SWAT – A Tool for Basin Hydrology and Sediment Yield Modeling

J.V. Tyagi
Scientist 'F'

1.0 OVERVIEW OF SWAT

SWAT is the acronym for Soil and Water Assessment Tool, a river basin, or watershed scale model developed by the USDA Agricultural Research Service (Arnold et al., 1998). SWAT is a spatially distributed, continuous time model that operates on a daily time step. It was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. It can incorporate the effects of tanks and the reservoirs/check dams off-stream as well as on-stream. SWAT requires specific input about weather, soil properties, topography, vegetation, and land management practices to model hydrology and water quality in a watershed (Neitsch et. al., 2002). The model allows a basin to be subdivided into sub-basins or watersheds which is particularly beneficial when different areas of the macro-watershed are dominated by land uses or soils different enough in properties to have different impacts on the hydrological response. Within SWAT the input information for each watershed is grouped and is called hydrologic response units or HRUs. The major advantage of the model is that unlike the other conventional conceptual simulation models it does not require much calibration and therefore can be used on ungauged watersheds. Model outputs include all water balance components (surface runoff, evaporation, lateral flow, recharge, percolation, sediment yield, etc.) at the level of each watershed and are available at daily, monthly or annual time steps.

2.0 COMPONENTS OF SWAT

The major components of SWAT can be grouped into two categories (i) land phase of the hydrologic cycle that controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin, and (ii) routing phase of the hydrologic cycle which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet.

2.1 LAND PHASE OF HYDROLOGIC CYCLE

The general sequence of processes used by SWAT to model the land phase of the hydrologic cycle is shown in Fig.1. The different inputs and processes involved in this phase of the hydrologic cycle are summarized in the following sections.

2.1.1 Weather

SWAT uses daily precipitation, air temperature, solar radiation, relative humidity and wind speed in driving hydrological balance. The model can read these inputs directly from the file or generate the values using average monthly data analyzed for a number of years. It includes the WXGEN weather generator model (Sharpley and Williams, 1990) to generate climate data or to fill in gaps in measured records. The weather generator first independently generates precipitation for the day, followed by generation of maximum and minimum temperature, solar radiation and relative humidity based on the presence or absence of rain for the day. Finally, wind speed is generated independently.

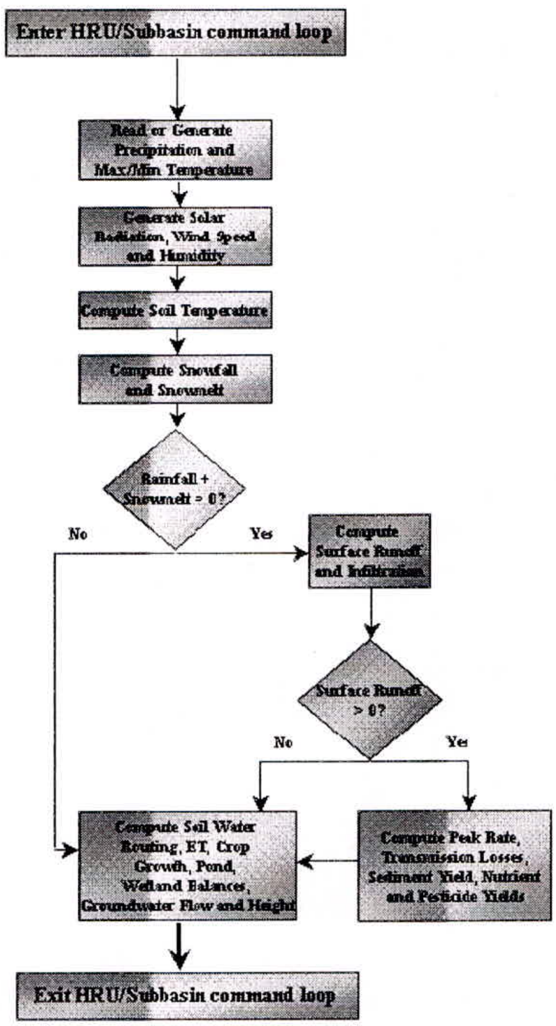

Fig. 1: Components of land phase of the hydrologic cycle

2.1.1.1 Precipitation

The precipitation generator uses a first-order Markov chain model to define a day as wet or dry (Williams and Nicks, 1985). The model generates a random number between 0 and 1 and compares it to the monthly wet-dry probabilities input by the user. If the random number is equal to or less than the wet-dry probability, the day is defined as wet and in case it is greater, the day is defined as dry. When a wet day is generated, a skewed distribution or exponential distribution is used to generate the precipitation amount.

