}\right)$$

$$LAI_i = \frac{(LAI_{max})(B_{AG})}{B_{AG} - \exp(0.5 - 0.0086B_{AG})} \left(1 - \frac{HIU_i}{DI}\right)^2$$

where $LAI_{max}$ is the maximum LAI potential for the crop, $B_{AG}$ is above ground biomass in kg ha$^{-1}$, and DI is the fraction of the growing season when LAI starts declining (<0.75).

The fraction of total biomass partitioned to the root system normally decreases from 0.3 to 0.5 in the seedling to 0.05 to 0.2 at maturity (Jones, 1985). The model estimates the root fraction to range linearly from 0.4 at emergence to 0.2 at maturity. Thus, the daily root fraction is computed with the equation

$$RWT_i = \left(0.4 - 0.25 HIU_i\right)$$

where $RWT$ is the fraction of total biomass partitioned to the root system on day $i$. Thus, $B_{AG}$ is calculated from the equation

$$B_{AG} = (1 - RWT) \left(\frac{B_{TOT}}{B_{TOT} + \left(1 - RWT\right)}\right)$$

where $B_{TOT}$ is total biomass in kg ha$^{-1}$ on day $i$.

**Nutrients**

Nitrogen. Amounts of NO$_3$N contained in runoff, lateral flow, and percolation are estimated as the products of the volume of water and the average concentration. Leaching and lateral subsurface flow in lower layers are treated with the same approach used in the upper layer, except that surface runoff is not considered. A loading function developed by McKerrow, et al. (1976) and modified by Williams and Hans (1978) for application to individual runoff events is used to estimate organic N loss. The loading function estimates the daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment yield, and the enrichment ratio. Also, crop use of N is estimated using a similarly modified approach. The simulated nitrogen cycle is presented in Figure 4 and is a simplification of the actual soil nitrogen cycle.

**Phosphorus.** The SWAT approach to estimating soluble P loss in surface runoff is based on the concept of partitioning pesticides into the solution and sediment phases as described by Leonard and Vadas (1980). Because P is mostly associated with the sediment phase, the soluble P runoff is predicted using a soluble P concentration in the top soil layer, runoff volume, and a partitioning factor. Sediment transport of P is simulated with a loading function as described in organic N transport. Crop use of P is also estimated with the supply and demand approach.

**Pesticides**

**GLEAMS (Knisel 1980) technology for simulating pesticide transport by runoff, percolate, soil evaporation, and sediment is used in the model (Figure 5).** Pesticides may be applied at any time and rate to plant foliage or below the soil surface at any depth. The plant leaf-area-index determines what fraction of foliar applied pesticide reaches the soil surface. Also, a fraction of the application rate (called application efficiency) is lost to the atmosphere. Each pesticide has a unique set of parameters including solubility, half life in soil and on foliage, wash off fraction, organic carbon adsorption coefficient, and cost. Pesticide on plant foliage and in the soil degrade exponentially according to the appropriate half lives. Pesticides transported by water and sediment is calculated for each runoff event and pesticide leaching is estimated for each soil layer when percolation occurs.

**Agricultural Management**

The agricultural management component provides submodels that simulate tillage systems, application of irrigation water, fertilizer, and pesticides and grazing systems.

**Tillage.** The tillage component was designed to incorporate surface residue and chemicals into the soil. The user inputs the day of the tillage operation.
and selects the tillage implement from the database (over 100 implements are listed). Each implement has an associated mixing efficiency (0-1) which partitions the amount of residue that is incorporated into the soil and the remainder that is left on the surface.

\[ RSD = RSD_0 \times (1 - EF) \]  \hspace{1cm} (33)

where RSD is the residue on the surface before tillage, RSD_0 is the residue after tillage, and EF is the mixing efficiency. Once the residue is incorporated, it has no impact on the model. Also, no adjustments are made to soil bulk density due to tillage.

Irrigation. Both dryland and irrigated agriculture can be simulated. Irrigation applications may be scheduled by the user or automatically applied by the model. The user-scheduled option requires the user to input application dates, amounts, and application efficiencies. Irrigation water is added to fill the upper layer to field capacity and then added to fill the successive lower layers to field capacity until all of the water is applied. If automatic irrigation is specified, the user must input the application efficiency and a plant water stress level to trigger irrigation. When the user-specified stress level is reached, water is applied according to the equation

\[ AIN = \frac{FC - SW}{1 - EF} \]  \hspace{1cm} (34)

where FC is the root zone field capacity (mm), SW is the root zone water content before irrigation in mm, EFF is the efficiency ratio, and AIR is the volume of irrigation water applied (mm).

