7 Phosphorus Modeling in Soil and Water Assessment Tool (SWAT) Model

Indrajeet Chaubey
University of Arkansas, Fayetteville, AR

K.W. Migliaccio
University of Florida Tropical Research and Education
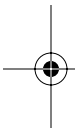Center, Homestead, FL

C.H. Green
U.S. Department of Agriculture-Agricultural
Research Service, Temple, TX

J.G. Arnold
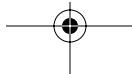U.S. Department of Agriculture-Agricultural
Research Service, Temple, TX

R. Srinivasan
Texas A&M University, College Station, TX

CONTENTS

7.1   SWAT MODEL BACKGROUND

The Soil and Water Assessment Tool (SWAT) model was developed by the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS). It is a theoretical model that functions on a continuous time step. Model components include weather, hydrology, erosion and sedimentation, plant growth, nutrients, pesticides, agricultural management, channel routing, and pond and reservoir routing. Agricultural components in the model include crop cycles from planting to harvesting, fertilization, tillage options, and animal production and have the capability to include point source loads (Neitsch et al. 2001a, 2001b). All model calculations are performed on a daily time step. The SWAT model predicts the influence of land-management practices on constituent yields from a watershed. SWAT is the continuation of over 30 years of model development within the USDA-ARS. The Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS), Groundwater Loading Effects of Agricultural Management Systems (GLEAMS), and Erosion Productivity Impact Calculator (EPIC) models (Knisel 1980; Leonard et al. 1987; Williams et al. 1984) have each contributed to the scaling up of past field-scale models to one that includes large river basins. Large-area simulations are possible due to the advances in computer software and hardware, including speed and storage, geographic information science (GIS), and spatial analysis and debugging tool software. SWAT model development primarily emphasizes (1) impacts of watershed management and climatic conditions; (2) flow and water quality loadings and fate; (3) flexibility in how a basin is descretized into smaller geographic areas; and (4) continuous time simulation. SWAT is a public domain model that is actively supported by the USDA-ARS at the Grassland, Soil, and Water Research Laboratory in Temple, Texas.

To adequately simulate hydrologic processes using the SWAT model for a basin, the basin is divided into sub-basins through which streams are routed. The subunits of the sub-basins are referred to as hydrologic response units (HRUs), which are a unique combination of soil- and land-use characteristics and are considered to be hydrologically homogeneous. The model calculations are performed on an HRU basis, and flow and water-quality variables are routed by HRUs and sub-basins to the basin outlet. The SWAT model simulates hydrology as a two-component system, comprised of land hydrology and channel hydrology. The land portion of the hydrologic

cycle is based on a water mass balance. Soil–water balance is the primary consideration by the model in each HRU, which is represented as (Arnold et al. 1998) (see Figure 7.1):

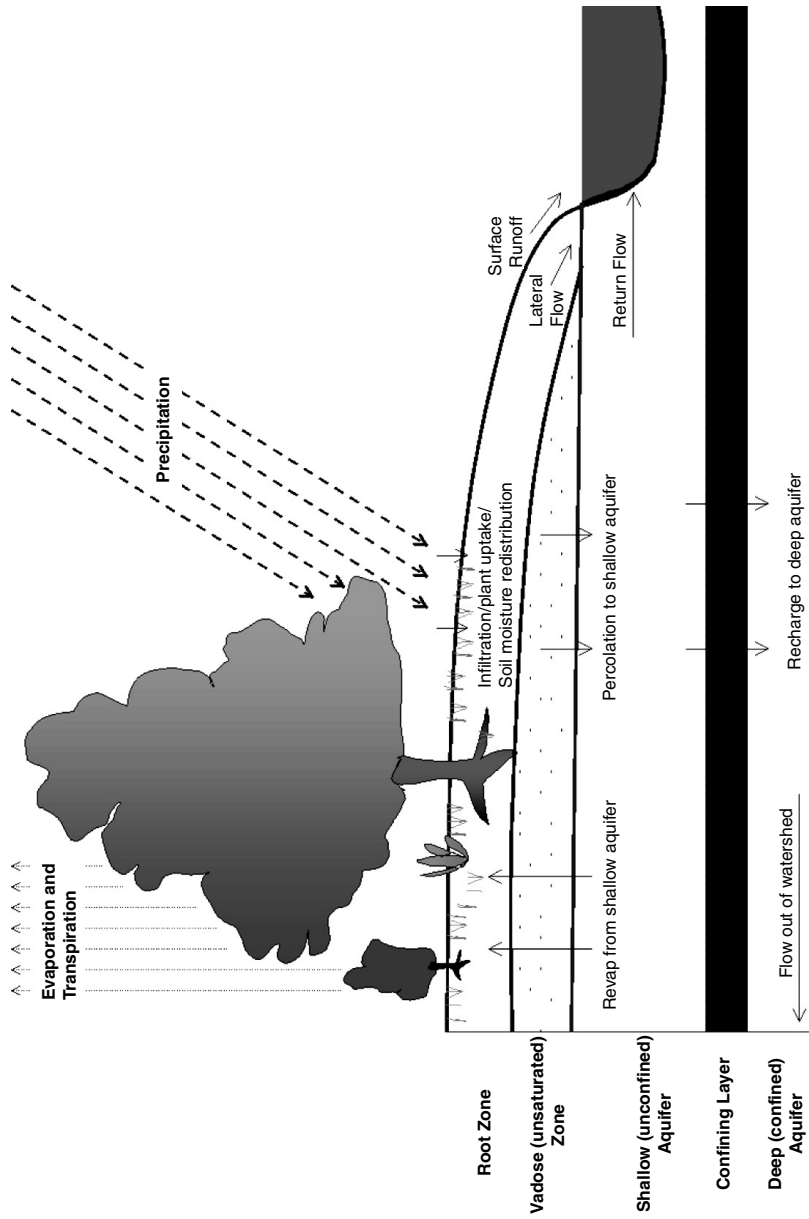$$SW_t = SW_0 + \sum_{t=1}^{t} (R_i - Q_i - ET_i - P_i - QR_i) \tag{7.1}$$

where SW_t is the soil water content after t days, SW_0 is the initial soil water content at the beginning of simulation, i is time in days for the simulation period t, and R, Q, ET, P, and QR, respectively, are the daily precipitation, runoff, evapotranspiration, percolation, and return flow. Water enters the SWAT model's watershed system boundary predominantly in the form of precipitation. Precipitation inputs for hydrologic calculations can be either measured data or simulated with the weather generator available in the SWAT model. Surface runoff is estimated using the Soil Conservation Service (SCS) curve number (CN) or the Green-Ampt infiltration equation. Percolation is modeled with a layered storage routing technique combined with a crack flow model. Potential evaporation can be calculated using the Hargreaves, Priestly-Taylor, or Penman-Monteith method (Arnold et al. 1998). The water balance of each HRU in the watershed contains four storage volumes: snow, the soil profile (0 to 2 m), the shallow aquifer (2 to 20 m), and the deep aquifer (> 20 m).

Loadings of flow, sediment, nutrients, pesticides, and bacteria from the upland areas to the main channel are routed through the stream network of the basin using a process similar to hydrologic model (HYMO) (Williams and Hann 1973). The stream processes modeled by SWAT are shown in Figure 7.2 and include channel sediment routing and nutrient and pesticide routing and transformation. The pond and reservoir routing allows for sediment settling and simplified nutrient and pesticide transformation routines. The command structure for routing runoff and chemicals through a basin is similar to the structure for routing flows through streams and reservoirs.
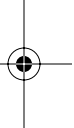
The SWAT watershed model also contains algorithms for simulating erosion from the watershed. Erosion is estimated using the Modified Universal Soil Loss Equation (MUSLE). MUSLE estimates sediment yield from the surface runoff volume, the peak runoff rate, the area of the HRU, the Universal Soil Loss Equation (USLE) soil erodibility factor, the USLE cover and management factor, the USLE support practice factor, the USLE topographic factor, and a coarse fragment factor.