2.1.1.2 Solar radiation and air temperature

Maximum and minimum air temperatures and solar radiation are generated from a normal distribution. The temperature model requires monthly means of maximum and minimum temperatures and their standard deviations as inputs, while the solar radiation model requires only monthly means of daily solar radiation. A continuity equation is incorporated into the generator to account for temperature and radiation variations caused by dry vs. rainy conditions. Maximum air temperature and solar radiation are adjusted downward when simulating rainy conditions and upwards when simulating dry conditions. The adjustments are made so that the long-term generated values for the average monthly maximum temperature and monthly solar radiation agree with the input averages.

2.1.1.3 Relative humidity

Daily average relative humidity (RH) values are calculated from a triangular distribution using average monthly relative humidity. As with temperature and radiation, the mean daily relative humidity is adjusted to account for wet- and dry-day effects. The RH generator requires four inputs: mean monthly RH, maximum RH value allowed in month, minimum relative humidity value allowed in month, and a random number between 0 and 1.

2.1.1.4 Wind speed

Wind Speed is required by SWAT when the Penman-Monteith equation is used to calculate potential evapotranspiration. Mean daily wind speed is generated in SWAT using a modified exponential equation. The mean monthly wind speed is required as input.

2.1.1.5 Snow cover and snow melt

SWAT classifies precipitation as rain or snow using the average daily temperature. In SWAT, the snow cover model allows non-uniform cover due to shading, drifting, topography and land cover. The user defines a threshold snow depth above which snow coverage will always extend over 100% of the area. As the snow depth in a sub-basin decreases below this value, the snow coverage is allowed to decline non-linearly based on an areal depletion curve.

Snow melt is controlled by the air and snow pack temperature, the melting rate, and the areal coverage of snow. Snow is melted on days when the maximum temperature exceeds 0°C using a linear function of the difference between the average snow pack-maximum air temperature and the base or threshold temperature for snow melt. Melted snow is treated the same as rainfall for estimating runoff and percolation. For snow melt, rainfall energy is set to zero and peak runoff rate is estimated assuming uniformly melted snow for 24 hour duration.

The model allows the subbasin to be split into a maximum of ten elevation bands. Snow cover and snow melt are simulated separately for each band to assess the differences in snow cover and snow melt caused by orographic variation in precipitation and temperature.

2.1.1.6 Soil temperature

Soil temperature impacts water movement and the decay rate of residue in the soil. Daily average soil temperature is calculated at the soil surface and the center of each soil layer. The soil surface temperature is a function of snow cover, plant cover and residue cover, the bare soil surface temperature, and the previous day's soil surface temperature. The soil layer temperature is a function of the surface temperature, mean annual air temperature and the depth in the soil at which variation in temperature due to changes in climatic conditions no longer occurs.

2.1.2 Hydrology

The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{n} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad (1)$$

where, SW_t is the final soil water content (mm H_2O), SW_o is the initial soil water content (mm H_2O), t is time in days, R_{day} is amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_a is the amount of evapotranspiration on day i (mm H_2O), w_{seep} is the amount of percolation and bypass exiting the soil profile bottom on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

Since the model maintains a continuous water balance, the subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. Thus runoff is predicted separately for each sub area and routed to obtain the total runoff for the basin. This increases the accuracy and gives a much better physical description of the water balance.

As precipitation occurs, it may be intercepted by the vegetation canopy or fall to the soil surface. Water on the soil surface will infiltrate into the soil profile or flow overland as runoff. Runoff moves relatively quickly toward a stream channel and contributes to short-term stream response. Infiltrated water may be held in the soil and later evapotranspired or it may slowly make its way to the surface-water system via underground paths. The potential pathways of water movement simulated by SWAT in the HRU (Fig. 2) are explained below.

