SOIL AND WATER ASSESSMENT TOOL THEORETICAL DOCUMENTATION

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S.L. NEITSCH, J.G. ARNOLD, J.R. KINIRY, J.R. WILLIAMS, K.W. KING

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GRASSLAND, SOIL AND WATER RESEARCH LABORATORY ○ AGRICULTURAL RESEARCH SERVICE
808 EAST BLACKLAND ROAD ○ TEMPLE, TEXAS 76502

BLACKLAND RESEARCH CENTER ○ TEXAS AGRICULTURAL EXPERIMENT STATION
720 EAST BLACKLAND ROAD ○ TEMPLE, TEXAS 76502

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CONTENTS

CHAPTER 1
INTRODUCTION

SECTION 1: CLIMATE

CHAPTER 2
EQUATIONS: ENERGY

Section 2: Hydrology

SECTION 3: NUTRIENTS/PESTICIDES

CHAPTER 11

CHAPTER 12

SECTION 4: EROSION

CHAPTER 13

CHAPTER 14

CHAPTER 15

CHAPTER 16

SECTION 5: LAND COVER/PLANT

CHAPTER 17

CHAPTER 18

CHAPTER 19

SECTION 6: MANAGEMENT PRACTICES

SECTION 7: MAIN CHANNEL PROCESSES

CHAPTER 26
EQUATIONS: PESTICIDE 401

SECTION 8: WATER BODIES

CHAPTER 27
EQUATIONS: IMPOUNDMENT WATER ROUTING 415

CHAPTER 28
EQUATIONS: SEDIMENT IN WATER BODIES 433

CHAPTER 29
EQUATIONS: NUTRIENTS IN WATER BODIES 437

CHAPTER 30
EQUATIONS: PESTICIDES IN WATER BODIES 447

SOIL AND WATER ASSESSMENT TOOL

CHAPTER 1

INTRODUCTION

SWAT is the acronym for **S**oil and **W**ater **A**ssessment **T**ool, a river basin, or watershed, scale model developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS). SWAT 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. To satisfy this objective, the model

- is physically based. Rather than incorporating regression equations to describe the relationship between input and output variables, SWAT requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modeled by SWAT using this input data.

Benefits of this approach are

- watersheds with no monitoring data (e.g. stream gage data) can be modeled
- the relative impact of alternative input data (e.g. changes in management practices, climate, vegetation, etc.) on water quality or other variables of interest can be quantified

- uses readily available inputs. While SWAT can be used to study more specialized processes such as bacteria transport, the minimum data required to make a run are commonly available from government agencies.
- is computationally efficient. Simulation of very large basins or a variety of management strategies can be performed without excessive investment of time or money.
- enables users to study long-term impacts. Many of the problems currently addressed by users involve the gradual buildup of pollutants and the impact on downstream water bodies. To study these types of problems, results are needed from runs with output spanning several decades.

SWAT is a continuous time model, i.e. a long-term yield model. The model is not designed to simulate detailed, single-event flood routing.

1.1 DEVELOPMENT OF SWAT

SWAT incorporates features of several ARS models and is a direct outgrowth of the SWRRB[1] model (Simulator for Water Resources in Rural Basins) (Williams et al., 1985; Arnold et al., 1990). Specific models that contributed significantly to the development of SWAT were CREAMS[2] (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), GLEAMS[3] (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al., 1987), and EPIC[4] (Erosion-Productivity Impact Calculator) (Williams et al., 1984).

Development of SWRRB began with modification of the daily rainfall hydrology model from CREAMS. The major changes made to the CREAMS hydrology model were: a) the model was expanded to allow simultaneous computations on several subbasins to predict basin water yield; b) a groundwater or return flow component was added; c) a reservoir storage component was added to calculate the effect of farm ponds and reservoirs on water and sediment yield; d) a weather simulation model incorporating data for rainfall, solar radiation, and temperature was added to facilitate long-term simulations and provide temporally and spatially representative weather; e) the method for predicting the peak runoff rates was improved; f) the EPIC crop growth model was added to account for annual variation in growth; g) a simple flood routing component was added; h) sediment transport components were added to simulate sediment movement

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[1] SWRRB is a continuous time step model that was developed to simulate nonpoint source loadings from watersheds.

[2] In response to the Clean Water Act, ARS assembled a team of interdisciplinary scientists from across the U.S. to develop a process-based, nonpoint source simulation model in the early 1970s. From that effort CREAMS was developed. CREAMS is a field scale model designed to simulate the impact of land management on water, sediment, nutrients and pesticides leaving the edge of the field. A number of other ARS models such as GLEAMS, EPIC, SWRRB and AGNPS trace their origins to the CREAMS model.

[3] GLEAMS is a nonpoint source model which focuses on pesticide and nutrient groundwater loadings.

[4] EPIC was originally developed to simulate the impact of erosion on crop productivity and has now evolved into a comprehensive agricultural management, field scale, nonpoint source loading model.

through ponds, reservoirs, streams and valleys; and i) calculation of transmission losses was incorporated.

The primary focus of model use in the late 1980s was water quality assessment and development of SWRRB reflected this emphasis. Notable modifications of SWRRB at this time included: a) incorporation of the GLEAMS pesticide fate component; b) optional SCS technology for estimating peak runoff rates; and c) newly developed sediment yield equations. These modifications extended the model’s capability to deal with a wide variety of watershed management problems.

In the late 1980s, the Bureau of Indian Affairs needed a model to estimate the downstream impact of water management within Indian reservation lands in Arizona and New Mexico. While SWRRB was easily utilized for watersheds up to a few hundred square kilometers in size, the Bureau also wanted to simulate stream flow for basins extending over several thousand square kilometers. For an area this extensive, the watershed under study needed to be divided into several hundred subbasins. Watershed division in SWRRB was limited to ten subbasins and the model routed water and sediment transported out of the subbasins directly to the watershed outlet. These limitations led to the development of a model called ROTO (Routing Outputs to Outlet) (Arnold et al., 1995), which took output from multiple SWRRB runs and routed the flows through channels and reservoirs. ROTO provided a reach routing approach and overcame the SWRRB subbasin limitation by “linking” multiple SWRRB runs together. Although this approach was effective, the input and output of multiple SWRRB files was cumbersome and required considerable computer storage. In addition, all SWRRB runs had to be made independently and then input to ROTO for the channel and reservoir routing. To overcome the awkwardness of this arrangement, SWRRB and ROTO were merged into a single model, SWAT. While allowing simulations of very extensive areas, SWAT retained all the features which made SWRRB such a valuable simulation model.

Since SWAT was created in the early 90s, it has undergone continued review and expansion of capabilities. The most significant improvements of the model between releases include:

♦ SWAT94.2: Multiple hydrologic response units (HRUs) incorporated.

♦ SWAT96.2: Auto-fertilization and auto-irrigation added as management options; canopy storage of water incorporated; a CO_2 component added to crop growth model for climatic change studies; Penman-Monteith potential evapotranspiration equation added; lateral flow of water in the soil based on kinematic storage model incorporated; in-stream nutrient water quality equations from QUAL2E added; in-stream pesticide routing.

♦ SWAT98.1: Snow melt routines improved; in-stream water quality improved; nutrient cycling routines expanded; grazing, manure applications, and tile flow drainage added as management options; model modified for use in Southern Hemisphere.

♦ SWAT99.2: Nutrient cycling routines improved, rice/wetland routines improved, reservoir/pond/wetland nutrient removal by settling added; bank storage of water in reach added; routing of metals through reach added; all year references in model changed from last 2 digits of year to 4-digit year; urban build up/wash off equations from SWMM added along with regression equations from USGS.

♦ SWAT2000: Bacteria transport routines added; Green & Ampt infiltration added; weather generator improved; allow daily solar radiation, relative humidity, and wind speed to be read in or generated; allow potential ET values for watershed to be read in or calculated; all potential ET methods reviewed; elevation band processes improved; enabled simulation of unlimited number of reservoirs; Muskingum routing method added; modified dormancy calculations for proper simulation in tropical areas.

In addition to the changes listed above, interfaces for the model have been developed in Windows (Visual Basic), GRASS, and ArcView. SWAT has also undergone extensive validation.

1.2 OVERVIEW OF SWAT

SWAT allows a number of different physical processes to be simulated in a watershed. These processes will be briefly summarized in this section. For more detailed discussions of the various procedures, please consult the chapter devoted to the topic of interest.

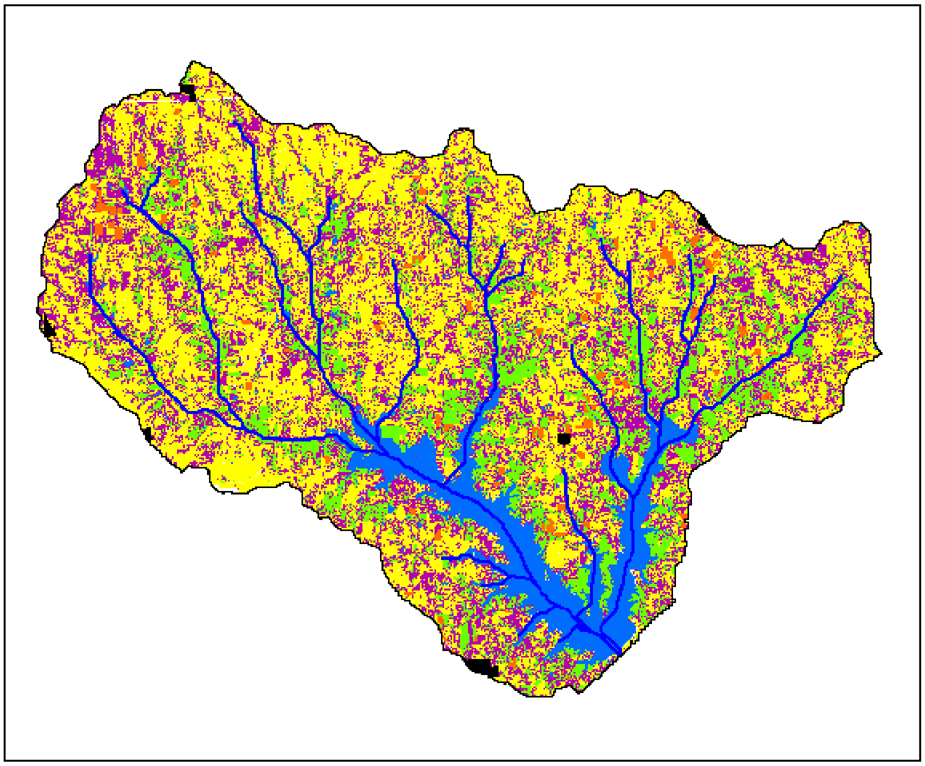

Figure 1.1: Map of the Lake Fork Watershed in Northeast Texas showing the land use distribution and stream network

For modeling purposes, a watershed may be partitioned into a number of subwatersheds or subbasins. The use of subbasins in a simulation is particularly beneficial when different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact hydrology. By partitioning the watershed into subbasins, the user is able to reference different areas of the watershed to one another spatially. Figure 1.2 shows a subbasin delineation for the watershed shown in Figure 1.1.