After the sediment yield is evaluated using the MUSLE equation, the SWAT model further corrects this value considering snow cover effect and sediment lag in surface runoff. The SWAT model also calculates the contribution of sediment to channel flow from lateral and groundwater sources. Eroded sediment that enters channel flow is simulated in the SWAT model to move downstream by deposition and degradation (Neitsch et al. 2001a).

Soil nitrogen (N) is simulated in the SWAT model and is partitioned into five N pools, with two being inorganic (ammonium-N [NH_4-N] and nitrate-N [NO_3-N]) and three being organic (active, stable, and fresh). The SWAT model simulates movement between N pools, such as mineralization, decomposition and immobilization, nitrification, denitrification, and ammonia volatilization. Other soil N processes such as N fixation by legumes and NO_3-N movement in water are also

FIGURE 7.1 Hydrologic cycle representation in the SWAT model. (From S.L. Neitsch et al., *Soil and Water Assessment Tool theoretical documentation version 2000, 2001*. 2001, available at http://www. brc.tamus.edu/swat/doc.html. With permission.)

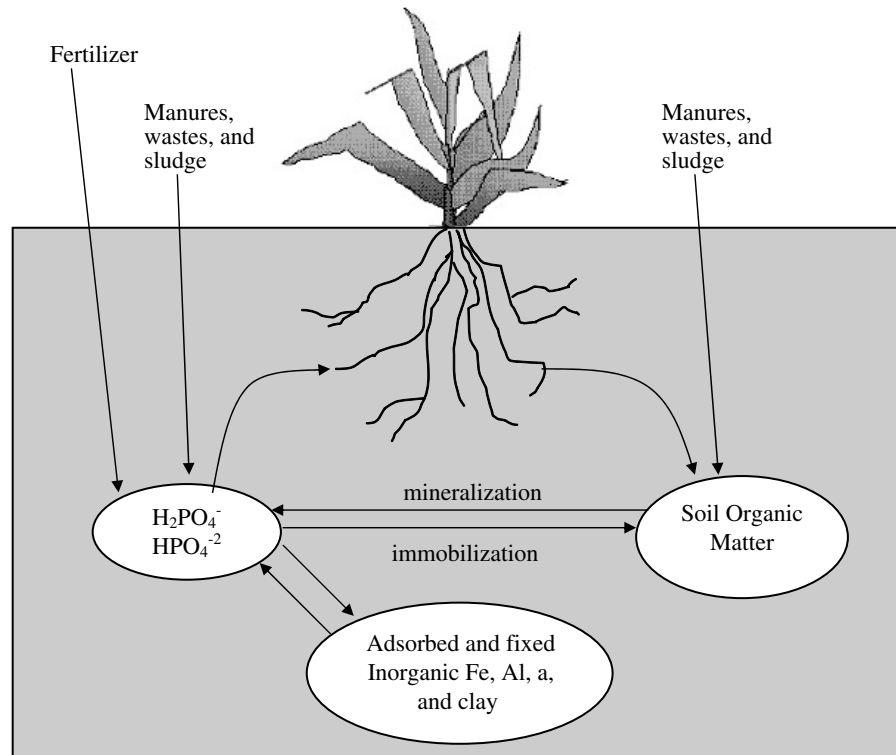**FIGURE 7.2** In-stream processes considered by the SWAT model. (From S.L. Neitsch et al., *Soil and Water Assessment Tool theoretical documentation version 2000, 2001.* 2001, available at http:// www.brc.tamus.edu/ swat/doc.html.With permission.)

included in the model. All soil N processes are simulated in the SWAT model using relationships described in the model's theoretical documentation (Neitsch et al. 2001a).

Once N enters channel flow, the SWAT model partitions N into four pools: organic N, NH_4-N, nitrite-N (NO_2-N), and NO_3-N. The SWAT model simulates changes in N that result in movement of N between pools. The algorithms used to describe N transformations in channel flow were adapted from the QUAL2E model by SWAT model developers (Neitsch et al. 2001a).

7.2 PHOSPHORUS MODELING IN SWAT: SOIL PHOSPHORUS INTERACTIONS

Figure 7.3 illustrates the major components of the phosphorus (P) cycle modeled in SWAT. Phosphorus can be added to the soil matrix in the form of inorganic P fertilizer, organic P fertilizer, and P present in plant residue. Soil P is divided into six pools. Three of the pools are characterized as mineral P, and three are characterized as organic P (Figure 7.4). Crop residue and microbial biomass contribute to the fresh organic P pool, and humic substances contribute to the active and stable organic P pools. Soil inorganic P is divided into solution, active, and stable pools. Despite the labeling in Figure 7.4, it is clear in the text of the *SWAT User's Manual* that solution P is actually labile P in conformance with the original EPIC version
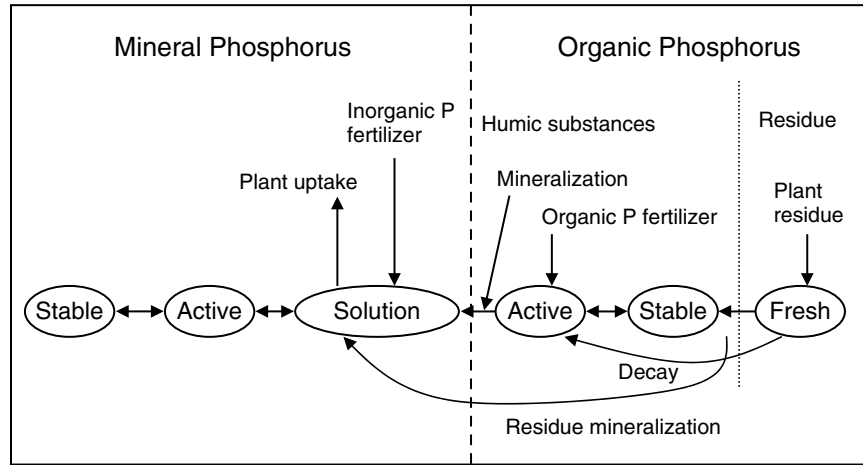
FIGURE 7.3 Phosphorus cycle processes modeled by SWAT. (From S.L. Neitsch et al., *Soil and Water Assessment Tool theoretical documentation version 2000, 2001.* 2001, available at http://www.brc.tamus.edu/swat/doc.html.With permission.)

of the P module as described in Jones et al. (1984), Sharpley et al. (1984), and Chapters 3 and 4 of this volume. Labile P is the P extracted by an anion exchange resin (Sharpley et al. 1984) and therefore represents solution P plus weakly sorbed P. This chapter uses the same notation as in the *SWAT User's Manual* (Neitsch et al. 2001a) for the equations, but an indication will be provided parenthetically in the text when solution P is actually labile P. Transformations of soil P among these six pools are regulated by algorithms that represent mineralization, decomposition, and immobilization. The solution (labile) pool is considered to be in rapid equilibrium (days to weeks) with active pools that subsequently are considered to be in slow equilibrium with stable pools.

7.2.1 Initialization of Soil Phosphorus Levels

Initial amounts of soluble (labile) and organic P contained in humic substances for all soil layers can be either specified by the model user or designated with SWAT model default values. The model initially sets concentration of solution (labile) P in all layers to 5 mg P kg^{-1} soil for unmanaged land under native vegetation and 25 mg P kg^{-1} soil for cropland conditions (Neitsch et al. 2001a).

FIGURE 7.4 Various pools of P and their interactions in soil matrix. (From S.L. Neitsch et al., *Soil and Water Assessment Tool theoretical documentation version 2000*, 2001, available at http://www.brc.tamus.edu/swat/doc.html.With permission.)

The active mineral pool P ($P_{\text{active\_mineral\_pool}}$) concentration (mg kg^{-1}) is initialized as

$$P_{\text{active\_mineral\_pool}} = P_{\text{solution}} \left(\frac{1 - PAI}{PAI} \right) \tag{7.2}$$

where P_{solution} is the amount of labile P (mg P kg^{-1}) and *PAI* is the P availability index. *PAI* is estimated using the method outlined by Sharpley et al. (1984).