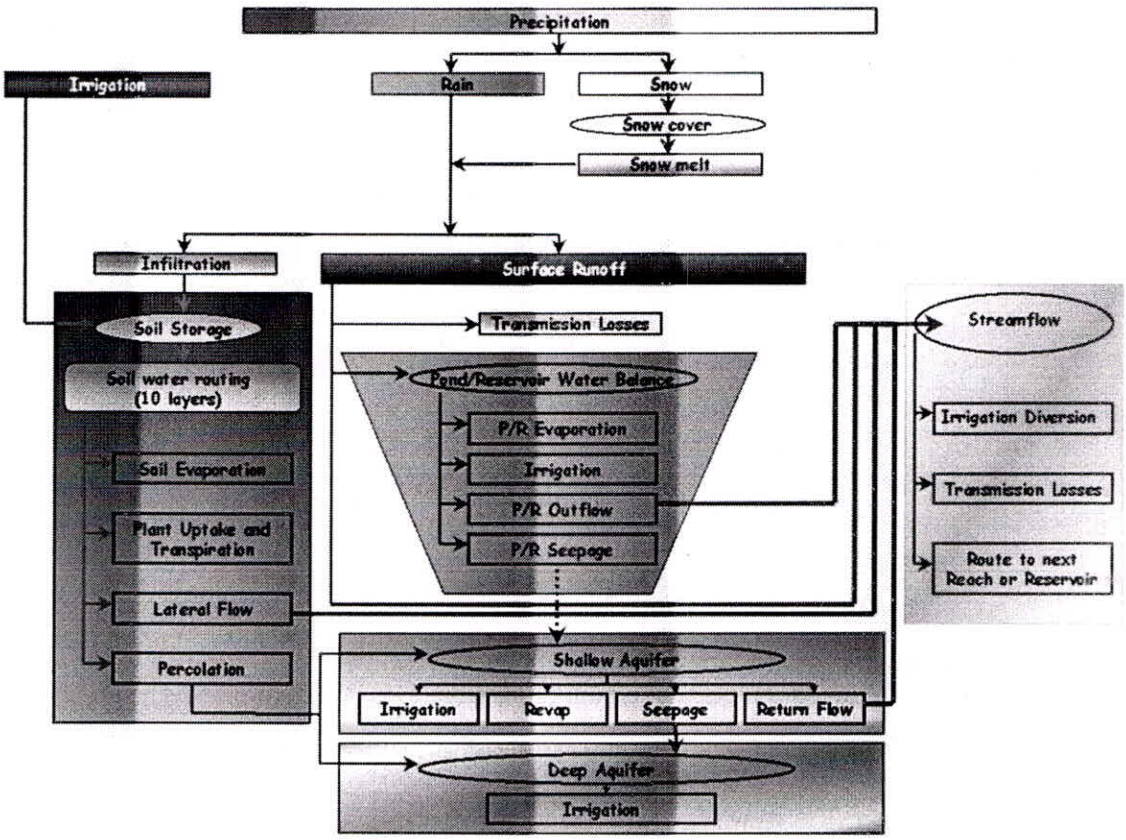

Fig. 2: Schematic of pathways available for water movement in SWAT

2.1.2.1 Canopy storage

When using the curve number method to compute surface runoff, canopy storage is taken into account in the surface runoff calculations. However, if methods such as Green & Ampt are used to model infiltration and runoff, canopy storage is modeled by SWAT separately and requires the input on maximum amount of water that can be stored in the canopy at the maximum leaf area index for the land cover. This value and the leaf area index are used by the model to compute the maximum storage at any time in the growth cycle of the land cover/crop. When evaporation is computed, water is first removed from canopy storage.

2.1.2.2 Infiltration and surface runoff

SWAT uses the modified SCS curve number method (USDA Soil Conservation Service, 1972) or the Green & Ampt infiltration equation (green and Ampt, 1911) to compute the direct surface runoff. The curve number method to calculate the surface runoff operates on a daily time-step and is unable to directly model infiltration. The amount of water entering the soil profile is calculated as the difference between the amount of rainfall and the amount of surface runoff. The Green & Ampt method requires sub-daily precipitation data and calculates infiltration as a function of the wetting front matric potential and effective hydraulic conductivity.

In computing the surface runoff using the curve number method, the curve number varies non linearly with the moisture content of the soil. The curve number drops as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation. Surface runoff volume predicted in SWAT using SCS curve number method is given below

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \qquad \text{for } R > 0.2S \qquad (2)$$

where, Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), and S is retention parameter (mm). The retention parameter varies spatially due to changes in soil, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as

$$S = 25.4(\frac{1000}{CN} - 10) \qquad (3)$$

where CN is the curve number for the day

The model calculates the peak runoff rate with a modified rational method. In brief, the rational method is based on the idea that if a rainfall of intensity *i* begins instantaneously and continues indefinitely, the rate of runoff will increase until the time of concentration, *tc*, when all of the subbasin is contributing to flow at the outlet. In the modified rational formula, the peak runoff rate is a function of the proportion of daily precipitation that falls during the subbasin *tc*, the daily surface runoff volume, and the subbasin time of concentration.

$$q_{peak} = \frac{\alpha_{tc} . Q_{surf} . Area}{3.6 . t_c} \tag{4}$$

where, q_{peak} is the peak runoff rate (m^3s^{-1}); α_{tc} is the fraction of daily rainfall that occurs during the time of concentration; *Area* is the sub-basin area (km^2); and t_c is the time of concentration for a sub-basin (hr).

The proportion of rainfall occurring during the subbasin *tc* is estimated as a function of total daily rainfall using a stochastic technique. The subbasin time of concentration is estimated by summing the overland flow time and the channel flow time:

$$t_c = t_{ov} + t_{ch} \tag{5}$$

where,, t_c is the time of concentration for a sub-basin (hr), t_{ov} is the time of concentration for overland flow (hr), and t_{ch} is the time of concentration for channel flow (hr).

The overland flow time of concentration, t_{ov}, is computed using the equation,

$$t_{ov} = \frac{L_{slp}^{0.6} . n^{0.6}}{18 . slp^{0.3}} \tag{6}$$

where, L_{slp} is the sub-basin slope length (m), n is the Mannings's roughness coefficient and slp is the average slope in the subbasin ($m \ m^{-1}$).