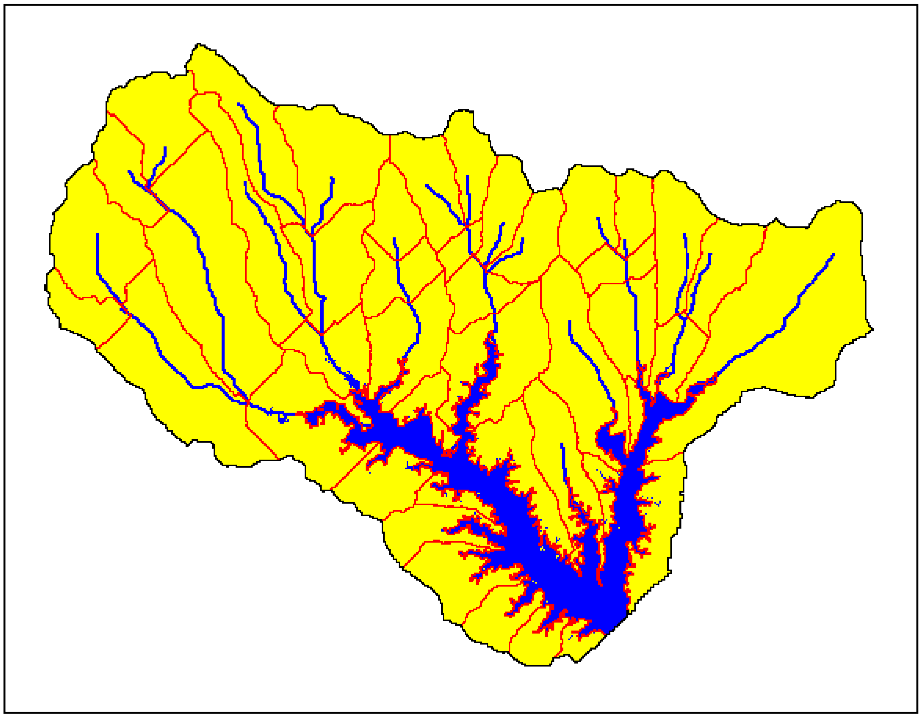

Figure 1.2: Subbasin delineation of the Lake Fork Watershed.

Input information for each subbasin is grouped or organized into the following categories: climate; hydrologic response units or HRUs; ponds/wetlands; groundwater; and the main channel, or reach, draining the subbasin. Hydrologic response units are lumped land areas within the subbasin that are comprised of unique land cover, soil, and management combinations.

No matter what type of problem studied with SWAT, water balance is the driving force behind everything that happens in the watershed. To accurately predict the movement of pesticides, sediments or nutrients, the hydrologic cycle as simulated by the model must conform to what is happening in the watershed. Simulation of the hydrology of a watershed can be separated into two major divisions. The first division is the land phase of the hydrologic cycle, depicted in Figure 1.3. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subbasin. The second division is the water or 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.

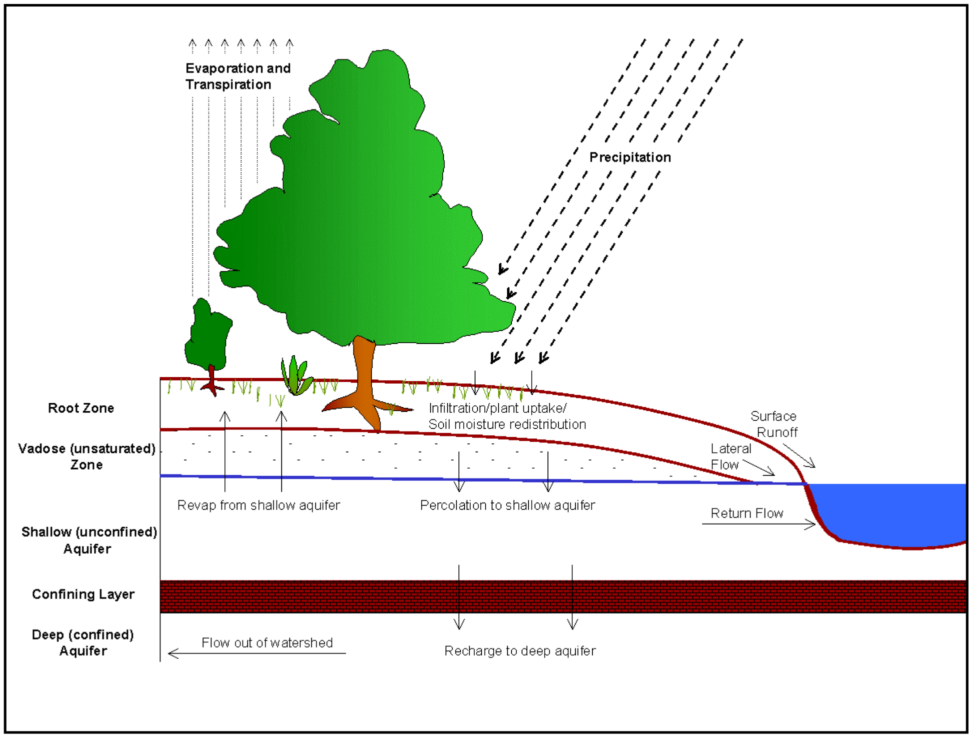

Figure 1.3: Schematic representation of the hydrologic cycle.

1.2.1 LAND PHASE OF THE HYDROLOGIC CYCLE

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

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the 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 water entering the vadose zone from the soil profile on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases accuracy and gives a much better physical description of the water balance.

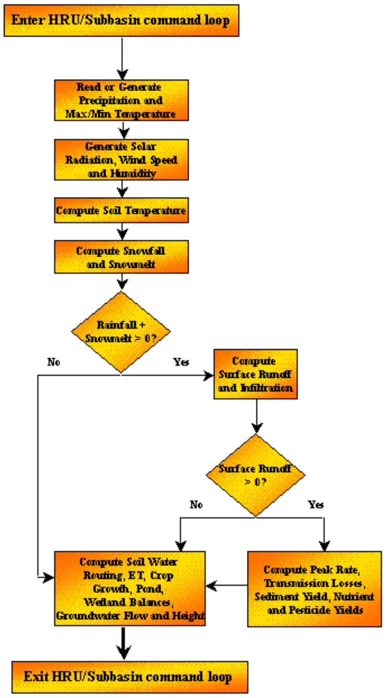

Figure 1.4: HRU/Subbasin command loop

Figure 1.4 shows the general sequence of processes used by SWAT to model the land phase of the hydrologic cycle. The different inputs and processes involved in this phase of the hydrologic cycle are summarized in the following sections.

1.2.1.1 CLIMATE

The climate of a watershed provides the moisture and energy inputs that control the water balance and determine the relative importance of the different components of the hydrologic cycle.

The climatic variables required by SWAT consist of daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity. The model allows values for daily precipitation, maximum/minimum air temperatures, solar radiation, wind speed and relative humidity to be input from records of observed data or generated during the simulation.

WEATHER GENERATOR. Daily values for weather are generated from average monthly values. The model generates a set of weather data for each subbasin. The values for any one subbasin will be generated independently and there will be no spatial correlation of generated values between the different subbasins.

> GENERATED PRECIPITATION**.** SWAT uses a model developed by Nicks (1974) to generate daily precipitation for simulations which do not read in measured data. This precipitation model is also used to fill in missing data in the measured records. The precipitation generator uses a first-order Markov chain model to define a day as wet or dry by comparing a random number (0.0-1.0) generated by the model to monthly wet-dry probabilities input by the user. If the day is classified as wet, the amount of precipitation is generated from a skewed distribution or a modified exponential distribution.
>
> GENERATED AIR TEMPERATURE AND SOLAR RADIATION**.** Maximum and minimum air temperatures and solar radiation are generated from a normal distribution. 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.

GENERATED WIND SPEED**.** A modified exponential equation is used to generate daily mean wind speed given the mean monthly wind speed.

GENERATED RELATIVE HUMIDITY**.** The relative humidity model uses a triangular distribution to simulate the daily average relative humidity from the monthly average. As with temperature and radiation, the mean daily relative humidity is adjusted to account for wet- and dry-day effects.

SNOW. SWAT classifies precipitation as rain or freezing rain/snow using the average daily temperature.

SNOW COVER. The snow cover component of SWAT has been updated from a simple, uniform snow cover model to a more complex model which 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 subbasin decreases below this value, the snow coverage is allowed to decline non-linearly based on an areal depletion curve.

SNOW MELT. Snow melt is controlled by the air and snow pack temperature, the melting rate, and the areal coverage of snow. If snow is present, it 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 the peak runoff rate is estimated assuming uniformly melted snow for a 24 hour duration.

ELEVATION BANDS. 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 elevation band. By dividing the subbasin into elevation bands, the model is able to assess the differences in snow cover and snow melt caused by orographic variation in precipitation and temperature.

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 temperature of the soil surface 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 temperature of a soil layer 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. This depth, referred to as the damping depth, is dependent upon the bulk density and the soil water content.

1.2.1.2 HYDROLOGY

As precipitation descends, it may be intercepted and held in 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 are illustrated in Figure 1.5.

CANOPY STORAGE. Canopy storage is the water intercepted by vegetative surfaces (the canopy) where it is held and made available for evaporation. 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 must be modeled separately. SWAT allows the user to input the 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.

INFILTRATION. Infiltration refers to the entry of water into a soil profile from the soil surface. As infiltration continues, the soil becomes increasingly wet, causing the rate of infiltration to decrease with time until it reaches a steady value. The initial rate of infiltration depends on the moisture content of the soil prior to the introduction of water at the soil surface. The final rate of infiltration is equivalent to the saturated hydraulic conductivity of the soil. Because the curve number method used to calculate surface runoff operates on a daily time-step, it 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 infiltration method does directly model infiltration, but it requires precipitation data in smaller time increments.