The stable mineral pool P ($P_{\text{stable\_mineral\_pool}}$) concentration (mg P kg^{-1}) is initialized as

$$P_{\text{stable\_mineral\_pool}} = 4 \, (P_{\text{active\_mineral\_pool}}) \tag{7.3}$$

Organic P concentration ($P_{\text{humic\_organic}}$) is calculated assuming an N to P ratio in humic substance of 8 to 1 and is calculated as

$$P_{\text{human\_organic}} = 0.125 (N_{\text{human\_organic}}) \tag{7.4}$$

where $N_{\text{humic\_organic}}$ is the concentration of humic organic nitrogen in the soil layer (mg kg^{-1}). Phosphorus in the fresh organic pool is set to 0.03% of the initial amount of residue on the soil surface (kg ha^{-1}).

The SWAT model makes all nutrient calculations on a mass basis even though all nutrient levels are input in the model as concentrations. The nutrient concentration (mg kg^{-1} or ppm) is converted to mass (kg P ha^{-1}) by multiplying it by the depth of the soil layer and soil bulk density and performing appropriate unit conversions.

7.2.2 Mineralization, Decomposition, and Immobilization

The P mineralization calculations also include immobilization and are based on
Jones et al. (1984). The fresh organic P associated with crop residue and microbial
biomass and active organic P pool associated with soil humus are two P reservoirs
considered by the model for mineralization.

Temperature factor ($\gamma_{\text{temperature}}$) and water factor ($\gamma_{\text{water}}$) are two parameters regulating the impact of temperature and water availability on P mineralization and
decomposition. These factors are calculated as

$$\gamma_{\text{temperature}} = 0.9 \left(\frac{T_{\text{soil}}}{T_{\text{soil}} + \exp[9.93 - 0.312 * T_{\text{soil}}]} \right)$$

$$\gamma_{\text{water}} = \frac{SW}{FC}$$

(7.5)

where T_{soil} is the temperature of the soil layer (°C), SW is water content of the soil
layer (mm), and FC is water content of the soil layer at field capacity (mm).
Temperature of the soil layers should be above 0°C for mineralization and decomposition to occur. The minimum value of γ_{water} allowed by the model is 0.05.

The amount of P present in active and stable organic pools associated with humus
is calculated as

$$organic\ P_{\text{active}} = organic\ P_{\text{humus}} \left(\frac{organic\ N_{\text{active}}}{organic\ N_{\text{active}} + organic\ N_{\text{stable}}} \right)$$

(7.6)

$$organic\ P_{\text{stable}} = organic\ P_{\text{humus}} \left(\frac{organic\ N_{\text{stable}}}{organic\ N_{\text{active}} + organic\ N_{\text{stable}}} \right)$$

(7.7)

where $organic\ P_{\text{active}}$ is the amount of P in the active organic pool (kg P ha^{-1}), $organic\ P_{\text{stable}}$ is the amount of P in the stable organic pool (kg P ha^{-1}), $organic\ P_{\text{humus}}$ is the
concentration of humic organic P in the soil layer (kg P ha^{-1}), $organic\ N_{\text{active}}$ is
the amount of nitrogen in the active organic pool (kg N ha^{-1}), and $organic\ N_{\text{stable}}$ is
the amount of nitrogen in the stable organic pool (kg N ha^{-1}).

The amount of P mineralized from the humus active organic pool is calculated
as follows and is added to the solution P pool in the soil layer.

$$P_{\text{mineral\_active}} = 1.4\ (\beta_{\text{mineral}})(\gamma_{\text{temperature}} \gamma_{\text{water}})^{0.5}(organic\ P_{\text{active}})$$

(7.8)

where $P_{\text{mineral\_active}}$ is the P mineralized from the humus active organic P pool (kg P ha^{-1}),
and β_{mineral} is the rate coefficient for mineralization of the humus active organic nutrients.

Mineralization and decomposition from the residue fresh organic P pool is calculated as

$$P_{\text{mineral}} = 0.8 \ (\delta_{\text{ntr}})(organic \ P_{\text{fresh}}) \tag{7.9}$$

$$P_{\text{decay}} = 0.2 \ (\delta_{\text{ntr}})(organic \ P_{\text{fresh}}) \tag{7.10}$$

where P_{mineral} is the amount of P mineralized from the fresh organic P pool (kg P ha^{-1}) and added to the solution P pool, P_{decay} is the amount of P decomposed from the fresh organic pool (kg P ha^{-1}) and added to the humus organic pool, and δ_{ntr} is the residue decay rate constant. δ_{ntr} is calculated as

$$\delta_{\text{ntr}} = \beta_{\text{residue}} \gamma_{\text{ntr}} \left(\sqrt{\gamma_{\text{temperature}} \gamma_{\text{water}}} \right) \tag{7.11}$$

where β_{residue} is the rate coefficient for mineralization of the residue fresh organic nutrients and γ_{ntr} is the nutrient cycling residue composition factor for the soil layer. γ_{ntr} is calculated as

$$\gamma_{\text{ntr}} = \min \left\{ \begin{array}{l} \exp\left(-0.693\left(\dfrac{\varepsilon_{\text{C:N}} - 25}{25}\right)\right) \\[2ex] \exp\left(-0.693\left(\dfrac{\varepsilon_{\text{C:P}} - 200}{200}\right)\right) \\[2ex] 1.0 \end{array} \right\} \tag{7.12}$$

where $\varepsilon_{\text{C:N}}$ is the C:N ratio on the residue in the soil layer and $\varepsilon_{\text{C:P}}$ is the C:P ratio on the residue in the soil layer. The C:N ratio of the residue is calculated as

$$\varepsilon_{\text{C:N}} = \frac{0.58 \ rsd}{organic \ N_{\text{fresh}} + \text{NO}_3} \tag{7.13}$$

where rsd is the amount of residue in the soil layer (kg ha^{-1}), 0.58 is the fraction of residue that is carbon, and NO_3 is the amount of nitrate in the soil layer (kg N ha^{-1}).

The C:P ratio is calculated as

$$\varepsilon_{\text{C:P}} = \frac{0.58 \ rsd}{organic \ P_{\text{fresh}} + P_{\text{solution}}} \tag{7.14}$$

7.2.3 INORGANIC PHOSPHORUS SORPTION

The inorganic P pool, originating either from mineralization of organic P or P applied directly as inorganic fertilizer, is simulated considering plant uptake and conversion to active and stable forms of inorganic P (Figure 7.4). The movement of P between

the solution (labile) and active mineral pools is estimated using the following equilibrium equations (Neitsch et al. 2001a):

$$P_{\text{soluble/active}} = P_{\text{solution}} - mineral\, P_{\text{active}}\left(\frac{PAI}{1-PAI}\right)$$

$$\text{if}\quad P_{\text{solution}} > mineral\, P_{\text{active}}\left(\frac{PAI}{1-PAI}\right)$$

$$P_{\text{soluble/active}} = 0.1\left(P_{\text{solution}} - mineral\, P_{\text{active}}\left(\frac{PAI}{1-PAI}\right)\right) \tag{7.15}$$

$$\text{if}\quad P_{\text{solution}} < mineral\, P_{\text{active}}\left(\frac{PAI}{1-PAI}\right)$$

where $P_{\text{solution/active}}$ is the amount of P transferred between the soluble (labile) and active mineral pool (kg/ha), P_{solution} is the amount of labile P (kg P ha^{-1}), and *PAI* is P availability index. A positive value of $P_{\text{solution/active}}$ indicates transfer of P from solution to the active mineral pool, and a negative value indicates that P is transferred from the active mineral pool to solution (labile) pool. Phosphorus availability index controls the equilibrium between the solution and active mineral pool and specifies what fraction of fertilizer P is in solution after the rapid reaction period.