The channel flow time of concentration, t_{ch} is computed using the equation,

$$t_{ch} = \frac{0.62 . L . n^{0.75}}{Area^{0.125} . slp_{ch}^{0.375}} \tag{7}$$

where, t_{ch} is the time of concentration for channel flow (hr), L is the channel length from the most distant point to the subbasin outlet (km), n is the Manning's roughness coefficient for the channel, *Area* is the subbasin area (km^2) and slp_{ch} is the channel slope ($m \ m^{-1}$)

2.1.2.3 Percolation

Percolation is calculated for each soil layer in the profile. Water is allowed to percolate if the water content exceeds the field capacity for that layer. The volume of water available for percolation in the soil layer is calculated as:

$$SW_{ly,excess} = SW_{ly} - FC_{ly} \qquad \text{if } SW_{ly} > FC_{ly} \tag{8}$$

$$SW_{ly,excess} = 0 \qquad \text{if } SW_{ly} \leq FC_{ly} \tag{9}$$

where, $SW_{ly,excess}$ and SW_{ly} are the drainable volume of water and water content in the soil layer, respectively on a given day (mm) and FC_{ly} is the water content of the soil layer at field capacity (mm).

The amount of water that moves from one layer to the underlying layer is calculated using storage routing methodology. The equation used to calculate the amount of water that percolates to the next layer is

$$w_{perc,ly} = SW_{ly,excess} \cdot \left(1 - \exp\left[\frac{-\Delta t}{TT_{perc}}\right]\right) \tag{10}$$

where, $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm), Δt is the length of the time step (hrs), and TT_{perc} is the travel time for percolation (hrs). The travel time for percolation (TT_{perc}) is unique for each layer. It is calculated as:

$$TT_{perc} = \frac{SAT_{ly} - FC_{ly}}{K_{sat}} \tag{11}$$

where TT_{perc} is the travel time for percolation (hrs), SAT_{ly} is the amount of water in the soil layer when completely saturated (mm) and K_{sat} is the saturated hydraulic conductivity.

2.1.2.4 Evapotranspiration

Evapotranspiration (ET) includes evaporation from the plant canopy, transpiration, sublimation and evaporation from the soil. Three methods have been incorporated into SWAT2000 to estimate ET: the Penman-Monteith method (Monteith, 1965; Allen, 1986; Allen et al., 1989), the Priestley-Taylor method (Priestley and Taylor, 1972) and the Hargreaves method (Hargreaves et al., 1985).

The Penman-Monteith equation combines components that account for energy needed to sustain evaporation, the strength of the mechanism required to remove the water vapor and aerodynamic and surface resistance terms. The Penman-Monteith equation is

$$\lambda E = \frac{\Delta.(H_{net} - G) + \rho_{air}.c_p.[e_z^{o} - e_z]/r_a}{\Delta + \gamma.(1 + r_c/r_a)} \tag{12}$$

where, λE is the latent heat flux density (MJm-^{2}d^{-1}), E is the depth rate evaporation (mmd^{-1}), D is the slope of the saturation vapor pressure-temperature curve, de/dT (kPa^{o}C^{-1}), H_{net} is the net radiation (MJm^{-2} d^{-1}), G is the heat flux density to the ground (MJ m^{-2}d^{-1}), ρ_{air} is the air density (kgm^{-3}), c_p is the specific heat at constant pressure (MJ kg-1^{o}C^{-1}), e_z^o *is* the saturation vapor pressure of air at height z (kPa), e_z is the water vapor pressure of air at height z (kPa), γ is the psychrometric constant (kPa^{o}C^{-1}), r_c is the plant canopy resistance (sm^{-1}), and r_a is the diffusion resistance of the air layer (aerodynamic resistance) (sm^{-1}).

Priestley and Taylor (1972) developed a simplified version of the combination equation for use when surface areas are wet. The aerodynamic component was removed and the energy component was multiplied by a coefficient, α_{pet} = 1.28, when the general surroundings are wet or under humid conditions:

$$\lambda E_O = \alpha_{pet} \cdot \frac{\Delta}{\Delta + \gamma} \cdot (H_{net} - G) \tag{13}$$

where, λ is the latent heat of vaporization (MJ kg^{-1}), *Eo* is the potential evapotranspiration (mm d^{-1}),α_{pet} is a coefficient, D is the slope of the saturation vapor pressure-temperature curve, de/dT (kPa^{o}C^{-1}), γ is the psychrometric constant (kPa^{o}C^{-1}), H_{net} is the net radiation (MJ m^{-2} d^{-1}), and G is the heat flux density to the ground (MJ m^{-2} d^{-1}). The Priestley-Taylor equation provides potential evapotranspiration estimates for low advective conditions. In semiarid or arid areas where the advection component of the energy balance is significant, the Priestley-Taylor equation will underestimate potential evapotranspiration.