REDISTRIBUTION. Redistribution refers to the continued movement of water through a soil profile after input of water (via precipitation or irrigation) has ceased at the soil surface. Redistribution is caused by differences in water content in the profile. Once the water content throughout the entire profile is uniform,

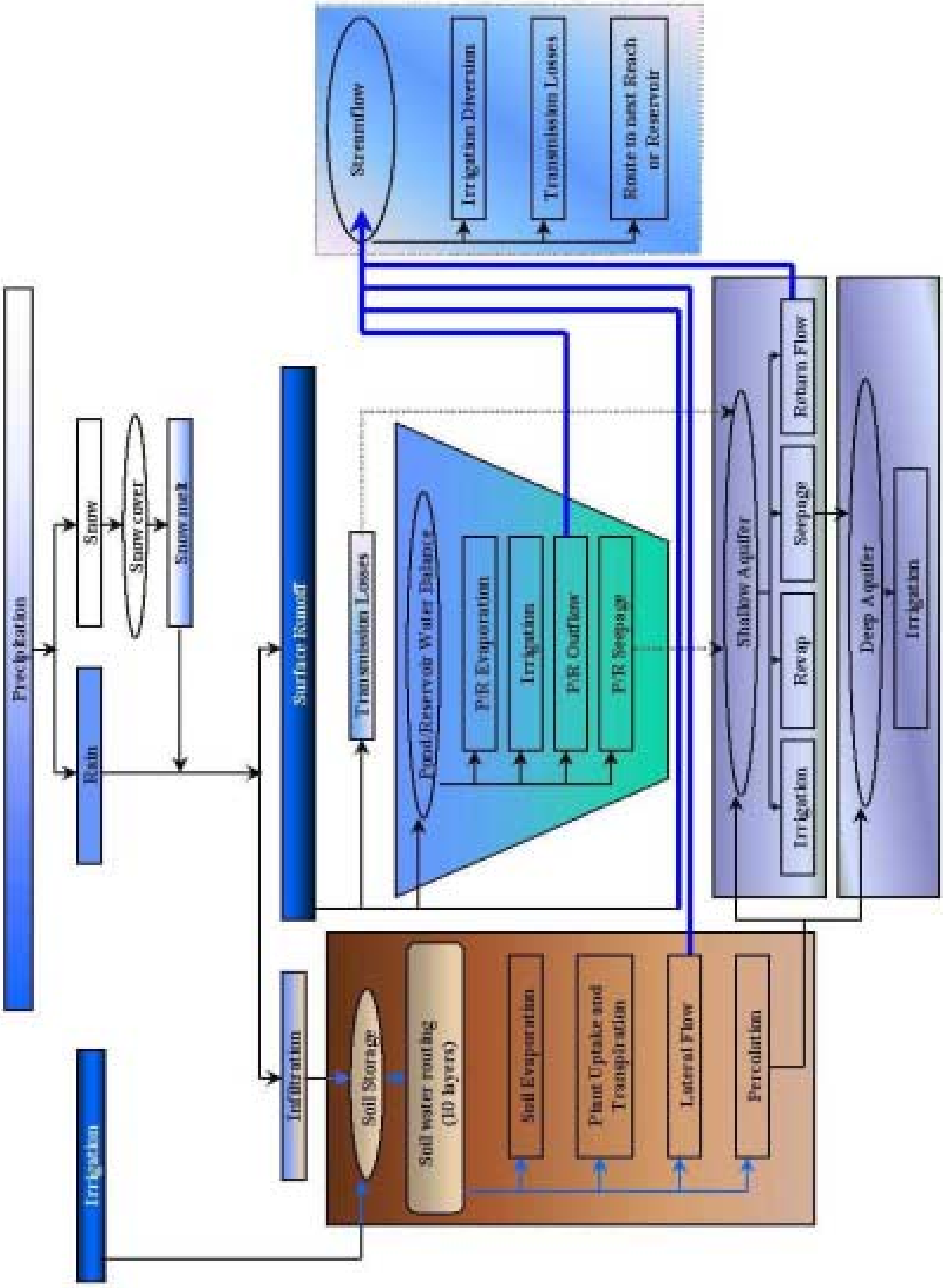

Figure 1.5: Schematic of pathways available for water movement in SWAT

redistribution will cease. The redistribution component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow, or percolation, occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. The flow rate is governed by the saturated conductivity of the soil layer. Redistribution is affected by soil temperature. If the temperature in a particular layer is 0°C or below, no redistribution is allowed from that layer.

EVAPOTRANSPIRATION. Evapotranspiration is a collective term for all processes by which water in the liquid or solid phase at or near the earth's surface becomes atmospheric water vapor. Evapotranspiration includes evaporation from rivers and lakes, bare soil, and vegetative surfaces; evaporation from within the leaves of plants (transpiration); and sublimation from ice and snow surfaces. The model computes evaporation from soils and plants separately as described by Ritchie (1972). Potential soil water evaporation is estimated as a function of potential evapotranspiration and leaf area index (area of plant leaves relative to the area of the HRU). Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant transpiration is simulated as a linear function of potential evapotranspiration and leaf area index.

> POTENTIAL EVAPOTRANSPIRATION. Potential evapotranspiration is the rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation which has access to an unlimited supply of soil water. This rate is assumed to be unaffected by micro-climatic processes such as advection or heat-storage effects. The model offers three options for estimating potential evapotranspiration: Hargreaves (Hargreaves et al., 1985), Priestley-Taylor (Priestley and Taylor, 1972), and Penman-Monteith (Monteith, 1965).

LATERAL SUBSURFACE FLOW. Lateral subsurface flow, or interflow, is streamflow contribution which originates below the surface but above the zone where rocks are saturated with water. Lateral subsurface flow in the soil profile (0-2m) is calculated simultaneously with redistribution. A kinematic storage model is used to predict lateral flow in each soil layer. The model accounts for variation in conductivity, slope and soil water content.

SURFACE RUNOFF. Surface runoff, or overland flow, is flow that occurs along a sloping surface. Using daily or subdaily rainfall amounts, SWAT simulates surface runoff volumes and peak runoff rates for each HRU.

> SURFACE RUNOFF VOLUME is computed using a modification of the SCS curve number method (USDA Soil Conservation Service, 1972) or the Green & Ampt infiltration method (Green and Ampt, 1911). In 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. 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. Water that does not infiltrate becomes surface runoff. SWAT includes a provision for estimating runoff from frozen soil where a soil is defined as frozen if the temperature in the first soil layer is less than 0°C. The model increases runoff for frozen soils but still allows significant infiltration when the frozen soils are dry.

PEAK RUNOFF RATE predictions are made with a modification of the 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, t_c, 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 t_c, the daily surface runoff volume, and the subbasin time of concentration. The proportion of rainfall occurring during the subbasin t_c is estimated as a function of total daily rainfall using a stochastic technique. The subbasin time of concentration is estimated using Manning's Formula considering both overland and channel flow.

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 non-linear function of storage.

TRIBUTARY CHANNELS. 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. SWAT uses the attributes of tributary channels to determine the time of concentration for the subbasin.

TRANSMISSION LOSSES. Transmission losses are losses of surface flow via leaching through the streambed. 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. SWAT uses Lane's method described in Chapter 19 of the SCS Hydrology Handbook (USDA Soil Conservation Service, 1983) 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.

RETURN FLOW. Return flow, or base flow, is the volume of streamflow originating from groundwater. 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 streams outside the watershed (Arnold et al., 1993). Water percolating past the bottom of the root zone is partitioned into two fractions—each fraction becomes recharge for one of the aquifers. In addition to return flow, water stored in the shallow aquifer may replenish moisture in the soil profile in very dry conditions or be directly removed by plant. Water in the shallow or deep aquifer may be removed by pumping.

1.2.1.3 LAND COVER/PLANT GROWTH

SWAT utilizes a single plant growth model to simulate all types of land covers. The model is able to differentiate between annual and perennial plants. Annual plants grow from the planting date to the harvest date or until the accumulated heat units equal the potential heat units for the plant. Perennial plants maintain their root systems throughout the year, becoming dormant in the winter months. They resume growth when the average daily air temperature exceeds the minimum, or base, temperature required. The plant growth model is used to assess removal of water and nutrients from the root zone, transpiration, and biomass/yield production.

POTENTIAL GROWTH. The potential increase in plant biomass on a given day is defined as the increase in biomass under ideal growing conditions. The potential increase in biomass for a day is a function of intercepted energy and the plant's efficiency in converting energy to biomass. Energy interception is estimated as a function of solar radiation and the plant's leaf area index.

POTENTIAL AND ACTUAL TRANSPIRATION. The process used to calculate potential plant transpiration is described in the section on evapotranspiration. Actual transpiration is a function of potential transpiration and soil water availability.

NUTRIENT UPTAKE. Plant use of nitrogen and phosphorus are estimated with a supply and demand approach where the daily plant nitrogen and phosphorus demands are calculated as the difference between the actual concentration of the element in the plant and the optimal concentration. The optimal concentration of the elements varies with growth stage as described by Jones (1983).

GROWTH CONTRAINTS. Potential plant growth and yield are usually not achieved due to constraints imposed by the environment. The model estimates stresses caused by water, nutrients and temperature.

1.2.1.4 EROSION

Erosion and sediment yield are estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). While the USLE uses rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yield. The substitution results in a number of benefits: the prediction accuracy of the model is increased, the need for a delivery ratio is eliminated, and single storm estimates of sediment yields can be calculated. The hydrology model supplies estimates of runoff volume and peak runoff rate which, with the subbasin area, are used to calculate the runoff erosive energy variable. The crop management factor is recalculated every day that runoff occurs. It is a function of above-ground biomass, residue on the soil surface, and the minimum C factor for the plant. Other factors of the erosion equation are evaluated as described by Wischmeier and Smith (1978).

1.2.1.5 NUTRIENTS

SWAT tracks the movement and transformation of several forms of nitrogen and phosphorus in the watershed. In the soil, transformation of nitrogen from one form to another is governed by the nitrogen cycle as depicted in Figure 1.6. The transformation of phosphorus in the soil is controlled by the phosphorus cycle shown in Figure 1.7. Nutrients may be introduced to the main channel and transported downstream through surface runoff and lateral subsurface flow.