In estimating slow sorption of P (where sorbed P is the stable pool), SWAT assumes that the stable mineral pool is four times the size of the active mineral pool. The movement of P between the active and stable pools is calculated using the following equations (Neitsch et al. 2001a):

$$P_{\text{active/stable}} = \beta_{\text{eqP}}\left(4\ mineral\, P_{\text{active}} - mineral\, P_{\text{stable}}\right)$$

$$\text{if}\quad mineral\, P_{\text{stable}} < 4\ mineral\, P_{\text{active}}$$

$$P_{\text{active/stable}} = \left(0.1\ \beta_{\text{eqP}}\right)\left(4\ mineral\, P_{\text{active}} - mineral\, P_{\text{stable}}\right) \tag{7.16}$$

$$\text{if}\quad mineral\, P_{\text{stable}} > 4\ mineral\, P_{\text{active}}$$

where $P_{\text{active/stable}}$ is the amount of P transferred between the active and stable mineral pools (kg P ha^{-1}), and β_{eqP} is the slow equilibrium rate constant (0.0006 d^{-1}). A positive value of $P_{\text{active/stable}}$ indicates transfer of P from the active mineral pool to the stable mineral pool, and a negative value indicates transfer of P from the stable mineral pool to the active mineral pool.

7.2.4 LEACHING

When plants take up P from the root zone in the soil solution, it creates a concentration gradient in the soil-solution matrix. SWAT considers diffusion — the migration of P ions over small distances (1 to 2 mm) in the soil solution in response to a concentration gradient — to be the primary mechanism of P movement in the soil.

Soluble P is simulated by the SWAT model to leach only from the top 10 mm of soil into the first soil layer. The mass of solution P leaching into the first soil layer is calculated as

$$P_{\text{perc}} = \frac{P_{\text{solution,surf}} w_{\text{perc,surf}}}{10 \, \rho_{\text{b}} \, depth_{\text{surf}} \, k_{\text{d,perc}}} \tag{7.17}$$

where P_{perc} is the amount of P moving from the top 10 mm into the first soil layer (kg P ha^{-1}), $P_{\text{solution,surf}}$ is the amount of labile P in the top 10 mm (kg P ha^{-1}), $w_{\text{perc,surf}}$ is the amount of water percolating to the first soil layer from the top 10 mm on a given day (mm), ρ_{b} is the soil bulk density of the top 10 mm (mg m^{-3}), $depth_{\text{surf}}$ is the depth of the surface layer, and $k_{\text{d,perc}}$ is the P percolation coefficient. The $k_{\text{d,perc}}$ is calculated as the ratio of the labile P concentration in the surface 10 mm of soil to the concentration of P in percolate.

7.2.5 FERTILIZER APPLICATION

SWAT provides the user with the option to incorporate both inorganic and organic fertilizer application to the land-management file. The amount and type of fertilizer applied, timing of application, and depth distribution of application are the input information needed by the model. The model user is required to define the weight fraction of different forms of nutrients in the fertilizer. To predict the interaction of fertilizer with soil and runoff, the model assumes that the effective depth of interaction of runoff with soil is top 10 mm and runoff transports nutrients that are available only in the top 10 mm of soil. The amount of fertilizer not applied in the top 10 mm of soil is added to the first soil layer (Neitsch et al. 2001a).

When applied fertilizer is in the form of organic manure, the model partitions the amount of P added to fresh organic and humus organic pools as follows:

$$organic \, P_{\text{fresh,fert}} = 0.5(fert_{\text{organicP}})(fert) \tag{7.18}$$

$$organic \, P_{\text{humus,fert}} = 0.5(fert_{\text{organicP}})(fert) \tag{7.19}$$

where *organic* $P_{\text{fresh,fert}}$ is the amount of P in the fresh organic pool added to the soil as a result of fertilizer application (kg P ha^{-1}), $fert_{\text{organicP}}$ is the fraction of organic P in fertilizer, *fert* is the amount of fertilizer applied to the soil (kg ha^{-1}), and *organic* $P_{\text{humus,fert}}$ is the amount of P in the humus organic pool added to the soil as a result of fertilizer application.

7.2.6 PHOSPHORUS UPTAKE BY PLANTS

The model calculates plant P demand (P_{uptake}, kg ha^{-1}) as follows:

$$P_{\text{uptake}} = 1.5(biomass_{\text{P,optimum}} - biomass_{\text{p}}) \qquad (7.20)$$

where $biomass_{\text{P,optimum}}$ is the expected amount of P content in plant biomass at a given plant stage, and $biomass_{\text{P}}$ is the actual amount of P content in plant biomass.

Because of the difference in depth distribution of root density in the soil profile, P uptake by plants also varies with soil depth. SWAT calculates P uptake from different soil depths as follows:

$$P_{\text{uptake,z}} = \frac{P_{\text{uptake}}}{1 - \exp(-\beta_{\text{p}})}\left(1 - \exp\left(-\beta_{\text{p}}\frac{z}{z_{\text{root}}}\right)\right) \qquad (7.21)$$

where $P_{\text{uptake,z}}$ is the potential P uptake by the plant to soil depth z (kg ha^{-1}), P_{uptake} is the potential P_{uptake} (kg ha^{-1}), z is soil depth from the surface (mm), and β_{p} is a distribution parameter for P uptake and can be adjusted by a model user. The P uptake for a soil layer is calculated as a difference between P uptake at the lower and upper boundary of that soil layer.

SWAT calculates the actual amount of P removed (P_{actual}) as

$$P_{\text{actual}} = \min\left\lfloor P_{\text{uptake}} + P_{\text{demand}}, P_{\text{solution}} \right\rfloor \qquad (7.22)$$

where P_{demand} is the P uptake demand not met by overlying soil layers (kg P ha^{-1}) and P_{solution} is the amount of labile P present in the soil (kg P ha^{-1}). The model assumes that plant uptake of P comes from the labile P pool (Figure 7.4).

If a sufficient amount of P is not available in the soil for optimum plant growth, plants may experience P stress. The P stress in plants is calculated as

$$P_{\text{stress}} = 1 - \frac{\varphi_{\text{P}}}{\varphi_{\text{P}} + \exp(3.535 - 0.02597\varphi_{\text{P}})} \qquad (7.23)$$

where P_{stress} is the P stress for a given day and φ_{P} is a scaling factor for P stress and is calculated as follows:

$$\varphi_{\text{P}} = 200\left(\frac{biomass_{\text{p}}}{biomass_{\text{p,opt}}} - 0.5\right) \qquad (7.24)$$

where $biomass_{\text{P}}$ is the actual P content of plant biomass and $biomass_{\text{P,opt}}$ is the optimum P content of plant biomass (kg P ha^{-1}) (Neitsch et al. 2001a).

7.3 PHOSPHORUS MOVEMENT IN SURFACE RUNOFF

7.3.1 SOLUBLE PHOSPHORUS

The SWAT model simulates the movement of P from the landscape into surface runoff as

$$P_{\text{surf}} = \frac{P_{\text{solution,surf}} \, Q_{\text{surf}}}{\rho_{\text{b}} \, depth_{\text{surf}} \, k_{\text{d,surf}}} \tag{7.25}$$

where P_{surf} is the amount of soluble P transported by surface runoff (kg P ha^{-1}), $P_{\text{solution,surf}}$ is the amount of labile P in the top 10 mm (kg P ha^{-1}), Q_{surf} is the amount of surface runoff on a given day (mm), and $k_{\text{d,surf}}$ is the P soil partitioning coefficient (m^3 mg^{-1}) (Neitsch et al. 2001b).