The Hargreaves method estimates potential evapotranspiration as a function of extraterrestrial radiation and air temperature. The modified equation used in SWAT2000 is:

$$\lambda E_O = 0.0023.H_O.(T_{mx} - T_{mn})0.5.(T_{av} + 17.8) \tag{14}$$

where, λ is the latent heat of vaporization (MJ kg^{-1}), E_o is the potential evapotranspiration (mm d^{-1}), H_0 is the extraterrestrial radiation (MJ m^{-2}d^{-1}), T_{mx} is the maximum air temperature for a given day (^{o}C), T_{mn} is the minimum air temperature for a given day (^{o}C), and T_{av} is the mean air temperature for a given day (^{o}C).

2.1.2.5 Lateral subsurface flow

Lateral subsurface flow, or interflow in the soil profile is calculated using a kinematic storage model developed by Sloan and Moore (1984). The kinematic wave approximation of saturated subsurface or lateral flow assumes that the lines of flow in the saturated zone are parallel to the impermeable boundary and the hydraulic gradient equals the slope of the bed.

The drainable volume of water stored in the saturated zone of the hill slope segment per unit area, $SW_{ly,excess}$, is

$$SW_{ly,excess} = (1000.H_o.\phi_d.Lhill)/2 \quad (15)$$

where, $SW_{ly,excess}$ is the drainable volume of water stored in the saturated zone of the hill slope per unit area (mm), H_o is the saturated thickness normal to the hill slope at the outlet expressed as a fraction of the total thickness (mm/mm), ϕ_d is the drainable porosity of the soil (mm/mm), L_{hill} is the hill slope length (m), and 1000 is a factor needed to convert meters to millimeters.

2.1.2.6 Ground water flow

SWAT partitions groundwater into two aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the watershed and a deep, confined aquifer which contributes return flow to stream outside the watershed. The water balance for the shallow aquifer is,

$$aq_{sh,i} = aq_{sh,i-1} + w_{rchrg} - Q_{gw} - w_{revap} - w_{deep} - w_{pump,sh} \quad (16)$$

where, $aq_{sh,i}$ is the amount of water stored in the shallow aquifer on day i (mm), $aq_{sh,i-1}$ is the amount of water stored in the shallow aquifer on day i-1 (mm), w_{rchrg} is the amount of recharge entering the aquifer (mm), Q_{gw} is the groundwater flow, or base flow, into the main channel (mm), w_{revap} is the amount of water moving into the soil zone in response to water deficiencies (mm), w_{deep} is the amount of water percolating from the shallow aquifer into the deep aquifer (mm), and $w_{pump,sh}$ is the amount of water removed from the shallow aquifer by pumping (mm).

The water balance for the deep aquifer is,

$$aq_{dpi} = aq_{dp,i-1} + w_{deep} - w_{pump,sh} \quad (17)$$

where, $aq_{dp,i}$ is the amount of water stored in the deep aquifer on day i (mm), $aq_{dp,i-1}$ is the amount of water stored in the deep aquifer on day i-1 (mm), and $w_{pump,dp}$ is the amount of water removed from the deep aquifer by pumping on day i (mm).

2.1.2.7 Transmission loss

Two types of channels are defined within a subbasin: the main channel and tributary channels. Tributary channels are minor or lower order channels branching off the main channel within the subbasin. Each tributary channel within a subbasin drains only a portion of the subbasin and does not receive groundwater contribution to its flow. All flow in the tributary channels is released and routed through the main channel of the subbasin.

Transmission losses occur in surface flow via leaching through the streambed of tributary channels. This type of loss occurs in ephemeral or intermittent streams where groundwater contribution occurs only at certain times of the year, or not at all. The abstractions, or transmission losses, reduces runoff volume as the flood waves travel downstream. Lane's method described in USDA SCS Hydrology Handbook (1983) is used to estimate transmission losses. Water losses from the channel are a function of channel width and length and flow duration. Both runoff volume and peak rate are adjusted when transmission losses occur in tributary channels.

2.1.2.8 Ponds

Ponds are water storage structures located within a subbasin which intercept surface runoff. The catchment area of a pond is defined as a fraction of the total area of the subbasin. Ponds are assumed to be located off the main channel in a subbasin and will never receive water from upstream subbasins. Pond water storage is a function of pond capacity, daily inflows and outflows, seepage and evaporation. Required inputs are the storage capacity and surface area of the pond when filled to capacity. Surface area below capacity is estimated as a nonlinear function of storage.