NITROGEN. The different processes modeled by SWAT in the HRUs and the various pools of nitrogen in the soil are depicted in Figure 1.6. Plant use of nitrogen is estimated using the supply and demand approach described in the section on plant growth. In addition to plant use, nitrate and organic N may be removed from the soil via mass flow of water. Amounts of NO_3-N contained in runoff, lateral flow and percolation are estimated as products of the volume of water and the average concentration of nitrate in the layer. Organic N transport with sediment is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978) for application to individual runoff events. The loading function estimates the daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment yield, and the enrichment ratio. The enrichment ratio is the concentration of organic N in the sediment divided by that in the soil.

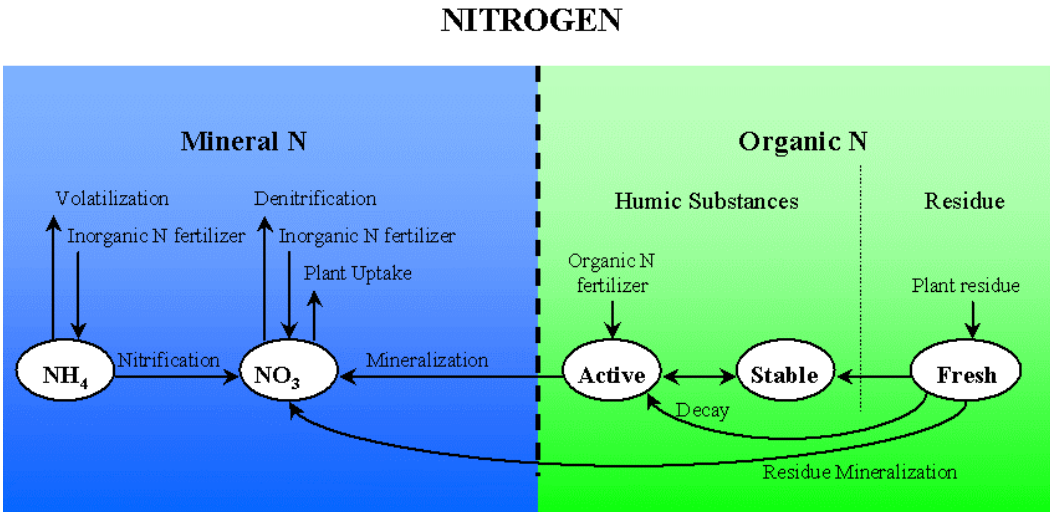

Figure 1.6: Partitioning of Nitrogen in SWAT

PHOSPHORUS. The different processes modeled by SWAT in the HRUs and the various pools of phosphorus in the soil are depicted in Figure 1.7. Plant use of phosphorus is estimated using the supply and demand approach described in the section on plant growth. In addition to plant use, soluble phosphorus and organic P may be removed from the soil via mass flow of water. Phosphorus is not a mobile nutrient and interaction between surface runoff with solution P in the top 10 mm of soil will not be complete. The amount of soluble P removed in runoff is predicted using solution P concentration in the top 10 mm of soil, the runoff volume and a partitioning factor. Sediment transport of P is simulated with a loading function as described in organic N transport.

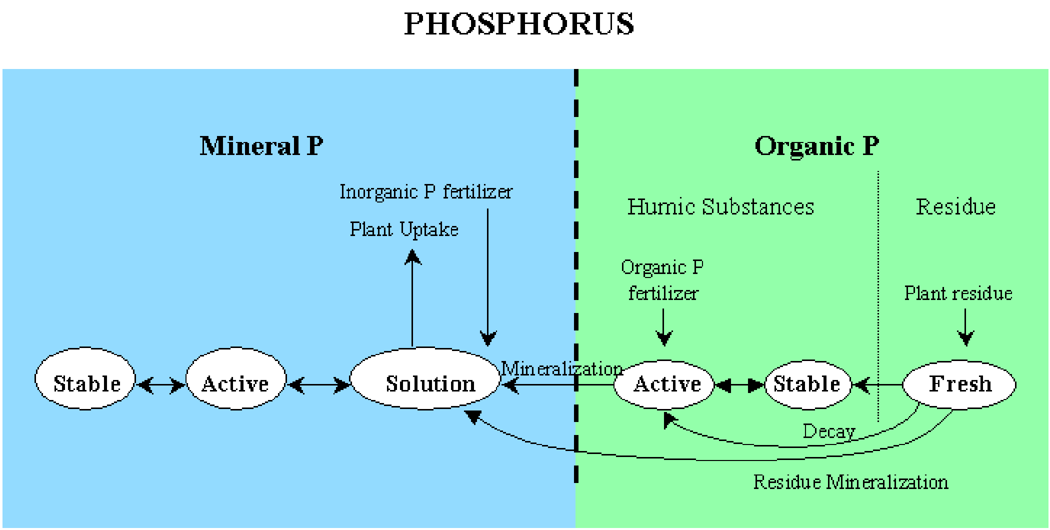

Figure 1.7: Partitioning of Phosphorus in SWAT

1.2.1.6 PESTICIDES

Although SWAT does not simulate stress on the growth of a plant due to the presence of weeds, damaging insects, and other pests, pesticides may be applied to an HRU to study the movement of the chemical in the watershed. SWAT simulates pesticide movement into the stream network via surface runoff (in solution and sorbed to sediment transported by the runoff), and into the soil profile and aquifer by percolation (in solution). 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). The movement of the pesticide is controlled by its solubility, degradation half-life, and soil organic carbon adsorption coefficient. Pesticide on plant foliage and in the soil degrade exponentially according to the appropriate half-life. Pesticide transport by water and sediment is calculated for each runoff event and pesticide leaching is estimated for each soil layer when percolation occurs.

PESTICIDES

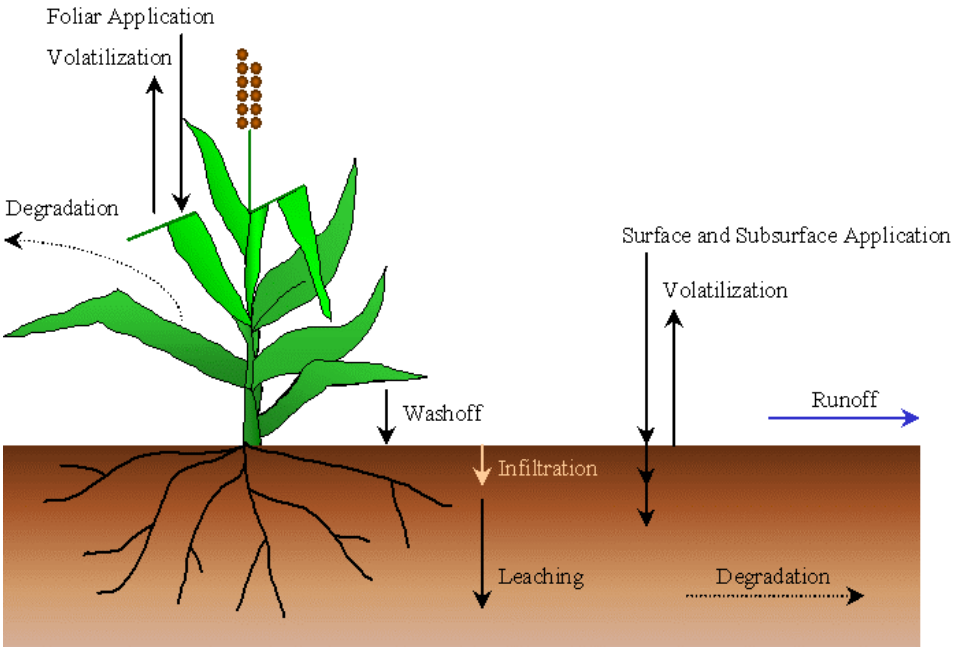

Figure 1.8 Pesticide fate and transport in SWAT

1.2.1.7 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.

ROTATIONS. The dictionary defines a rotation as the growing of different crops in succession in one field, usually in a regular sequence. A rotation in SWAT refers to a change in management practices from one year to the next. There is no limit to the number of years of different management operations specified in a rotation. SWAT also does not limit the number of land cover/crops grown within one year in the HRU. However, only one land cover can be growing at any one time.

WATER USE. The two most typical uses of water are for application to agricultural lands or use as a town's water supply. SWAT allows water to be applied on an HRU from any water source within or outside the watershed. Water may also be transferred between reservoirs, reaches and subbasins as well as exported from the watershed.

1.2.2 ROUTING PHASE OF THE HYDROLOGIC CYCLE

Once SWAT determines the loadings of water, sediment, nutrients and pesticides to the main channel, the loadings are routed through the stream network of the watershed using a command structure similar to that of HYMO (Williams and Hann, 1972). In addition to keeping track of mass flow in the channel, SWAT models the transformation of chemicals in the stream and streambed. Figure 1.9 illustrates the different in-stream processes modeled by SWAT.

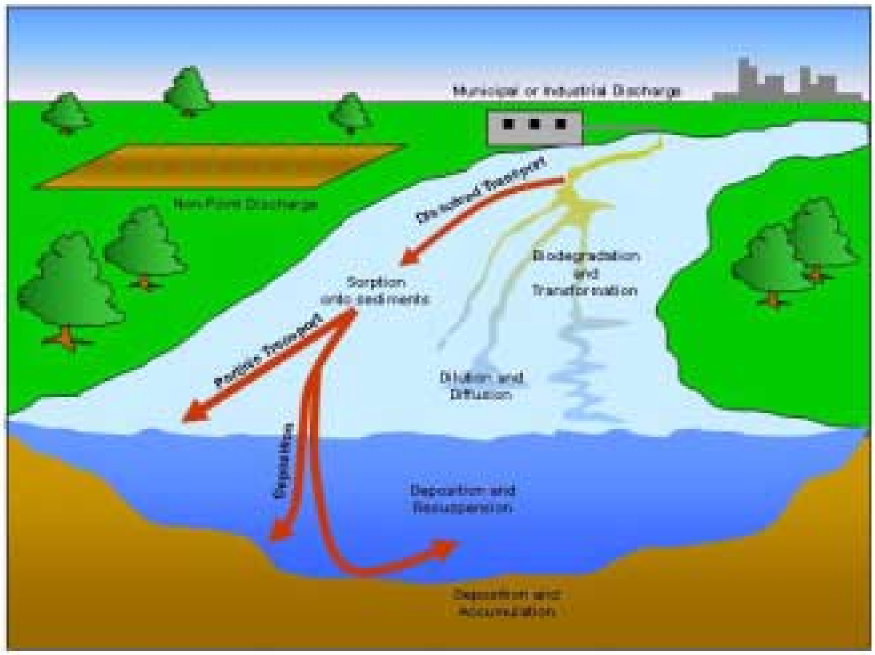

Figure 1.9: In-stream processes modeled by SWAT

1.2.2.1 ROUTING IN THE MAIN CHANNEL OR REACH

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

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.