7.3.2 ORGANIC AND MINERAL PHOSPHORUS ATTACHED TO SEDIMENT IN SURFACE RUNOFF

SWAT estimates the mass of P transported with sediment to the stream using a loading function developed by McElroy et al. (1976) and Williams and Hann (1978). This function is

$$sediment \, P_{\text{surf}} = 0.001(conc_{\text{sedP}})\left(\frac{sed}{area_{\text{HRU}}}\right)\varepsilon_{\text{P:sed}} \tag{7.26}$$

where $sediment \, P_{\text{surf}}$ is the amount of P transported with sediment to the main channel in surface runoff (kg P ha^{-1}), $conc_{\text{sedP}}$ is the concentration of P attached to sediment in top 10 mm (g P metric ton soil^{-1}), sed is the sediment yield on a given day (metric tons), $area_{\text{HRU}}$ is the HRU area (ha), and $\varepsilon_{\text{P:sed}}$ is the P enrichment ratio. The $conc_{\text{sedP}}$ is calculated as

$$conc_{\text{sedP}} = 100\left(\frac{mineral \, P_{\text{act,surf}} + mineral \, P_{\text{stable,surf}} + organic \, P_{\text{humic,surf}} + organic \, P_{\text{frsh,surf}}}{\rho_{\text{b}}(depth_{\text{surf}})}\right) \tag{7.27}$$

As P is transported with runoff, its concentration in the runoff sediment increases as compared to the soil surface concentration due to relative ease with which smaller sediment particles are eroded and the settling of relatively coarse sediment particles during transport. This process is called P enrichment. The ratio of the concentration of P transported with the sediment to the concentration of P in the soil surface layer is defined as the P enrichment ratio ($\varepsilon_{\text{P:sed}}$). SWAT calculates $\varepsilon_{\text{P:sed}}$ for each storm event as (Menzel 1980)

$$\varepsilon_{\text{P:sed}} = 0.78(conc_{\text{sed,surq}})^{-0.2468} \tag{7.28}$$

where $conc_{\text{sed,surq}}$ is the concentration of sediment in surface runoff (mg sediment m^{-3}) and is calculated as

$$conc_{\text{sed,surq}} = \frac{sed}{10(area_{\text{HRU}})(Q_{\text{surf}})} \tag{7.29}$$

When the time of concentration of runoff exceeds 1 day, which is typical for many large watersheds, only a portion of the surface runoff and lateral flow reaches the main channel on the day they are generated. A storage feature is used by the model to account for delay of surface runoff and lateral flow release to the main channel. Both dissolved and sediment attached P in the surface and lateral flow experience a lag that is a function of the surface runoff lag coefficient, time of concentration for the HRU, and lateral flow travel time (Neitsch et al. 2001a).

7.4   IN-STREAM PHOSPHORUS CYCLE

SWAT model users have an option to include or exclude in-stream processes in SWAT simulations. When the in-stream component is included, the model routes the state variables through additional algorithms that have been adapted from QUAL2E, a steady-state stream water-quality model developed by Brown and Barnwell (1987). These QUAL2E additional algorithms are included to simulate in-stream processes otherwise not considered by SWAT.

The differences between the algorithms used in SWAT and QUAL2E are predominantly related to model characteristics of being a dynamic (SWAT) or steady-state model (QUAL2E). The steady-state constituent concentrations are calculated in the QUAL2E model using a mass transport equation that includes advection, dispersion, dilution, constituent reactions and interactions, and source and sink components (Barnwell et al. 1987):

$$\frac{\partial C}{\partial t} = \frac{\partial \left(A_x D_L \frac{\partial C}{\partial x} \right)}{A_x \partial x} - \frac{\partial (A_x \bar{u} C)}{A_x \partial x} \frac{dC}{dt} + \frac{s}{v} \tag{7.30}$$

where C is concentration, A_x is the cross-sectional area, D_L is the dispersion coefficient, $\bar{u}$ is mean velocity, s is external sources or sinks, and v is incremental volume. In Equation 7.30, the partial derivative of C with respect to t refers to the local concentration gradient, whereas $dC\,dt^{-1}$ refers to constituent changes such as growth and decay. Each QUAL2E constituent concentration is solved using Equation 7.30 with respective constituent parameters. For example, in QUAL2E organic P is calculated as

$$\frac{dP_1}{dt} = \alpha_2 \rho A - \beta_4 P_1 - \sigma_5 P_1 \tag{7.31}$$

where P_1 is the concentration of organic P in the water, α_2 is the P content of algae, ρ is algal respiration rate, A is algal biomass concentration, β_4 is the organic P decay

rate, and σ_5 is the organic P settling rate. The QUAL2E organic P differential equation and other QUAL2E differential equations are solved using the classical implicit backward difference method (Barnwell et al. 1987). These methods are appropriate for the QUAL2E steady-state model. Integration of QUAL2E equations into the SWAT model required some modification of the equations to accommodate for SWAT model daily continuous simulation.

The P cycle simulated in QUAL2E includes minimal sediment interactions. One sink of organic P is governed by the σ_5 parameter representing organic P settling, implying the addition of organic P to the stream bed. The additional P-sediment type of interaction in the QUAL2E model is expressed by the σ_2 parameter, which describes the benthos source rate for dissolved P. These two parameters, σ_2 and σ_5, are not mathematically associated with each other. No other sediment-P interactions are accounted for with the given, off-the-shelf QUAL2E model. However, there is potential for modification of the code to include sediment-P interactions such as P adsorption to sediment.

A comparison between QUAL2E and SWAT model constituent concentration equations indicated minimal differences between the two. This can be illustrated by comparing the QUAL2E model organic P equation (Equation 7.31) with the SWAT model organic P equation (Equation 7.32). Organic P in SWAT is calculated as

$$\Delta orgP_{\text{str}} = (\alpha_2 \rho_a algae - \beta_{P,4} orgP_{\text{str}} - \sigma_5 orgP_{\text{str}})TT \tag{7.32}$$

where $\Delta orgP_{\text{str}}$ is the change in organic P concentration, α_2 is the fraction of algal biomass that is P, ρ_a is the local respiration or death rate of algae, *algae* is the algal biomass concentration at the beginning of the day, $\beta_{P,4}$ is the rate constant for mineralization of organic P, $orgP_{\text{str}}$ is the organic P concentration at the beginning of the day, σ_5 is the rate coefficient for organic P settling, and *TT* is the flow travel time in the reach segment for that day (Neitsch et al. 2001a). Hence, the dominant difference between the two is that the SWAT equation includes a dynamic variable *TT* for variable rates of flow travel time. The SWAT model also allows the user to adjust organic P inputs on a daily basis, which is not available in QUAL2E. This results in the $orgP_{\text{str}}$ variable being dynamic in the SWAT model instead of a steady-state constraint as in QUAL2E.

7.5 VERSIONS OF SWAT

SWAT model simulations have provided water-resource managers with a tool to be able to plan and make decisions in evaluating water supplies and nonpoint source pollution impacts in large river basins. Ultimately, SWAT is designed to be a model that (1) is computationally efficient; (2) allows considerable spatial detail; (3) requires readily available inputs; (4) is continuous in time; (5) is capable of simulating land-management scenarios; and (6) gives reasonable results.

The model is continually evolving to increase simulation accuracy of land-use changes and agricultural management on stream flow and constituent yields. SWAT2000 was enhanced with bacterial transport routines, urban routines, the

Green-Ampt infiltration equation, an improved weather generator, the ability to read in daily solar radiation, relative humidity, wind speed and potential evapotranspiration (ET), the Muskingum channel routing, and modified dormancy calculations for tropical areas. For the SWAT2000 version, theoretical documentation and a user manual are available with descriptions of the model algorithms, input and output files, and variables (Neitsch et al. 2001a, 2001b).

ArcView SWAT (AVSWAT) version 1.0 (Di Luzio et al. 2002) is a GIS-based hydrological system that links the SWAT model and ArcView GIS software. Its main purpose is to enhance the hydrological characterization of a watershed in the assessment of nonpoint and point pollution. The AVSWAT system has user-friendly tools to assist the user in setting up and completing a model simulation (Di Luzio et al. 2004). The main components include a preprocessor, interface, and postprocessor of the SWAT2000 model (Di Luzio et al. 2002). Without exiting the ArcView GIS environment, the user applies tools for the following to occur: watershed delineation, definition and editing of the hydrological and agricultural management inputs, and running and calibration of the model. AVSWAT is organized accordingly: (1) watershed delineation; (2) HRU definition tool; (3) model databases editor; (4) weather stations definition; (5) input parameterization and editor; (6) model run; (7) read and map chart results; and (8) calibration tool. The pertinent GIS data that must be included to describe the watershed are the digital elevation model, the land-use and land-cover map, and the soil map (Di Luzio et al. 2004).

SWAT was integrated as a component of the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) version 3.0, which is a software system developed by the U.S. Environmental Protection Agency Office of Water to meet the requirements of developing Total Maximum Daily Load (TMDL) programs. With over 30 years of USDA modeling experience, the SWAT model has proven successful in the watershed assessments of both agricultural and urban scenario management effects on water quality, rendering it useful for the Clean Water Act's requirement for the creation of TMDLs that appraise pollution for each listed water system.