2.1.3 Erosion and Sediment Yield

The erosion and sediment yield for each HRU in the SWAT model is computed with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975):

$$sed = 11.8.(Q_{surf}.q_{peak}.area_{hru})^{0.56}.K_{USLE}.C_{USLE}.P_{USLE}.LS_{USLE}.CFRG \tag{18}$$

where, sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the USLE soil erodibility factor, C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and $CFRG$ is the coarse fragment factor.

K_{USLE} is calculated using the following equation (Williams, 1995)

$$K_{USLE} = f_{csand} \cdot f_{cl-si} \cdot f_{orgc} \cdot f_{hisand} \tag{19}$$

where f_{csand} is a factor that gives low soil erodibility factors for soils with high coarse sand contents and high values for soils with little sand, f_{cl-si} is a factor that gives low soil erodibility factors for soils with high clay to silt ratios, f_{orgc} is a factor that reduces soil erodibility for soils with high organic carbon content, and f_{hisand} is a factor that reduces soil erodibility for soils with extremely high sand contents. These factors are calculated as:

$$f_{csand} = \left(0.2 + 0.3.\exp\left[-0.256.m_s.\left(1 - \frac{m_{silt}}{100}\right)\right]\right) \quad (20)$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3} \quad (21)$$

$$f_{orgc} = \left(1 - \frac{0.25.orgC}{orgC + \exp[3.72 - 2.95.orgC]}\right) \quad (22)$$

$$f_{hisand} = \left(1 - \frac{0.7.\left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp\left[-5.51 + 22.9.\left(1 - \frac{m_s}{100}\right)\right]}\right) \quad (23)$$

where m_s is the percent sand content (0.05-2.00 mm dia. particles), m_{silt} is the percent silt content (0.002-0.05mm dia. particles), m_c is the percent clay content (<0.002 mm dia. particles), and orgC is the percent organic carbon content of the layer

C_{USLE} factor is estimated using the following equation:

$$C_{USLE} = \{\exp(\ln(0.8) - \ln(C_{USLE})).\exp(-0.00115.rsd_{surf}) + \ln(C_{USLE,mn})\} \quad (24)$$

where, $C_{USLE,mn}$ is the minimum value of the crop cover management factor for the land cover and rsd_{surf} is the amount of residue on the soil surface (kg/ha).

LS_{USLE} factor is estimated using the following equation:

$$LS_{USLE} = \left(\frac{L_{hill}}{22.1}\right)^m.(65.41.\sin^2(\alpha_{hill}) + 4.56.\sin\alpha_{hill} + 0.065) \quad (25)$$

where, L_{hill} is the slope length (m), m is the exponential term, and α_{hill} is the angle of the slope. The exponential m is calculated as:

$$m = 0.6.(1 - \exp[-35.835.slp]) \quad (26)$$

where slp is the slope of the HRU expressed as rise over run (m/m). The relationship between α_{hill} and slp is:

$$slp = \tan\alpha_{hill} \quad (27)$$

The coarse fragment factor is calculated as:

$$CFRG = \exp(-0.053.rock) \tag{28}$$

2.1.4 Nutrients and Pesticides

SWAT models the complete nutrient cycle for nitrogen and phosphorus. Three forms of nitrogen in mineral soils are organic nitrogen associated with humus, mineral forms of nitrogen held by soil colloids, and mineral forms of nitrogen in solution. Nitrogen may be added to the soil by fertilizer, manure, fixation by symbiotic or non-symbiotic bacteria, and rain. Nitrogen is removed from the soil by plant uptake, leaching, volatilization, denitrification and erosion. SWAT monitors the five different pools of nitrogen in the soil. Unlike nitrogen which is highly mobile, phosphorus solubility is limited in most environments. Phosphorus combines with other ions to form a number of insoluble compounds that precipitate out of solution. These characteristics contribute to a build-up of phosphorus near the soil surface that is readily available for transport in surface runoff. SWAT monitors six different pools of phosphorus in the soil. Three pools are inorganic forms of phosphorus while the other three pools are organic forms of phosphorus.

SWAT simulates pesticide movement into the stream network via surface runoff, and into the soil profile and aquifer by percolation. The equations used to model the movement of pesticide in the land phase of the hydrologic cycle were adopted from GLEAMS (Leonard et.al., 1987).

2.1.5 Crop Growth

The plant growth component of SWAT is a simplified version of the EPIC plant growth model. As in EPIC, phenological plant development is based on daily accumulated heat units, potential biomass is based on a method developed by Monteith, a harvest index is used to calculate yield, and plant growth can be inhibited by temperature, water, nitrogen or phosphorus stress.

2.1.6 Agricultural Management

SWAT allows the user to define management practices taking place in every HRU. The user may define the beginning and the ending of the growing season, specify timing and amounts of fertilizer, pesticide and irrigation applications as well as timing of tillage operations. At the end of the growing season, the biomass may be removed from the HRU as yield or placed on the surface as residue.