SEDIMENT ROUTING. The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. Previous versions of SWAT used stream power to estimate deposition/degradation in the channels (Arnold et al, 1995). Bagnold (1977) defined stream power as the product of water density, flow rate and water surface slope. Williams (1980) used Bagnold's definition of stream power to develop a method for determining degradation as a function of channel slope and velocity. In this version of SWAT, the equations have been simplified and the maximum amount of sediment that can be transported from a reach segment is a function of the peak channel velocity. Available stream power is used to reentrain loose and deposited material until all of the material is removed. Excess stream power causes bed degradation. Bed degradation is adjusted for stream bed erodibility and cover.

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 sorbed to sediments are allowed to be deposited with the sediment on the bed of the channel.

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 sorbed phases are governed by first-order decay relationships. The major in-stream processes simulated by the model are settling, burial, resuspension, volatilization, diffusion and transformation.

1.2.2.2 ROUTING IN THE RESERVOIR

The water balance for reservoirs includes inflow, outflow, rainfall on the surface, evaporation, seepage from the reservoir bottom and diversions.

RESERVOIR OUTFLOW. 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.

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.

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.

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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CLIMATE

The climatic inputs to the model are reviewed first because it is these inputs that provide the moisture and energy that drive all other processes simulated in the watershed. The climatic processes modeled in SWAT consist of precipitation, air temperature, soil temperature and solar radiation. Depending on the method used to calculate potential evapotranspiration, wind speed and relative humidity may also be modeled.

CHAPTER 2

EQUATIONS: ENERGY

Once water is introduced to the system as precipitation, the available energy, specifically solar radiation, exerts a major control on the movement of water in the land phase of the hydrologic cycle. Processes that are greatly affected by temperature and solar radiation include snow fall, snow melt and evaporation. Since evaporation is the primary water removal mechanism in the watershed, the energy inputs become very important in reproducing or simulating an accurate water balance.

2.1 SUN-EARTH RELATIONSHIPS

A number of basic concepts related to the earth's orbit around the sun are required by the model to make solar radiation calculations. This section summarizes these concepts. Iqbal (1983) provides a detailed discussion of these and other topics related to solar radiation for users who require more information.

2.1.1 DISTANCE BETWEEN EARTH AND SUN

The mean distance between the earth and the sun is 1.496 x 10^8 km and is called one astronomical unit (AU). The earth revolves around the sun in an elliptical orbit and the distance from the earth to the sun on a given day will vary from a maximum of 1.017 AU to a minimum of 0.983 AU.

An accurate value of the earth-sun distance is important because the solar radiation reaching the earth is inversely proportional to the square of its distance from the sun. The distance is traditionally expressed in mathematical form as a Fourier series type of expansion with a number of coefficients. For most engineering applications a simple expression used by Duffie and Beckman (1980) is adequate for calculating the reciprocal of the square of the radius vector of the earth, also called the eccentricity correction factor, E_0, of the earth's orbit:

$$E_0 = (r_0/r)^2 = 1 + 0.033\cos[(2\pi d_n/365)] \qquad 2.1.1$$

where r_0 is the mean earth-sun distance (1 AU), r is the earth-sun distance for any given day of the year (AU), and d_n is the day number of the year, ranging from 1 on January 1 to 365 on December 31. February is always assumed to have 28 days, making the accuracy of the equation vary due to the leap year cycle.

2.1.2 SOLAR DECLINATION

The solar declination is the earth's latitude at which incoming solar rays are normal to the earth's surface. The solar declination is zero at the spring and fall equinoxes, approximately +23½° at the summer solstice and approximately -23½° at the winter solstice.

A simple formula to calculate solar declination from Perrin de Brichambaut (1975) is:

$$\delta = \sin^{-1}\left\{0.4\sin\left[\frac{2\pi}{365}(d_n - 82)\right]\right\} \qquad 2.1.2$$

where δ is the solar declination reported in radians, and d_n is the day number of the year.

2.1.3 SOLAR NOON, SUNRISE, SUNSET AND DAYLENGTH

The angle between the line from an observer on the earth to the sun and a vertical line extending upward from the observer is called the zenith angle, θ_z (Figure 2-1). Solar noon occurs when this angle is at its minimum value for the day.

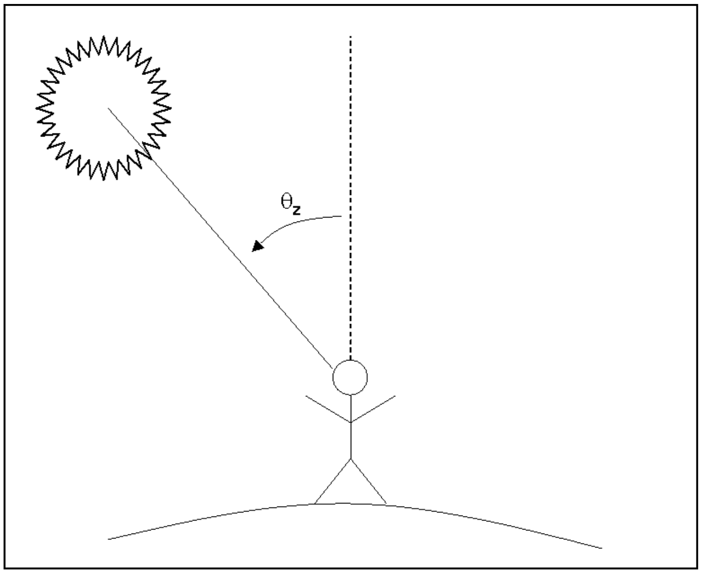

Figure 2-1: Diagram illustrating zenith angle

For a given geographical position, the relationship between the sun and a horizontal surface on the earth's surface is:

$$\cos\theta_z = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega t \qquad 2.1.3$$

where δ is the solar declination in radians, ϕ is the geographic latitude in radians, ω is the angular velocity of the earth's rotation (0.2618 rad h^{-1} or 15° h^{-1}), and t is the solar hour. t equals zero at solar noon, is a positive value in the morning and is a negative value in the evening. The combined term ωt is referred to as the hour angle.

Sunrise, T_{SR}, and sunset, T_{SS}, occur at equal times before and after solar noon. These times can be determined by rearranging the above equation as:

$$T_{SR} = +\frac{\cos^{-1}[-\tan\delta\tan\phi]}{\omega} \qquad 2.1.4$$

and

$$T_{SS} = -\frac{\cos^{-1}[-\tan\delta\tan\phi]}{\omega} \qquad 2.1.5$$

Total daylength, T_{DL}, is calculated:

$$T_{DL} = \frac{2\cos^{-1}[-\tan\delta\tan\phi]}{\omega} \qquad 2.1.6$$

At latitudes above 66.5° or below -66.5°, the absolute value of [-tanδ tanφ] can exceed 1 and the above equation cannot be used. When this happens, there is either no sunrise (winter) or no sunset (summer) and T_{DL} must be assigned a value of 0 or 24 hours, respectively.

To determine the minimum daylength that will occur during the year, equation 2.1.6 is solved with the solar declination set to -23.5° (-0.4102 radians) for the northern hemisphere or 23.5° (0.4102 radians) for the southern hemisphere.

The only SWAT input variable used in the calculations reviewed in Section 2.1 is given in Table 2-1.

Table 2-1: SWAT input variables that used in earth-sun relationship calculations.

Variable name	Definition	File Name
LATITUDE	Latitude of the subbasin (degrees).	.sub

2.2 SOLAR RADIATION

2.2.1 EXTRATERRESTRIAL RADIATION

The radiant energy from the sun is practically the only source of energy that impacts climatic processes on earth. The solar constant, I_{SC}, is the rate of total solar energy at all wavelengths incident on a unit area exposed normally to rays of the sun at a distance of 1 AU from the sun. Quantifying this value has been the object of numerous studies through the years. The value officially adopted by the Commission for Instruments and Methods of Observation in October 1981 is

$$I_{SC} = 1367 \text{ W m}^{-2} = 4.921 \text{ MJ m}^{-2} \text{ h}^{-1}$$

On any given day, the extraterrestrial irradiance (rate of energy) on a surface normal to the rays of the sun, I_{0n}, is:

$$I_{0n} = I_{SC} E_0 \qquad 2.2.1$$

where E_0 is the eccentricity correction factor of the earth's orbit, and I_{0n} has the same units as the solar constant, I_{SC}.

To calculate the irradiance on a horizontal surface, I_0,

$$I_0 = I_{0n} \cos\theta_z = I_{SC} E_0 \cos\theta_z \qquad 2.2.2$$

where $\cos\theta_z$ is defined in equation 2.1.3.

The amount of energy falling on a horizontal surface during a day is given by

$$H_0 = \int_{sr}^{ss} I_0 dt = 2\int_0^{ss} I_0 dt \qquad 2.2.3$$

where H_0 is the extraterrestrial daily irradiation (MJ m^{-2} d^{-1}), *sr* is sunrise, and *ss* is sunset. Assuming that E_0 remains constant during the one day time step and converting the time *dt* to the hour angle, the equation can be written

$$H_0 = \frac{24}{\pi} I_{SC} E_0 \int_0^{\omega T_{SR}} (\sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega t) d\omega t \qquad 2.2.4$$

or

$$H_0 = \frac{24}{\pi} I_{SC} E_0 [\omega T_{SR} (\sin\delta \sin\phi) + (\cos\delta \cos\phi \sin(\omega T_{SR}))] \qquad 2.2.5$$

where I_{SC} is the solar constant (4.921 MJ m^{-2} h^{-1}), E_0 is the eccentricity correction factor of the earth's orbit, ω is the angular velocity of the earth's rotation (0.2618 rad h^{-1}), the hour of sunrise, T_{SR}, is defined by equation 2.1.4, δ is the solar declination in radians, and ϕ is the geographic latitude in radians. Multiplying all the constants together gives

$$H_0 = 37.59 E_0 [\omega T_{SR} \sin\delta \sin\phi + \cos\delta \cos\phi \sin(\omega T_{SR})] \qquad 2.2.6$$

2.2.2 SOLAR RADIATION UNDER CLOUDLESS SKIES

When solar radiation enters the earth's atmosphere, a portion of the energy is removed by scattering and adsorption. The amount of energy lost is a function of the transmittance of the atmosphere, the composition and concentration of the constituents of air at the location, the path length the radiation travels through the air column, and the radiation wavelength.