Fertilization. Fertilizer applications can also be scheduled by the user or automatically applied by the model. The user-scheduled option requires the user to input the application date, total amount of N and P, fraction of organic and inorganic N and P, and the soil layer of application. The model adds the amount of fertilizer to the proper nutrient pool (organic and inorganic) and to the specified soil layer. The automatic fertilization option requires the user to input the plant nitrogen stress level (0-1) to trigger fertilization, the amount of NO3 in the soil profile after fertilization, the soil layer of the application, the maximum amount of NO3 that can be applied in one year, and the minimum time between fertilizer applications.

When the plant N stress level reaches the specified trigger level, the model automatically applies fertilizer to the NO3 storage of the specified soil layer to bring the entire profile to the specified level.

\[ ANO3 = FNMX - \sum WNO3_i \]  \hspace{1cm} (35)

\[ WNO3_{ft} = WNO3_{ft} + ANO3 \]  \hspace{1cm} (36)
where ANO3 is the amount of NO3 applied, FNMX is the amount of NO3 in the soil after fertilization, n is the number of soil layers, and f is the soil layer of the application. Organic N is also added according the amount of NO3 applied and the fraction of organic N (input).

\[
ON = ON + ANO3 \left( \frac{f_{on}}{1 - f_{on}} \right)
\]

where f_{on} is the fraction of organic N in the total N application (0-1). Automatic P fertilization also occurs when the N stress level is reached. The user inputs a low, medium, or high level of P management, and the model automatically restores the upper two soil layers to 10, 25, and 50 ppm of soluble P, respectively. Organic P is added like organic N in the previous equation.

Pesticide Applications. The user inputs the pesticide number, the date, and the amount of pesticide applied. The user must also input the application efficiency factor to account for losses to the atmosphere. The amount of pesticide reaching the ground (added to the upper soil layer) and the amount intercepted by plants is computed as a function of LAI.
Grazing. Livestock grazing is simulated as a daily harvest operation. Users specify a daily grazing rate in kg ha\(^{-1}\) and the date grazing begins and ends.

\[ B_{AG} = B_{AG \cdot B_{EAT}} \]  
(38)

where \( B_{EAT} \) is the daily amount of biomass removed by livestock in kg ha\(^{-1}\). Any number of grazing periods may occur during a year, and the grazing schedule may vary from year to year within a rotation.

Channel Routing. The channel routing module consists of flood routing, sediment, and chemical routing components. A detailed description of the routing components is found in Arnold et al. (1995).

Channel Flood Routing. The flood routing model uses a variable storage coefficient method developed by Williams (1989). Channel inputs include the reach length, channel slope, bankfull width and depth, channel side slope, floodplain slope, and Manning's n for channel and floodplain. Flow rate and average velocity are calculated using Manning's equation and travel time is computed by dividing channel length by velocity. Outflow from a channel is also adjusted for transmission losses, evaporation, diversions, and return flow.

Channel Sediment Routing. The sediment routing model (Arnold et al., 1995) consists of two components: sediment deposition and degradation (deposition and advection). The deposition component is based on velocity and the degradation component is based on Bagnold's stream power concept (Williams, 1980). Position is the channel and floodplain from the basin to the basin outlet is based on sediment particle size. Fall velocity is calculated as a function of particle diameter squared using Stokes Law. Depth of fall through a routing reach is the product of fall velocity and travel time. The delivery rate for each particle size is a linear function of fall velocity, travel time, and flow depth. The power is used to predict degradation in the reach. Bagnold (1977) defined stream power as the product of water density, flow rate, and water depth. Williams (1980) modified Bagnold's term to place more weight on high values of power, stream power raised to 1.5. Available power is used to extract loose and deposited, until all of the material is removed. Excess power causes bed degradation. Sed degradation is calculated using the USLE soil erodibility and cover of the channel and floodplain.

Reservoir Nutrient and Pesticide Routing. Nutrient transformations are simulated with a modified form of the QUAL2E model (Rama-narayanan et al., 1996). The components include algae, chlorophyll a dissolved oxygen, carbon dioxide, oxygen demand, organic nitrogen, ammonium nitrogen, nitrate nitrogen, and soluble phosphorus. Water temperature is estimated from air temperature based on a relationship developed by Stefan and Freudhonne (1993) through regression analysis of numerous, over observations. The relationship appears consistent with most rivers with the exceptions of natural springs and anthropological activity.