The latest version, SWAT2003, includes additional improvements.

- The model contains a bacteria component that includes *E. coli* and fecal coliform. This component has been tested through a study in Walnut Creek, Iowa.
- Tile flow has been improved to more adequately simulate the presence of a water table and its draw down due to tile drains. Initially the lower soil levels are saturated, creating a water table. Rather than being based on soil moisture content, flow is a function of the water table above the tile.
- The presence of potholes has been added; however, additional work must be completed before it can be used.
- A curve number option based on antecedent weather (i.e., precipitation and climate) was developed rather than solely being based on soil moisture content.
- An autocalibration and sensitivity analysis option was added to SWAT2003, and progress continues to make this component more efficient and effective.
- Finally, with the enhancements added to SWAT2003, future support will focus on this version rather than maintaining SWAT2000.

As natural resource protection, including water quality, maintains its importance, this model will continue to develop and improve according to environmental necessity while aiming to keep the model user-friendly yet adequate to efficiently simulate watershed processes. SWAT has been modified or supplemented or has formed the basis for new model developments for special requirements of various catchments throughout the world.

- Watson et al. (2005) adapted SWAT to improve the Leaf Area Index simulation for the eucalyptus and pine forests common to Australia. The SWAT model is more suited to crops and deciduous vegetation.
- Extended SWAT (E-SWAT) is a computer program designed by Griensven (2002) that uses a time step of a user-defined fraction of an hour to calculate the rainfall and runoff and an hourly time step to calculate in-stream river-routing processes.
- SWAT Giessen (SWAT-G) (Eckhardt et al. 2002), is a river-basin scale model that operates on a daily time step and was designed for usage in low mountain range areas with high proportions of interflow.
- Sophocleous et al. (1999) linked SWAT with the Modular Groundwater Flow (MODFLOW) model (McDonald and Harbaugh 2003) model to increase the accuracy of groundwater simulations.
- Lenhart et al. (2002) added an improved sediment concept to SWAT-G.
- In 1998, Krysanova et al. (1998) based the Soil and Water Integrated Model (SWIM) on SWAT hydrologic components.

7.6 SWAT MODEL APPLICATIONS

The SWAT model has been used extensively to evaluate watershed management options. For example, the SWAT model has been implemented to assess alternative management practices that incorporate both point and nonpoint sources (Kirsch et al. 2002; Santhi et al. 2001a, 2001b, 2001c). The SWAT model has also been used to investigate land-use changes such as the conversion of agriculture and forestland into turf grass usage (e.g., golf courses, residential neighborhoods) (King et al. 2001). These SWAT model applications were successful because of sufficient model calibration and validation, which ensured that the model represented the system being considered.

Investigators that have included sensitivity analysis consider specific output variables. The parameter having the greatest relative sensitivity for output variables of flow, NO_3-N, and TP were identified as the CN parameter (Cotter et al. 2003). Another study, focusing on base-flow predictions, identified several soil and ground-water parameters that influenced their output values (Spruill et al. 2000).

A larger contingency of SWAT model developers has documented parameters used in calibration (Table 7.1). SWAT model calibration results are also often reported in model publications (Tables 7.2 and 7.3); however, model calibrations should be considered with respect to their individual modeling objectives.

The number of calibration sites included in model calibration is one modeling objective to consider. Although a single site calibration is the most often presented

TABLE 7.1
Review of Parameters Used in Calibration as a Function of Output Variable Predicted in Published SWAT Model Applications

	Output Variable	Calibration Parameters	
Flow	CANMX[d]	Soil properties[a]	ALPHA BF[h]
	Crop growth routine[e]	AWC[f,g]	SURLAG[h]
	Curve number[a,b,c,d,e,f,g,h]	EPCO[c]	
	ESCO[c,e,f,h]	Groundwater parameters[e]	
	Revap coefficients[b,c,d]	Soil hydraulic conductivity[e]	
	Soil bulk density[e]		
Sediment	AMP[d,h]	SLSUBBSN[d,h]	OVN[h]
	Channel cover[e]	SPCON[c,d,h]	ROCK[h]
	Channel erosion[e]	SPEXP[c,d]	USLE_P[h]
	CH_N2[d]	USLE_K(1)[d,h]	
	MUSLE parameters[e]	SLOPE[d,h]	
	PRF[d, h]	CH_N1[d,h]	
TP	ANION_EXCL[d]	UBP[d,h]	RS5[h]
	ERORGP[d]	PHSKD[c,d,h]	
	Initial soil conc[c]	AI2[h]	
	PPERCO[c,d,h]	BC4[h]	
	PSP[d]	CMN[h]	
	SOL_BD[d]		
TN	CMN[e]	Initial soil conc[c]	NPERCO[c, d]

Notes: TP = total phosphorus; TN = total nitrogen.

[a] J.G. Arnold and P.M. Allen, *J. Hydrol.* 176, 57, 1996.

[b] R. Srinivasan, T.S. Ramanarayanan et al., *J. Am. Water Resour. Assoc.* 34(1), 91, 1998.

[c] C. Santhi, J.G. Arnold et al., *J. Am. Water Resour. Assoc.* 37(5), 1169, 2001a.

[d] A.S. Cotter, M.S. thesis, Department of Biological and Agricultural Engineering,   University of Arkansas, Fayetteville, 2002.

[e] K. Kirsch, A. Kirsch et al., *Trans. ASAE* 45(6), 1757, 2002.

[f] J.G. Arnold, R.S. Muttiah et al., *J. Hydrol.* 227, 21–40, 2000.

[g] J.G. Arnold, R. Srinivasan et al., *Water Sci. Technol.* 39(3), 121–133, 1999.

[h] K.L. White and I. Chaubey, *J. Am. Water Resour. Assoc.* 41(5), 1077–1086, 2005.

application of the SWAT model, multisite calibration is becoming more common (Arnold et al. 1999; Kirsch et al. 2002; Santhi et al. 2001a). The increased frequency of multisite applications is likely due to greater availability of measured data and to improved model sophistication and computing abilities.

Another modeling objective that influences model calibration is the number of response variables selected for calibration. The most commonly calibrated watershed response variable in SWAT model publications is stream flow (Arnold and Allen 1996; Manguerra and Engel 1998; Peterson and Hamlett 1998; Sophocleous et al. 1999). However, multivariable calibrations are often conducted when multiple

TABLE 7.2
Summary of Monthly Calibrations Performed on SWAT Models with Their Respective Statistic of Measurement of NS (with Respective R^2 Shown in Parenthesis)

Reference	Base Flow	Storm Flow	Total Flow	Sediment	Phosphorus	Nitrogen
Arnold and Allen (1996)	(0.38 to 0.51)	(0.79 to 0.94)	(0.63 to 0.95)			
Arnold and Allen (1999)	(0.62 to 0.98)					
Arnold et al. (1999)[a]			−1.11 to 0.87 (0.23 to 0.96)			
Arnold et al. (2000)[a]			(0.63)			
Spruill et al. (2000)			0.58, 0.89			
Santhi et al. (2001b)[a]			0.79, 0.83 (0.80, 0.89)	0.80, 0.69 (0.81, 0.87)	0.53 to 0.70 (0.60 to 0.71)	−0.08 to 0.59 (0.60 to 0.72)
Cotter (2002)			0.76 (0.77)	0.50 (0.69)	0.66 (0.83)	0.44 (0.54)
Hanratty and Stefan (1998)			0.78	0.59	0.54	0.57, 0.68
Di Luzio et al. (2002)			0.82	0.78	0.58, 0.70	0.60
Tripathi et al. (2003)			0.98 (0.97)	0.79 (0.89)		
Srinivasan et al. (1998)[a]			0.77, 0.84 (0.87, 0.84)			
Srinivasan and Arnold (1994)			0.86			
White and Chaubey (2005)[a]			0.50 to 0.89 (0.41 to 0.91)	0.23 to 0.76 (0.45 to 0.85)	0.40 to 0.67 (0.50 to 0.82)	−2.36 to 0.29 (0.01 to 0.84)

Notes: NS = Nash-Sutcliffe efficiency coefficient.