Due to the complexity of the process and the detail of the information required to accurately predict the amount of radiant energy lost while passing through the atmosphere, SWAT makes a broad assumption that roughly 20% of the extraterrestrial radiation is lost while passing through the atmosphere under cloudless skies. Using this assumption, the maximum possible solar radiation, H_{MX}, at a particular location on the earth's surface is calculated as:

$$H_{MX} = 30.0 E_0 \left[\omega T_{SR} \sin\delta \sin\phi + \cos\delta \cos\phi \sin(\omega T_{SR}) \right] \qquad 2.2.7$$

where the maximum possible solar radiation, H_{MX}, is the amount of radiation reaching the earth's surface under a clear sky (MJ m^{-2} d^{-1}).

2.2.3 DAILY SOLAR RADIATION

The solar radiation reaching the earth's surface on a given day, H_{day}, may be less than H_{MX} due to the presence of cloud cover. The daily solar radiation data required by SWAT may be read from an input file or generated by the model.

The variable SLRSIM in the input control code (.cod) file identifies the method used to obtain solar radiation data. To read in daily solar radiation data, the variable is set to 1 and the name of the solar radiation data file and the number of solar radiation records stored in the file are set in the control input/output (file.cio) file. To generate daily solar radiation values, SLRSIM is set to 2. The equations used to generate solar radiation data in SWAT are reviewed in Chapter 4. SWAT input variables that pertain to solar radiation are summarized in Table 2-2.

Table 2-2: SWAT input variables used in solar radiation calculations.

Variable name	Definition	File Name
LATITUDE	Latitude of the subbasin (degrees).	.sub
SLRSIM	Solar radiation input code: 1-measured, 2-generated	.cod
NSTOT	Number of solar radiation records within the .slr file (required if SLRSIM = 1)	file.cio
SLRFILE	Name of measured solar radiation input file (.slr) (required if SLRSIM = 1)	file.cio
ISGAGE	Number of solar radiation record used within the subbasin (required if SLRSIM = 1)	file.cio

see description of .slr file in the User's Manual for input and format requirements if measured daily solar radiation data is being used

2.2.4 HOURLY SOLAR RADIATION

The extraterrestrial radiation falling on a horizontal surface during one hour is given by the equation:

$$I_0 = I_{SC} E_0 \left(\sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega t \right) \qquad 2.2.8$$

where I_0 is the extraterrestrial radiation for 1 hour centered around the hour angle ωt.

An accurate calculation of the radiation for each hour of the day requires a knowledge of the difference between standard time and solar time for the location. SWAT simplifies the hourly solar radiation calculation by assuming that solar noon occurs at 12:00pm local standard time.

When the values of I_0 calculated for every hour between sunrise and sunset are summed, they will equal the value of H_0. Because of the relationship between I_0 and H_0, it is possible to calculate the hourly radiation values by multiplying H_0 by the fraction of radiation that falls within the different hours of the day. The benefit of this alternative method is that assumptions used to estimate the difference between maximum and actual solar radiation reaching the earth's surface can be automatically incorporated in calculations of hourly solar radiation at the earth's surface.

SWAT calculates hourly solar radiation at the earth's surface with the equation:

$$I_{hr} = I_{frac} \cdot H_{day} \qquad 2.2.9$$

where I_{hr} is the solar radiation reaching the earth's surface during a specific hour of the day (MJ m^{-2} hr^{-1}), I_{frac} is the fraction of total daily radiation falling during that hour, and H_{day} is the total solar radiation reaching the earth's surface on that day.

The fraction of total daily radiation falling during an hour is calculated

$$I_{frac} = \frac{\left(\sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega t_i \right)}{\sum_{t=SR}^{SS} \left(\sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega t \right)} \qquad 2.2.10$$

where t_i is the solar time at the midpoint of hour i.

2.2.5 DAILY NET RADIATION

Net radiation requires the determination of both incoming and reflected short-wave radiation and net long-wave or thermal radiation. Expressing net radiation in terms of the net short-wave and long-wave components gives:

$$H_{net} = H_{day} \downarrow - \alpha \cdot H_{day} \uparrow + H_L \downarrow - H_L \uparrow \qquad 2.2.11$$

or

$$H_{net} = (1 - \alpha) \cdot H_{day} + H_b \qquad 2.2.12$$

where H_{net} is the net radiation (MJ m^{-2} d^{-1}), H_{day} is the short-wave solar radiation reaching the ground (MJ m^{-2} d^{-1}), α is the short-wave reflectance or albedo, H_L is the long-wave radiation (MJ m^{-2} d^{-1}), H_b is the net incoming long-wave radiation (MJ m^{-2} d^{-1}) and the arrows indicate the direction of the radiation flux.

2.2.5.1 NET SHORT-WAVE RADIATION

Net short-wave radiation is defined as $(1 - \alpha) \cdot H_{day}$. SWAT calculates a daily value for albedo as a function of the soil type, plant cover, and snow cover. When the snow water equivalent is greater than 0.5 mm,

$$\alpha = 0.8 \qquad 2.2.13$$

When the snow water equivalent is less than 0.5 mm and no plants are growing in the HRU,

$$\alpha = \alpha_{soil} \qquad 2.2.14$$

where α_{soil} is the soil albedo. When plants are growing and the snow water equivalent is less than 0.5 mm,

$$\alpha = \alpha_{plant} \cdot (1 - cov_{sol}) + \alpha_{soil} \cdot cov_{sol} \qquad 2.2.15$$

where α_{plant} is the plant albedo (set at 0.23), and cov_{sol} is the soil cover index. The soil cover index is calculated

$$cov_{sol} = \exp(-5.0 \times 10^{-5} \cdot CV) \qquad 2.2.16$$

where CV is the aboveground biomass and residue (kg ha^{-1}).

2.2.5.2 NET LONG-WAVE RADIATION

Long-wave radiation is emitted from an object according to the radiation law:

$$H_R = \varepsilon \cdot \sigma \cdot T_K^{\ 4} \qquad 2.2.17$$

where H_R is the radiant energy (MJ m^{-2} d^{-1}), ε is the emissivity, σ is the Stefan-Boltzmann constant (4.903 × 10^{-9} MJ m^{-2} K^{-4} d^{-1}), and T_K is the mean air temperature in Kelvin (273.15 + °C).

Net long-wave radiation is calculated using a modified form of equation 2.2.17 (Jensen et al., 1990):

$$H_b = f_{cld} \cdot (\varepsilon_a - \varepsilon_{vs}) \cdot \sigma \cdot T_K^{\ 4} \qquad 2.2.18$$

where H_b is the net long-wave radiation (MJ m^{-2} d^{-1}), f_{cld} is a factor to adjust for cloud cover, ε_a is the atmospheric emittance, and ε_{vs} is the vegetative or soil emittance.

Wright and Jensen (1972) developed the following expression for the cloud cover adjustment factor, f_{cld}:

$$f_{cld} = a \cdot \frac{H_{day}}{H_{MX}} - b \qquad 2.2.19$$

where a and b are constants, H_{day} is the solar radiation reaching the ground surface on a given day (MJ m^{-2} d^{-1}), and H_{MX} is the maximum possible solar radiation to reach the ground surface on a given day (MJ m^{-2} d^{-1}).

The two emittances in equation 2.2.18 may be combined into a single term, the net emittance ε'. The net emittance is calculated using an equation developed by Brunt (1932):

$$\varepsilon' = \varepsilon_a - \varepsilon_{vs} = -\left(a_1 + b_1 \cdot \sqrt{e}\right) \qquad 2.2.20$$

where a_1 and b_1 are constants and e is the vapor pressure on a given day (kPa). The calculation of e is given in Chapter 3.

Combining equations 2.2.18, 2.2.19, and 2.2.20 results in a general equation for net long-wave radiation:

$$H_b = -\left[a \cdot \frac{H_{day}}{H_{MX}} - b\right] \cdot \left[a_1 + b_1\sqrt{e}\right] \cdot \sigma \cdot T_K^{\ 4} \qquad 2.2.21$$

Experimental values for the coefficients a, b, a_1 and b_1 are presented in Table 2.3. The default equation in SWAT uses coefficent values proposed by Doorenbos and Pruitt (1977):

$$H_b = -\left[0.9 \cdot \frac{H_{day}}{H_{MX}} + 0.1\right] \cdot \left[0.34 - 0.139\sqrt{e}\right] \cdot \sigma \cdot T_K^{\,4} \qquad 2.2.22$$

Table 2-3: Experimental coefficients for net long-wave radiation equations (from Jensen et al., 1990)

Region	**(a,**	**b)**	**(a_1,**	**b_1)**
Davis, California	(1.35,	-0.35)	(0.35,	-0.145)
Southern Idaho	(1.22,	-0.18)	(0.325,	-0.139)
England	not available		(0.47,	-0.206)
England	not available		(0.44,	-0.253)
Australia	not available		(0.35,	-0.133)
General	(1.2,	-0.2)	(0.39,	-0.158)
General-humid areas	(1.0,	0.0)		
General-semihumid areas	(1.1,	-0.1)		

Table 2-4: SWAT input variables used in net radiation calculations.

Variable name	**Definition**	**File Name**
SOL_ALB	α_{soil}: moist soil albedo	.sol
MAX TEMP	T_{mx}: Daily maximum temperature (°C)	.tmp
MIN TEMP	T_{mn}: Daily minimum temperature (°C)	.tmp
SOL_RAD	H_{day}: Daily solar radiation reaching the earth's surface (MJ m^{-2} d^{-1})	.slr

2.3 TEMPERATURE

Temperature influences a number of physical, chemical and biological processes. Plant production is strongly temperature dependent, as are organic matter decomposition and mineralization. Daily air temperature may be input to the model or generated from average monthly values. Soil and water temperatures are derived from air temperature.

2.3.1 DAILY AIR TEMPERATURE

SWAT requires daily maximum and minimum air temperature. This data may be read from an input file or generated by the model. The user is strongly recommended to obtain measured daily temperature records from gages in or near the watershed if at all possible. The accuracy of model results is significantly improved by the use of measured temperature data.

The variable TMPSIM in the input control code (.cod) file identifies the method used to obtain air temperature data. To read in daily maximum and minimum air temperature data, the variable is set to 1 and the name of the temperature data file(s) and the number of temperature records stored in the file are set in the control input/output (file.cio) file. To generate daily air temperature values, TMPSIM is set to 2. The equations used to generate air temperature data in SWAT are reviewed in Chapter 4. SWAT input variables that pertain to air temperature are summarized in Table 2-5.

Table 2-5: SWAT input variables that pertain to daily air temperature.