Instream pesticide transformations are simulated with a modified form of a toxic model developed by Chopra (1989). The toxic is partitioned into dissolved and particulate in both the water and sediment layers. The major processes include reactions, volatilization, settling, diffusion, resuspension, and burial.

Reservoir Routing. Similar to channel routing, the reservoir routing module has water balance, sediment, and chemical routing components.

Reservoir Water Balance and Routing. The water balance for reservoirs includes inflow, outflow, rainfall on the surface, evaporation, seepage from the reservoir bottom, and diversions and return flow. There are currently three methods to estimate outflow. The first step of the method is to calculate the model to simulate the other components of the water balance. The second method is to calculate the contribution of each of the major processes. Inflow occurs at a specified release rate when volume exceeds the principle storage. Volume exceeding the emergency spillway is released within one day. For larger managed reservoirs, a monthly target volume approach is used.

Reservoir Sediment Routing. Inflow sediment yield to ponds and reservoirs (P/R) is computed with MUSLE. The outflow from P/R is calculated as the product of outflow volume and sediment concentration. Outflow P/R concentration is estimated using a simple continuity equation based on volumes and concentrations of inflow, outflow, and pond storage. Initial pond concentration is input and between storm concentration decreases as a function of time and median particle size of inflow sediment.

Reservoir Nutrients and Pesticides. A simple model for phosphorus mass balance was taken from Thorrmann and Mueller (1987). The model assumes: (1) completely mixed lake; (2) phosphorus limited; and
(3) total phosphorus can be a measure of trophic status. The first assumption ignores lake stratification and is a substitution of phytoplankton in the epilimnion. The second assumption is generally valid when non-point sources dominate and the third assumption implies that a relationship exists between total phosphorus and biomass. This phosphorus balance equation includes the concentration in the lake, inflow, outflow, and an overall loss rate.

The lake toxic (pesticide) balance model is based on Chapra (1989) and assumes well mixed conditions. The system is partitioned into a well mixed surface water layer underlain by a well mixed sediment layer. The toxic is partitioned into dissolved and particulate in both the water and sediment layers. The major processes simulated by the model are loading, outflow, reactions, volatilization, settling, diffusion, resuspen-

sion, and burial.

WATER TRANSFER AND MANAGEMENT

For large basins it may be necessary to simulate water transfer. The transfer algorithm allows water to be transferred from any reach or reservoir to any other reach or reservoir in the watershed. It will also allow water to be diverted and applied directly to irrigated watersheds. There are four main steps to the algorithm:

1. Compute the maximum amount of water that can be transferred. This is the volume of water in the reservoir or the daily flow in the channel reach.

2. Compute the amount that is actually transferred. There are currently three options for determining the actual transfer amount: (a) specify the fraction of flow or volume to divert (0-1); (b) specify the minimum flow or volume remaining in the channel or reservoir after the water has been transferred; and (c) specify a daily amount to be diverted. More complex rules could be incorporated such as multiple destinations from multiple sources. An expert system may be appropriate for complex systems regarding order and amount to multiple destinations based on land use, previous weather conditions, soil water contents, reservoir levels, legal flow limits, etc.

3. Transfer the water to the destination. If the designation is a reach or reservoir, the actual transfer amount is added to the current storage in the reach or reservoir. If the destination is a subwatershed, a threshold must be reached before water is transferred and irrigation begins. If soil water content or crop stress drops below the input threshold, irrigation occurs. The amount of water needed for irrigation (Arnold and Stockle, 1992) is

\[
\text{AIR} = \left(\frac{f_d}{f_c} \right) (PC - SW) \times 1.0 - EF_t
\]

where AIR is the column of irrigation water to be applied, \( f_d \) is an input parameter to allow for different irrigation, PC is the root zone field capacity, SW is the root zone soil water content before irrigation, and \( EF_t \) is the irrigation efficiency of 0.5 to 1.0. Remove the water from the departure channel or reservoir. This is done by simply subtracting the actual transfer amount, or AIR, from the volume of water in the reservoir or the daily flow in the reach.

MODEL LIMITATIONS

SWAT is a long term water and sediment yield model that operates on a daily time step. Daily precipita-
tion is input to the model and an empirical curve number equation is applied to daily rainfall without accounting for intensity. There are several reasons why the curve number approach was chosen over an infiltration equation for large area simulation that include:

1. Breakpoint rainfall (less than one day increments) is not readily available and is difficult to process. Storm disaggregation models have been developed (Oheyesekera et al., 1987); however, they are stochastic with respect to intensities and often require inputs that are not readily available.