[a] Multiple calibration sites used in SWAT model calibration.

TABLE 7.3
Summary of Annual Calibrations Performed on SWAT Models with Their Respective Statistic of Measurement of NS (R²)

Reference	Base Flow	Total Flow	Sediment	Phosphorus
Arnold et al. (1999)[a]		–1.11 to 0.87 (0.23 to 0.96)		
Arnold et al. (2000)[a]	(0.62)	(0.89)		
Kirsch and Kirsch (2001)		0.76 (0.78)	0.75 (0.82)	0.07 (0.95)
Kirsch et al. (2002)[a]		0.18 to 0.84 (0.28 to 0.98)		

Note: NS = Nash-Sutcliffe efficiency coefficient.

[a] Multiple calibration sites used in SWAT model calibration.

response variables are chosen (Cotter et al. 2003; Kirsch et al. 2002; Santhi et al. 2001a; White and Chaubey 2005). The increase in the number of variables in the calibration process requires model developers to designate multi-objective functions that consider multiple variables.

When evaluating a multivariable objective function, SWAT model users generally calibrate flow first when performing calibration. This is followed by sediment calibration and then by any nutrient calibrations (Cotter et al. 2003; Grizzetti et al. 2003; Kirsch and Kirsch 2001; Santhi et al. 2001b). Previous investigations have reported different evaluation priorities for nitrogen and P. For example, Santhi et al. (2001b) evaluated nitrogen and P components by first calibrating organic nitrogen and organic P and then calibrating mineral nitrogen and mineral P, whereas Cotter et al. (2003) evaluated nitrate first, followed by total P calibration.

The prediction capacity of the SWAT model is fairly simple. The model predicts discrete output variable values for a given time step. However, there is uncertainty associated with this value. To account for a portion of the uncertainty in the SWAT model, stochastic techniques can be used. Cotter (2002) conducted stochastic evaluation for a SWAT model using CN. Stochastic analysis was completed by generating input parameter probability distribution functions (PDFs) and output PDFs followed by an assessment of model performance. Similar stochastic analyses using the CN were explored by Chaubey et al. (2003). However, further investigation into stochastic analyses of SWAT model parameters is needed to provide some measure of uncertainty in model predictions, particularly for parameters that are identified as influencing output variables.

7.7 MODEL LIMITATIONS

A major limitation of large-area hydrologic modeling is the spatial detail required to correctly simulate environmental processes. For example, it is difficult to capture the spatial variability associated with precipitation within a watershed. Another limitation is the accuracy of hydrologic response units simulating field variations including conservation practices. SWAT is being altered to account for landscape

spatial positioning so that conservation practices such as riparian buffers and vegetative filter strips can be adequately simulated. SWAT does not simulate detailed event-based flood and sediment routing.

7.8 SWAT MODIFICATIONS

The SWAT model modifications under consideration are (1) the dynamics of P exchange between the solution and active mineral (organic) pools; (2) the desorption of P from soil to runoff water; (3) the simulation of surface applied manures and the loss of P from surface manures to runoff water; (4) soil cracking; (5) the addition of best management practices that can be correctly simulated such as vegetated filter strips and buffer zones; and (6) the improvement of autocalibration and sensitivity analysis components. The factors are addressed further in the following.

- SWAT assumes equilibrium between P in solution and in the active mineral pools. SWAT is being modified to slow the availability of P from the solution to the active mineral pool while transfer from the active mineral to the solution pool is instantaneous. This is potentially important when a runoff event occurs shortly after a manure application, before the solution and active mineral pools have time to reestablish equilibrium.
- After an exhaustive literature search, it was determined that SWAT's simulation of P desorption is comparable to other hydrologic models. Models to date regard that P desorption occurs at the same rate as P adsorption. Several research studies have demonstrated that this does not occur; however, models remain unchanged. As research data become available to suffice the P adsorption–desorption dilemma, the developers plan to address this important concept.
- SWAT currently assumes that the P in manure is added directly to the P pools in the upper soil layer (1 cm). Phosphorus may remain soluble in a manure layer longer than a soil layer, and thus SWAT may underestimate P movement shortly after a manure application. A conceptual model for SWAT that considers a manure layer that slowly moves the P into the soil has been developed. This improvement will take more time to implement and validate.
- The ability to predict runoff and storage requires understanding the processes of soil cracking (Arnold et al. 2005). Flow through each soil layer is combined with a crack flow model in conjunction with a storage routing technique for percolation to occur. Soil shrinkage cracking allows for a greater distribution of water, nutrients, and pesticides to the subsoil, rendering the solution unavailable for plant uptake and a source of groundwater pollution. Seasonal cracking also contributes to poor estimates of runoff and infiltration in areas with expansive soils. SWAT has incorporated a crack flow model. For a Texas watershed, the model was able to simulate surface runoff accurately for the winter months when the cracks were swelled closed and in the fall for recharge events when crack volume went from 70 to 10 mm. Future research is planned

to determine the impact of cracking on groundwater recharge and contaminant transport.

- The addition of best management practices such as vegetated filter strips, riparian zones, wetlands, as well as others, is known to be of importance so that SWAT can correctly simulate agricultural management in the watersheds. A component that has to be refined initially is the configuration of HRUs. This has to be done to account for more detailed variations in topography and management practices rather than each sub-basin remaining entirely independent of its adjoining sub-basins. A major concern before it will be changed is to determine the overall goal of the model. To accommodate smaller areas so that the watershed simulation will be more accurate, the model's complexity will have to increase rendering it less user-friendly. The ability to model best management practices means that the hydrology component must be redesigned to allow for more subtle topographical changes between sub-basins, thereby increasing the model's complexity. All of these adjustments are being considered while trying to maintain a less complex, more user-friendly model.

- Much work has been completed regarding the autocalibration sensitivity analysis component of SWAT through Griensven (2002). A procedure based on multi-objective calibration that incorporates the Shuffled Complex Evolution algorithm was utilized effectively for autocalibration. The optimization allows for up to 100 output variables to be considered simultaneously. The Shuffled Complex Evolution algorithm accepts as many as 30 objective functions for aggregation into a single global optimization criterion. A weighting problem is avoided due to the use of a statistical method that enables the aggregation of the objective functions for individual variables. A sensitivity analysis using the one-factor-at-a-time approach was successfully employed to identify the significant parameters for the optimization.

7.9 CONCLUSIONS

The Soil and Water Assessment Tool model is a physically based semi-distributed parameter model that performs all calculations on a daily time step to quantify effects of watershed management and climate conditions of flow, sediment, nutrient, and pesticide response from an agricultural watershed. SWAT simulates hydrology as a two-component system: land hydrology and channel hydrology. Components of P modeled by SWAT include soil P — water — plant interactions such as mineralization, decomposition, and immobilization; P sorption; leaching; and organic and inorganic fertilizer P application. In addition, P movement in surface runoff, including both soluble and sediment attached P, and in-stream P cycle are modeled in SWAT. A GIS interface of the model is available for easy preparation of input files and display of output results. SWAT is also integrated as a component of the Better Assessment Science Integrating Point and Nonpoint Sources suit of models developed by the U.S. EPA for TMDL development. The SWAT model has been extensively applied in many watersheds in the U.S. and other parts of the world to make watershed management decisions.

REFERENCES

Arnold, J.G. and P.M. Allen. 1996. Estimating hydrologic budgets for three Illinois watersheds. *J. Hydrol.* 176:57–77.

Arnold, J.G. and P.M. Allen. 1999. Automated methods for estimating baseflow and ground water recharge from stream flow records. *J. Am. Water Resour. Assoc.* 35(2):411–424.

Arnold, J.G., R.S. Muttiah et al. 2000. Regional estimation of base flow and groundwater recharge in the upper Mississippi basin. *J. Hydrol.* 227:21–40.

Arnold, J.G., K.N. Potter et al. 2005. Estimation of soil cracking and the effect on surface runoff in a Texas blackland prairie watershed. *Hydrol. Process.* 19(3):589–603.

Arnold, J.G., R. Srinivasan et al. 1998. Large area hydrologic modeling and assessment. I: model development. *J. Am. Water Resour. Assoc.* 34(1):73–89.