Variable name	**Definition**	**File Name**
TMPSIM	Air temperature input code: 1-measured, 2-generated	.cod
NTGAGE	Number of temperature gage (.tmp) files used in simulation file (required if TMPSIM = 1)	file.cio
NTTOT	Number of temperature records used in simulation (required if TMPSIM = 1)	file.cio
NTFIL	Number of temperature records within each .tmp file file (required if TMPSIM = 1)	file.cio
TFILE	Name of measured temperature input file (.tmp) Up to 18 files may be used. (required if TMPSIM = 1)	file.cio
ITGAGE	Number of temperature record used within the subbasin (required if TMPSIM = 1)	file.cio

see description of .tmp file in the User's Manual for input and format requirements if measured temperature data is being used

2.3.2 HOURLY AIR TEMPERATURE

Air temperature data are usually provided in the form of daily maximum and minimum temperature. A reasonable approximation for converting these to hourly temperatures is to assume a sinusoidal interpolation function between the minimum and maximum daily temperatures. The maximum daily temperature is assumed to occur at 1500 hours and the minimum daily temperature at 300 hours (Campbell, 1985). The temperature for the hour is then calculated with the equation:

$$T_{hr} = \overline{T}_{av} + \frac{\left(T_{mx} - T_{mn}\right)}{2} \cdot \cos\left(0.2618 \cdot \left(hr - 15\right)\right) \qquad 2.3.1$$

where T_{hr} is the air temperature during hour hr of the day (°C), $\overline{T}_{av}$ is the average temperature on the day (°C), T_{mx} is the daily maximum temperature (°C), and T_{mn} is the daily minimum temperature (°C).

Table 2-6: SWAT input variables that pertain to hourly air temperature.

Variable name	Definition	File Name
MAX TEMP	T_{mx}: Daily maximum temperature (°C)	.tmp
MIN TEMP	T_{mn}: Daily minimum temperature (°C)	.tmp

2.3.3 SOIL TEMPERATURE

Soil temperature will fluctuate due to seasonal and diurnal variations in temperature at the surface. Figure 2-2 plots air temperature and soil temperature at 5 cm and 300 cm below bare soil at College Station, Texas.

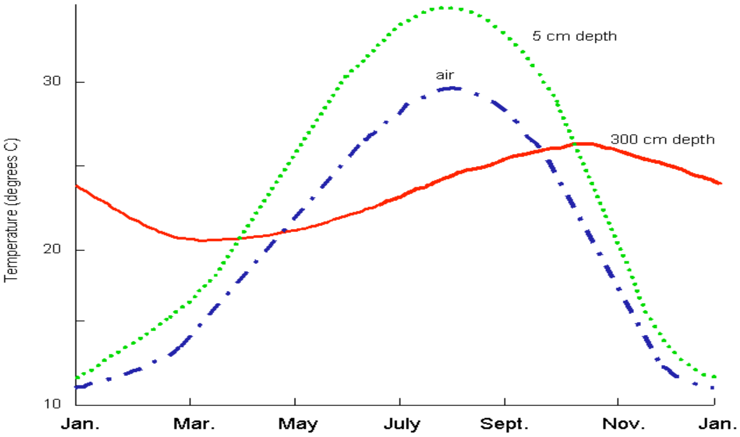

Figure 2-2: Four-year average air and soil temperature at College Station, Texas.

This figure illustrates several important attributes of temperature variation in the soil. First, the annual variation in soil temperature follows a sinusoidal function. Second, the fluctuation in temperature during the year (the amplitude of the sine wave) decreases with depth until, at some depth in the soil, the temperature remains constant throughout the year. Finally, the timing of maximum and minimum temperatures varies with depth. Note in the above graph that there is a three month difference between the recording of the minimum temperature at the surface (January) and the minimum temperature at 300 cm (March).

Carslaw and Jaeger (1959) developed an equation to quantify the seasonal variation in temperature:

$$T_{soil}(z,d_n) = \overline{T}_{AA} + A_{surf}\exp(-z/dd)\sin(\omega_{tmp}d_n - z/dd) \qquad 2.3.2$$

where $T_{soil}(z,d_n)$ is the soil temperature (°C) at depth z (mm) and day of the year d_n, $\overline{T}_{AA}$ is the average annual soil temperature (°C), A_{surf} is the amplitude of the surface fluctuations (°C), dd is the damping depth (mm), and ω_{tmp} is the angular frequency. When $z = 0$ (soil surface), equation 2.3.2 reduces to $T_{soil}(0,d_n) = \overline{T}_{AA} + A_{surf}\sin(\omega_{tmp}d_n)$. As $z \to \infty$, equation 2.3.2 becomes $T_{soil}(\infty,d_n) = \overline{T}_{AA}$.

In order to calculate values for some of the variables in this equation, the heat capacity and thermal conductivity of the soil must be known. These are properties not commonly measured in soils and attempts at estimating values from other soil properties have not proven very effective. Consequently, an equation has been adopted in SWAT that calculates the temperature in the soil as a function of the previous day's soil temperature, the average annual air temperature, the current day's soil surface temperature, and the depth in the profile.

The equation used to calculate daily average soil temperature at the center of each layer is:

$$T_{soil}(z,d_n) = \ell \cdot T_{soil}(z,d_n - 1) + [1.0 - \ell] \cdot \left[df \cdot \left[\overline{T}_{AAair} - T_{ssurf}\right] + T_{ssurf}\right] \qquad 2.3.3$$

where $T_{soil}(z,d_n)$ is the soil temperature (°C) at depth z (mm) and day of the year d_n, ℓ is the lag coefficient (ranging from 0.0 to 1.0) that controls the influence of the previous day's temperature on the current day's temperature, $T_{soil}(z,d_n\text{-}1)$ is the soil temperature (°C) in the layer from the previous day, df is the depth factor that quantifies the influence of depth below surface on soil temperature, $\overline{T}_{AAair}$ is the average annual air temperature (°C), and T_{ssurf} is the soil surface temperature on the day. SWAT sets the lag coefficient, ℓ, to 0.80. The soil temperature from the previous day is known and the average annual air temperature is calculated from the long-term monthly maximum and minimum temperatures reported in the weather generator input (.wgn) file. This leaves the depth factor, df, and the soil surface temperature, T_{ssurf}, to be defined.

The depth factor is calculated using the equation:

$$df = \frac{zd}{zd + \exp(-0.867 - 2.078 \cdot zd)} \qquad 2.3.4$$

where zd is the ratio of the depth at the center of the soil layer to the damping depth:

$$zd = \frac{z}{dd} \qquad 2.3.5$$

where z is the depth at the center of the soil layer (mm) and dd is the damping depth (mm).

From the previous three equations (2.3.3, 2.3.4 and 2.3.5) one can see that at depths close to the soil surface, the soil temperature is a function of the soil surface temperature. As the depth increases, soil temperature is increasingly influenced by the average annual air temperature, until at the damping depth, the soil temperature is within 5% of $\overline{T}_{AAair}$.

The damping depth, dd, is calculated daily and is a function of the maximum damping depth, bulk density and soil water. The maximum damping depth, dd_{max}, is calculated:

$$dd_{\max} = 1000 + \frac{2500\rho_b}{\rho_b + 686\exp(-5.63\rho_b)} \qquad 2.3.6$$

where dd_{max} is the maximum damping depth (mm), and ρ_b is the soil bulk density (Mg/m^3).

The impact of soil water content on the damping depth is incorporated via a scaling factor, φ, that is calculated with the equation:

$$\varphi = \frac{SW}{(0.356 - 0.144\rho_b) \cdot z_{tot}} \qquad 2.3.7$$

where SW is the amount of water in the soil profile expressed as depth of water in the profile (mm H_2O), ρ_b is the soil bulk density (Mg/m^3), and z_{tot} is the depth from the soil surface to the bottom of the soil profile (mm).

The daily value for the damping depth, dd, is calculated:

$$dd = dd_{\max} \cdot \exp\left[\ln\left(\frac{500}{dd_{\max}}\right) \cdot \left(\frac{1-\varphi}{1+\varphi}\right)^2\right] \qquad 2.3.8$$

where dd_{max} is the maximum damping depth (mm), and φ is the scaling factor for soil water.

The soil surface temperature is a function of the previous day's temperature, the amount of ground cover and the temperature of the surface when no cover is present. The temperature of a bare soil surface is calculated with the equation:

$$T_{bare} = \overline{T}_{av} + \varepsilon_{sr} \frac{(T_{mx} - T_{mn})}{2} \qquad 2.3.9$$

where T_{bare} is the temperature of the soil surface with no cover (°C), $\overline{T}_{av}$ is the average temperature on the day (°C), T_{mx} is the daily maximum temperature (°C), T_{mn} is the daily minimum temperature (°C), and ε_{sr} is a radiation term. The radiation term is calculated with the equation:

$$\varepsilon_{sr} = \frac{H_{day} \cdot (1-\alpha) - 14}{20} \qquad 2.3.10$$

where H_{day} is the solar radiation reaching the ground on the current day (MJ m^{-2} d^{-1}), and α is the albedo for the day.

Any cover present will significantly impact the soil surface temperature. The influence of plant canopy or snow cover on soil temperature is incorporated with a weighting factor, *bcv*, calculated as:

$$bcv = \max \left\{ \begin{array}{c} \dfrac{CV}{CV + \exp\left(7.563 - 1.297 \times 10^{-4} \cdot CV\right)} \\ \dfrac{SNO}{SNO + \exp\left(6.055 - 0.3002 \cdot SNO\right)} \end{array} \right\} \qquad 2.3.11$$

where *CV* is the total aboveground biomass and residue present on the current day (kg ha^{-1}) and *SNO* is the water content of the snow cover on the current day (mm H_2O). The weighting factor, *bcv*, is 0.0 for a bare soil and approaches 1.0 as cover increases.

The equation used to calculate the soil surface temperature is:

$$T_{ssurf} = bcv \cdot T_{soil}\left(1, d_n - 1\right) + \left(1 - bcv\right) \cdot T_{bare} \qquad 2.3.12$$

where T_{ssurf} is the soil surface temperature for the current day (°C), *bcv* is the weighting factor for soil cover impacts, $T_{soil}(1,d_n\text{-}1)$ is the soil temperature of the first soil layer on the previous day (°C), and T_{bare} is the temperature of the bare soil surface (°C). The influence of ground cover is to place more emphasis on the previous day's temperature near the surface.