2. Subbasins are often relatively large (several km²) when simulating large river basins. It is relatively easy to obtain a weighted curve number and realistically simulate runoff. However, it is more difficult to "lamp" saturated conductivity (a critical soil property for infiltration equations) since it can vary spatially by orders of magnitude over relatively short distances.

3. Soils data is often not available with sufficient spatial detail for large basins to justify using an infiltration equation.

4. It relates runoff to soil type, land use, and management practices.

5. It is computationally difficult.

One of the major limitations to large area hydrolog ic modeling is the spatial variability associated with precipitation. There are more than 8000 rainfall locations in the U.S. with more than 30 years of daily precipitation data. There are, on the average, two or three gages per county, which leaves several kilometers between gages. This can cause considerable errors in runoff estimation if one gage is used to
represent an entire subwatershed or even if an attempt is made to "spatially weight" precipitation for a subwatershed. Also, the data files are difficult to manipulate and contain considerable days of missing records.

Weather generators can be extremely useful when measured data is unavailable and management scenarios are being compared. Daily weather generator parameters are available for generating weather sequences at a point. However, spatially correlated generators required for large area hydrologic simulations have not been developed. The physical processes driving large area weather phenomena are not fully understood and many technical obstacles need to be overcome before spatially correlated rainfall generation is possible. Another possibility is to utilize the WSR-88D radar technology (formerly called NEXRAD - Next Generation Weather Radar) to measure aerial precipitation rates needed to drive large area hydrologic models. ABS researchers at Durant, Oklahoma, are currently testing WSR-88D and are simulating runoff based on WSR-88D estimates of precipitation.

SWAT does not simulate detailed event-based flood and sediment routing. It was developed to predict agricultural management impacts on long-term (hundreds of years) erosion and sedimentation rates. The model operates on a daily time step, although a shorter and more flexible time increment would be a major enhancement to the model.

The sediment routing equations are relatively simplistic and assume that the channel dimensions are static throughout the simulation. This may be unrealistic since simulations may be made for 100 years or more. The addition of algorithms to simulate channel downcutting and side slope stability would allow channel dimensions to be continuously updated. Another limitation is the simplistic way the channel bed is described. The erodibility factor should be replaced with more detailed models that account for cohesive, noncohesive, and armored channels.

Reservoir routing was originally developed for small reservoirs and assumes well-mixed conditions. The reservoir outflow calculations are simplistic and do not account for controlled operation. To adequately simulate large reservoirs, these items need to be addressed.

SUMMARY AND CONCLUSIONS

A conceptual, continuous time model called SWAT (Soil and Water Assessment Tool) was developed to assist water resource managers in assessing water supplies and nonpoint source pollution on watersheds and large river basins. The model operates on a daily time step and allows a basin to be subdivided into grid cells or natural subwatersheds. Major components of the hydrologic balance and their interactions are simulated including surface runoff, lateral flow in the soil profile, groundwater flow, evapotranspiration, channel routing, and pond and reservoir storage.

The primary considerations in model development were to stress (1) land management, (2) water quality loadings, (3) flexibility in basin discretization, and (4) continuous time simulation. An attempt was made to simulate the major hydrologic components and their interactions as simply and yet as realistically as possible. An attempt was also made to use inputs that are readily available over large areas so the model can be used routinely in planning and decision making.

SWAT is currently being utilized in several large area projects. SWAT provides the modeling capabilities of the HUMUS (Hydrologic Unit Model) of the United States project (Srinivasan et al., 1993). The HUMUS project simulates the hydrologic budget (Arnold et al., 1996) and sediment movement for approximately 2,000 8-digit hydrologic unit areas that have been delineated by the USGS. Findings of the project will be used in the Resource conservation Act (RCA) Assessment conducted by the Natural Resources Conservation Commission, scheduled for completion in 1997. Scenarios include projected ag and municipal water use, tillage and cropping system trends. The model is being used by NOAA to estimate nonpoint source loadings into all U. S. coastal areas as part of the National Coastal Pollutant Discharge Inventory. EPA is also utilizing the model to determine the severity of sediment contamination by pesticides in the U. S.

LITERATURE CITED


Large Area Hydrologic Modeling and Assessment – Part I: Model Development


JAWRA