Arnold, J.G., R. Srinivasan et al. 1999. Water resources of the Texas gulf basin. *Water Sci. Technol.* 39(3):121–133.

Barnwell, T.O., Jr., L.C. Brown et al. 1987. QUAL2E — a case study in water quality modeling software: systems analysis in water quality management. *Proceedings of the Symposium Systems Analysis in Water Quality Management* London, June 30-July 2, 1987. M. B. Beck (Ed.). Oxford: Pergamon Press.

Brown, L.C. and T.O.J. Barnwell. 1987. *The Enhanced Water Quality Model QUAL2E and QUAL2E-UNCAS Documentation and User Manual*. U.S. Environmental Protection Agency.

Chaubey, I., T.A. Costello et al. 2003. Stochastic validation of SWAT model. American Society of Agricultural Engineers Total Maximum Daily Load Environmental Regulation Conference II, Albuquerque, NM, ASAE, St. Joseph, MI.

Cotter, A.S. 2002. Critical evaluation of TMDL data requirements for agricultural watersheds. M.S. thesis, Department of Biological and Agricultural Engineering, University of Arkansas, Fayetteville.

Cotter, A.S., I. Chaubey et al. 2003. Water quality model output uncertainty as affected by spatial resolution of input data. *J. Am. Water Resour. Assoc.* 39(4):977–986.

Di Luzio, M., J.G. Arnold et al. 2004. A GIS-coupled hydrological model system for the watershed assessment of agricultural nonpoint and point sources of pollution. *Trans. GIS* 8:113–136.

Di Luzio, M., R. Srinivasan et al. 2002. Integration of watershed tools and SWAT model into BASINS. *J. Am. Water Resour. Assoc.* 38(4):1127–1141.

Eckhardt, K., S. Haverkamp et al. 2002. SWAT-G, a version of SWAT99.2 modified for application to low mountain range catchments. *Phys. Chem. Earth* 27:641–644.

Griensven, A.V. 2002. Developments towards integrated water quality modeling for river basin. Ph.D. dissertation., Vrije Universiteit, Brussel.

Grizzetti, B., F. Bouraoui et al. 2003. Modelling diffuse emission and retention of nutrients in the Vantaanjoki watershed (Finland) using the SWAT model. *Ecol. Model.* 169(1):25–38.

Hanratty, M.P. and H.G. Stefan. 1998. Ecosystem processes: simulating climate change effects in a Minnesota agricultural watershed. *J. Environ. Qual.* 27:1524–1532.

Jones, G.C.A., C.V. Cole, A.N. Sharpley, and J.R. Williams. 1984. A simplified soil and plant phosphorus model. I. Documentation. *Soil Sci. Soc. Am. J.* 40:800–805.

King, K.W., R.D. Harmel et al. 2001. Impact of a turfgrass system on nutrient loadings to surface water. *J. Am. Water Resour. Assoc.* 37(3):629–640.

Kirsch, K.J. and A.E. Kirsch. 2001. Using SWAT to predict erosion and phosphorus loads in the Rock River Basin, Wisconsin. *Intl. Symp. ASAE* 701P0007, Honolulu, HI.

Kirsch, K., A. Kirsch et al. 2002. Predicting sediment and phosphorus loads in the Rock River Basin using SWAT. *Trans. ASAE* 45(6):1757–1769.

Knisel, W.G. 1980. CREAMS: a field scale model for chemicals, runoff and erosion from agricultural management systems. USDA Conservation Research Report No. 26, Washington, D.C.

Krysanova, V., D.I. Muller-Wohlfeil et al. 1998. Development and test of a spatially distributed hydrological water quality model for mesoscale watersheds. *Ecol. Model.* 106(2–3):261–289.

Lenhart, T., K. Eckhardt et al. 2002. Comparison of two different approaches of sensitivity analysis. *Phys. Chem. Earth* 27:645–654.

Leonard, R., W.G. Knisel et al. 1987. GLEAMS: groundwater loading effects of agricultural management systems. *Trans. ASAE* 30(5):1403–1417.

Manguerra, H. and B.A. Engel. 1998. Hydrologic parameterization of watersheds for runoff prediction using SWAT. *J. Am. Water Resour. Assoc.* 34(5):1149–1162.

McDonald, M.G. and A.W. Harbaugh. 2003. The history of MODFLOW. *Ground Water* 41(2):280–283.

McElroy, A.D., S.Y. Chiu et al. 1976. Loading function for assessment of water pollution from nonpoint sources. Environmental Protection Agency, EPA 600/2-76-151, Washington, D.C.

Menzel, R.G. 1980. Enrichment ratios for water quality modeling — CREAMS: a field scale model for chemicals, runoff, and erosion from agricultural management systems. U.S. Department of Agriculture, Conservation Research Report No. 26, Washington, D.C.

Neitsch, S.L., J.G. Arnold et al. 2001a. Soil and Water Assessment Tool theoretical documentation version 2000. Available at http://www.brc.tamus.edu/swat/doc.html.

Neitsch, S.L., J.G. Arnold et al. 2001b. Soil and Water Assessment Tool user's manual version 2000. Available at http://www.brc.tamus.edu/swat/doc.html.

Peterson, J.R. and J.M. Hamlett. 1998. Hydrologic calibration of the SWAT model in a watershed containing fragipan soils. *J. Am. Water Resour. Assoc.* 34(3):531–544.

Santhi, C., J.G. Arnold et al. 2001a. Validation of the SWAT model on a large river basin with point and nonpoint sources. *J. Am. Water Resour. Assoc.* 37(5):1169–1188.

Santhi, C., J.D. Atwood et al. 2001b. *Environmental and Economic Impacts of Reaching and Doubling the USDA Buffer Initiative Program on Water Quality.* St. Joseph, MI: American Society of Agricultural Engineers.

Santhi, C., J.R. Williams et al. 2001c. Application of a watershed model to evaluate management effects on point and nonpoint source pollution. *Trans. ASAE* 44(6):1559–1570.

Sharpley, A.N., C.A. Jones et al. 1984. A simplified soil and plant phosphorus model. II: prediction of labile, organic, and sorbed phosphorus. *Soil Sci. Soc. Am. J.* 48:805–809.

Sophocleous, M.A., J.K. Koelliker et al. 1999. Integrated numerical modeling for basin-wide water management: the case of the Rattlesnake Creek Basin in south-central Kansas. *J. Hydrol.* 214:179–196.

Spruill, C.A., S.R. Workman et al. 2000. Simulation of daily and monthly stream discharge from small watersheds using the SWAT model. *Trans. ASAE* 43(6):1431–1439.

Srinivasan, R. and J.G. Arnold. 1994. Integration of a basin scale water quality model with GIS1. *Water Resour. Bull.* 30(3):453–462.

Srinivasan, R., T.S. Ramanarayanan et al. 1998. Large area hydrologic modeling and assessment. II: model application. *J. Am. Water Resour. Assoc.* 34(1):91–101.

Tripathi, M.P., R.K. Panda et al. 2003. Identification and prioritization of critical subwatershed for soil conservation management using the SWAT model. *Biosys. Eng.* 85:365–369.

Wastson, B.M., N. Coops et al. 2005. Simulating leaf area index of eucalyptus forests and pine plantations for a catchment-scale balance model. *Engineers Australia 29th Hydrology and Water Resources Symposium*, February, 21–23 2005, Canberra, Australia.

White, K.L. and I. Chaubey. 2005. Sensitivity analysis, calibration, and validation for a multi-site and multi-variable SWAT model. *J. Am. Water Resour. Assoc.* 41(5):1077–1086.

Williams, J.R. and R.W.J. Hann. 1973. *Hymo: Problem-Oriented Computer Language for Hydrologic Modeling — User's Manual.* U.S. Agriculture Research Service Southern Region 9:76.

Williams, J.R. and R.W. Hann. 1978. *Optimal Operations of Large Agricultural Watersheds with Water Quality Constraints.* Texas Water Resources Institute.

Williams, J.R., C.A. Jones et al. 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Trans. ASAE* 27:129–144.