In addition to these basic management practices, operations such as grazing, automated fertilizer and water applications, and incorporation of every conceivable management option for water use are available. The latest improvement to land management is the incorporation of routines to calculate sediment and nutrient loadings from urban areas.

2.1 ROUTING PHASE OF HYDROLOGIC CYCLE

2.1.1 Main Channel Routing

Routing in the main channel can be divided into four components: water, sediment, nutrients and organic chemicals.

2.1.1.1 Channel flood routing

As water flows downstream, a portion may be lost due to evaporation and transmission through the bed of the channel. Another potential loss is removal of water from the channel for agricultural or human use. Flow may be supplemented by the fall of rain directly on the channel and/or addition of water from point source discharges. Flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method. Users are required to define the width and depth of the channel when filled to the top of the bank as well as the channel length, slope along the channel length and Manning's 'n' value. Manning's equation for uniform flow in a channel is used to calculate the rate and velocity of flow in a reach segment for a given time step.

The variable storage routing method was developed by Williams (1969) and used in the HYMO (Williams and Hann, 1973) and ROTO (Arnold et al., 1995) models. For a given reach segment, variable storage routing is based on the continuity equation:

$$V_{in} - V_{out} = \Delta V_{stored} \tag{29}$$

where V_{in} is volume of inflow during the time step (m^3), V_{out} is the volume of outflow during the time step (m^3), and □ V_{stored} is the change in volume of storage during the time step (m^3).

This equation can be presented as:

$$\Delta t.\left(\frac{q_{in,1} + qi_{n,2}}{2}\right) - \Delta t.\left(\frac{q_{out,1} + q_{out,2}}{2}\right) = V_{stored2} - V_{stored1} \tag{30}$$

where, Δt is the length of the time step (s) and $q_{in,1}$ and $q_{in,2}$ are the inflow rate at the beginning and end of the time step (m^3 /s), respectively. $q_{out,1}$ and $q_{out,2}$ are the outflow rate at the beginning and end of the time step (m^3/s). $V_{stored,1}$ and $V_{stored,2}$ are the storage volume at the beginning and end of the time step (m^3).

Travel time, TT (s) is computed by dividing the volume of water in the channel by flow rate.

$$TT = \frac{V_{stored}}{q_{out}} = \frac{V_{stored,1}}{q_{out,1}} = \frac{V_{stored,2}}{q_{out,2}} \tag{31}$$

The relationship between travel time and storage coefficient is represented as:

$$q_{out,2} = \left(\frac{2.\Delta t}{2.TT + \Delta t}\right).q_{in,av} + \left(1 - \frac{2.\Delta t}{2.TT + \Delta t}\right).q_{out,1} \tag{32}$$

The storage coefficient (*SC*) is calculated as:

$$SC = \frac{2.\Delta t}{2.TT + \Delta t} \tag{33}$$

Finally the volume of outflow is calculated as

$$V_{out,2} = SC.(V_{in} + V_{stored1}) \tag{34}$$

The transmission and evaporation losses, bank storage and the channel water balance at the end of time step in the main channel reach are estimated using appropriate equations.

2.1.1.2 Channel sediment routing

Sediment transport in the channel network is a function of two processes, deposition and degradation, operating simultaneously in the reach. SWAT computes these two processes using the same channel dimensions for the entire simulation. The model simulates downcutting and widening of the stream channel and update channel dimensions throughout the simulation. In SWAT2000, the equations are simplified and the maximum amount of sediment that can be transported from a reach segment is a function of the peak channel velocity. The peak channel velocity, $v_{ch,pk}$ is calculated as,

$$v_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}} \tag{35}$$

where, $q_{ch,pk}$ is the peak flow rate (m^3/s) and A_{ch} is the cross-sectional area of flow in the channel (m^2).

The peak flow rate is defined as:

$$q_{ch,pk} = prf.q_{ch} \tag{36}$$

where, *prf* is the peak rate adjustment factor and q_{ch} is the average rate of flow (m^3/s).

The maximum amount of sediment that can be transported from a reach segment is calculated as:

$$conc_{sed,ch,mx} = c_{sp}.v_{ch,pk}^{spexp} \quad (37)$$

where, $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (ton/m^3), c_{sp} is a coefficient defined by the user, $v_{ch,pk}$ is the peak channel velocity (m/s), and *spexp* is an exponent defined by the user. The exponent, *spexp*, normally varies between 1 and 2.

The maximum concentration of sediment calculated with equation 36 is compared to the concentration of sediment in the reach at the beginning of the time step, $conc_{sed,ch,i}$. If $conc_{sed,ch,i} > conc_{sed,ch\,mx}$, deposition is the dominant process in the reach segment and the net amount of sediment deposited is calculated:

$$sed_{dep} = (conc_{sed,ch,i} - conc_{sed,ch,mx}).V_{ch} \quad (38)$$

where, sed_{dep} is the amount of sediment deposited in the reach segment (metric tons), and V_{ch} is the volume of water in the reach segment (m^3).

If $conc_{sed,ch,i} < conc_{sed,ch,mx}$, degradation is the dominant process in the reach segment and the net amount of sediment reentrained is calculated as:

$$sed_{\deg} = (conc_{sed,ch,mx} - conc_{sed,ch,i}).V_{ch}.K_{CH}.C_{CH} \quad (39)$$

where sed_{deg} is the amount of sediment reentrained in the reach segment (metric tons), K_{CH} is the channel erodibility factor (cm/hr/Pa), and C_{CH} is the channel cover factor.

Once the amount of deposition and degradation has been calculated, the final amount of sediment in the reach is determined:

$$sed_{ch} = sed_{ch,i} - sed_{dep} + sed_{\deg} \quad (40)$$

where sed_{ch} is the amount of suspended sediment in the reach (metric tons), $sed_{ch,i}$ is the amount of suspended sediment in the reach at the beginning of the time period (metric tons).

The amount of sediment transported out of the reach, sed_{out} (metric tons) is calculated:

$$sed_{out} = sed_{ch}.\frac{V_{out}}{V_{ch}} \quad (41)$$

where, V_{out} is the volume of outflow during the time step (m^3), and V_{ch} is the volume of water in the reach segment (m^3).

SWAT also models channel downcutting and widening. Sediment transport calculations have traditionally been made with the same channel dimensions throughout a simulation. When channel downcutting and widening is simulated, channel dimensions are allowed to change during the simulation period. Three channel dimensions are allowed to vary in channel downcutting and widening simulations: bankfull depth, $depth_{bnkfull}$, channel width, $W_{bnkfull}$, and channel slope, slp_{ch}. The new channel dimensions are updated using appropriate equations when the volume of water in the reach exceeds 1.4×10^6 m^3.

2.1.1.3 Channel nutrient routing

Nutrient transformations in the stream are controlled by the in-stream water quality component of the model. The in-stream kinetics used in SWAT for nutrient routing are adapted from QUAL2E (Brown and Barnwell, 1987). The model tracks nutrients dissolved in the stream and nutrients adsorbed to the sediment. Dissolved nutrients are transported with the water while those adsorbed to sediments are allowed to be deposited with the sediment on the bed of the channel.

2.1.1.4 Channel pesticide routing

While an unlimited number of pesticides may be applied to the HRUs, only one pesticide may be routed through the channel network of the watershed due to the complexity of the processes simulated. As with the nutrients, the total pesticide load in the channel is partitioned into dissolved and sediment-attached components. While the dissolved pesticide is transported with water, the pesticide attached to sediment is affected by sediment transport and deposition processes. Pesticide transformations in the dissolved and adsorbed phases are governed by first-order decay relationships. The major in-stream processes simulated by the model are settling, burial, re-suspension, volatilization, diffusion and transformation.

2.1.2 Routing in the Reservoir

2.1.2.1 Reservoir water balance

The water balance for reservoirs includes inflow, outflow, rainfall on the surface, evaporation, seepage from the reservoir bottom and diversions. The model offers three alternatives for estimating outflow from the reservoir. The first option allows the user to input measured outflow. The second option, designed for small, uncontrolled reservoirs, requires the users to specify a water release rate. When the reservoir volume exceeds the principle storage, the extra water is released at the specified rate. Volume exceeding the emergency spillway is released within one day. The third option, designed for larger, managed reservoirs, has the user specify monthly target volumes for the reservoir.

2.1.2.2 Reservoir sediment routing

Sediment inflow may originate from transport through the upstream reaches or from surface runoff within the subbasin. The concentration of sediment in the reservoir is estimated using a simple continuity equation based on volume and concentration of inflow, outflow, and water retained in the reservoir. Settling of sediment in the reservoir is governed by an equilibrium sediment concentration and the median sediment particle size. The amount of sediment in the reservoir outflow is the product of the volume of water flowing out of the reservoir and the suspended sediment concentration in the reservoir at the time of release.

2.1.2.3 Reservoir nutrients

A simple model for nitrogen and phosphorus mass balance was taken from Chapra (1997). The model assumes: 1) the lake is completely mixed; 2) phosphorus is the limiting nutrient; and, 3) total phosphorus is a measure of the lake trophic status. The first assumption ignores lake stratification and intensification of phytoplankton in the epilimnon. 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. The phosphorus mass balance equation includes the concentration in the lake, inflow, outflow and overall loss rate.

2.1.2.4 Reservoir pesticides

The lake pesticide balance model is taken from Chapra (1997) and assumes well mixed conditions. The system is partitioned into a well mixed surface water layer underlain by a well mixed sediment layer. The pesticide is partitioned into dissolved and particulate phases in both the water and sediment layers. The major processes simulated by the model are loading, outflow, transformation, volatilization, settling, diffusion, resuspension and burial.

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