SWAT input variables that directly impact soil temperature calculations are listed in Table 2-7. There are several other variables that initialize residue and snow cover in the subbasins or HRUs (SNO_SUB and SNOEB in .sub; RSDIN in .hru). The influence of these variables will be limited to the first few months of simulation. Finally, the timing of management operations in the .mgt file will affect ground cover and consequently soil temperature.

Table 2-7: SWAT input variables that pertain to soil temperature.

Variable name	Definition	File Name
TMPMX	Average maximum air temperature for month (°C)	.wgn
TMPMN	Average minimum air temperature for month (°C)	.wgn
SOL_Z	z: Depth from soil surface to bottom of layer (mm)	.sol
SOL_BD	ρ_b: Moist bulk density (Mg m^{-3} or g cm^{-3})	.sol
SOL_ALB	Moist soil albedo.	.sol
MAX TEMP	T_{mx}: Daily maximum temperature (°C)	.tmp
MIN TEMP	T_{mn}: Daily minimum temperature (°C)	.tmp

2.3.4 WATER TEMPERATURE

Water temperature is required to model in-stream biological and water quality processes. SWAT uses an equation developed by Stefan and Preud'homme (1993) to calculate average daily water temperature for a well-mixed stream:

$$T_{water} = 5.0 + 0.75\overline{T}_{av} \qquad 2.3.13$$

where T_{water} is the water temperature for the day (°C), and $\overline{T}_{av}$ is the average temperature on the day (°C).

Due to thermal inertia of the water, the response of water temperature to a change in air temperature is dampened and delayed. When water and air temperature are plotted for a stream or river, the peaks in the water temperature plots usually lag 3-7 hours behind the peaks in air temperature. As the depth of the river increases, the lag time can increase beyond this typical interval. For very large rivers, the lag time can extend up to a week. Equation 2.3.13 assumes that the lag time between air and water temperatures is less than 1 day.

In addition to air temperature, water temperature is influenced by solar radiation, relative humidity, wind speed, water depth, ground water inflow, artificial heat inputs, thermal conductivity of the sediments and the presence of impoundments along the stream network. SWAT assumes that the impact of these other variables on water temperature is not significant.

Table 2-8: SWAT input variables that pertain to water temperature.

Variable name	Definition	File Name
MAX TEMP	T_{mx}: Daily maximum temperature (°C)	.tmp
MIN TEMP	T_{mn}: Daily minimum temperature (°C)	.tmp

2.4 WIND SPEED

Wind speed is required by SWAT if the Penman-Monteith equation is used to estimate potential evapotranspiration and transpiration. SWAT assumes wind speed information is collected from gages positioned 1.7 meters above the ground surface.

When using the Penman-Monteith equation to estimate transpiration, the wind measurement used in the equation must be above the canopy. In SWAT, a minimum difference of 1 meter is specified for canopy height and wind speed measurements. When the canopy height exceeds 1 meter, the original wind measurements is adjusted to:

$$z_w = h_c + 100 \qquad 2.4.1$$

where z_w is the height of the wind speed measurement (cm), and h_c is the canopy height (cm).

The variation of wind speed with elevation near the ground surface is estimated with the equation (Haltiner and Martin, 1957):

$$u_{z2} = u_{z1} \cdot \left[\frac{z_2}{z_1} \right]^{aa} \qquad 2.4.2$$

where u_{z1} is the wind speed (m s^{-1}) at height z_1 (cm), u_{z2} is the wind speed (m s^{-1}) at height z_2 (cm), and aa is an exponent between 0 and 1 that varies with atmospheric stability and surface roughness. Jensen (1974) recommended a value of 0.2 for *aa* and this is the value used in SWAT.

The daily wind speed data required by SWAT may be read from an input file or generated by the model. The variable WNDSIM in the input control code (.cod) file identifies the method used to obtain wind speed data. To read in daily wind speed data, the variable is set to 1 and the name of the wind speed data file and the number of different records stored in the file are set in the control input/output (file.cio) file. To generate daily wind speed values, WNDSIM is set to 2. The equations used to generate wind speed data in SWAT are reviewed in Chapter 4.

Table 2-9: SWAT input variables used in wind speed calculations.

Variable name	Definition	File Name
WNDSIM	Wind speed input code: 1-measured, 2-generated	.cod
NWTOT	Number of wind speed records within the .wnd file (required if WNDSIM = 1)	file.cio
WNDFILE	Name of measured wind speed input file (.wnd) (required if WNDSIM = 1)	file.cio
IWGAGE	Number of wind speed record used within the subbasin (required if WNDSIM = 1)	file.cio
see description of .wnd file in the User's Manual for input and format requirements if measured daily wind speed data is being used		

2.5 NOMENCLATURE

A_{surf}	Amplitude of the surface fluctuations in soil temperature (°C)
AU	Astronomical unit (1 AU = 1.496 x 10^8 km)
CV	Total aboveground biomass and residue present on current day (kg ha^{-1})
E_0	Eccentricity correction factor of earth $(r_0/r)^2$
H_0	Extraterrestrial daily irradiation (MJ m^{-2} d^{-1})
H_b	Net outgoing long-wave radiation (MJ m^{-2} d^{-1})
H_{day}	Solar radiation reaching ground on current day of simulation (MJ m^{-2} d^{-1})
H_L	Long-wave radiation (MJ m^{-2} d^{-1})
H_{MX}	Maximum possible solar radiation (MJ m^{-2} d^{-1})
H_{net}	Net radiation on day (MJ m^{-2} d^{-1})
H_R	Radiant energy (MJ m^{-2} d^{-1})
I_{frac}	Fraction of daily solar radiation falling during specific hour on current day of simulation
I_{hr}	Solar radiation reaching ground during specific hour on current day of simulation (MJ m^{-2} h^{-1})
I_{SC}	Solar constant (4.921 MJ m^{-2} h^{-1})
I_0	Extraterrestrial daily irradiance incident on a horizontal surface (MJ m^{-2} h^{-1})
I_{0n}	Extraterrestrial daily irradiance incident on a normal surface (MJ m^{-2} h^{-1})
SNO	Water content of snow cover on current day (mm H_2O)
SW	Amount of water in soil profile (mm H_2O)
T_{bare}	Temperature of soil surface with no cover (°C)
T_{DL}	Daylength (h)
T_{hr}	Air temperature during hour (°C)
T_K	Mean air temperature in Kelvin (273.15 + °C)
T_{mn}	Minimum air temperature for day (°C)
T_{mx}	Maximum air temperature for day (°C)
T_{soil}	Soil temperature (°C)
T_{ssurf}	Soil surface temperature (°C)
T_{SR}	Time of sunrise in solar day (h)
T_{SS}	Time of sunset in solar day (h)
T_{water}	Average daily water temperature (°C)
$\overline{T}_{AA}$	Average annual soil temperature (°C)

$\overline{T}_{AAair}$	Average annual air temperature (°C)
$\overline{T}_{av}$	Average air temperature for day (°C)

a	Constant in equation used to calculate the cloud cover adjustment factor
a_1	Constant in equation used to calculate net emissivity
aa	Exponent between 0 and 1 that varies with atmospheric stability and surface roughness that is used in calculating wind speed at different heights
b	Constant in equation used to calculate the cloud cover adjustment factor
b_1	Constant in equation used to calculate net emissivity
bcv	weighting factor for impact of ground cover on soil surface temperature
cov_{sol}	Soil cover index for albedo determination
d_n	Day number of year, 1 on January 1 and 365 on December 31
dd	Damping depth (mm)
dd_{max}	Maximum damping depth (mm)
df	Depth factor used in soil temperature calculations
e	Vapor pressure (actual) on a given day (kPa)
f_{cld}	Factor to adjust for cloud cover in net long-wave radiation calculation
h_c	Canopy height (cm)
hr	Hour of day (1-24)
r	Actual earth-sun distance (AU)
r_0	Mean earth-sun distance, 1 AU
t	Number of hours before (+) or after (-) solar noon
t_i	Solar time at the midpoint of the hour *i*
u_{z1}	Wind speed (m s^{-1}) at height z_1 (cm)
u_{z2}	Wind speed (m s^{-1}) at height z_2 (cm)
z	Depth below soil surface (mm)
z_1	Height of wind speed measurement (cm)
z_2	Height of wind speed measurement (cm)
z_{tot}	Depth to bottom of soil profile (mm)
z_w	Height of the wind speed measurement (cm)
zd	Ratio of depth in soil to damping depth

α	Short-wave reflectance or albedo
α_{plant}	Plant albedo (set at 0.23)
α_{soil}	Soil albedo
δ	Solar declination (radians)
ε	Emissivity
ε'	Net emittance
ε_a	Atmospheric emittance
ε_{sr}	Radiation term for bare soil surface temperature calculation
ε_{vs}	Vegetative or soil emittance
ℓ	Lag coefficient that controls influence of previous day's temperature on current days temperature
σ	Stefan-Boltzmann constant (4.903×10^{-9} MJ m^{-2} K^{-4} d^{-1})
θ_z	Zenith angle (radians)

ϕ	Latitude in radians
ρ_b	Soil bulk density (Mg m^{-3})
φ	Scaling factor for impact of soil water on damping depth
ω	Angular velocity of the earth's rotation (0.2618 radians h^{-1})
ω_{tmp}	Angular frequency in soil temperature variation

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CHAPTER 3

EQUATIONS: ATMOSPHERIC WATER

Precipitation is the mechanism by which water enters the land phase of the hydrologic cycle. Because precipitation controls the water balance, it is critical that the amount and distribution of precipitation in space and time is accurately simulated by the model.

3.1 PRECIPITATION

The precipitation reaching the earth's surface on a given day, R_{day}, may be read from an input file or generated by the model. Users are strongly recommended to incorporate measured precipitation into their simulations any time the data is available. The ability of SWAT to reproduce observed stream hydrographs is greatly improved by the use of measured precipitation data.

Unfortunately, even with the use of measured precipitation the model user can expect some error due to inaccuracy in precipitation data. Measurement of precipitation at individual gages is subject to error from a number of causes and additional error is introduced when regional precipitation is estimated from point values. Typically, total or average areal precipitation estimates for periods of a year or longer have relative uncertainties of 10% (Winter, 1981).

Point measurements of precipitation generally capture only a fraction of the true precipitation. The inability of a gage to capture a true reading is primarily caused by wind eddies created by the gage. These wind eddies reduce the catch of the smaller raindrops and snowflakes. Larson and Peck (1974) found that deficiencies of 10% for rain and 30% for snow are common for gages projecting above the ground surface that are not designed to shield wind effects. Even when the gage is designed to shield for wind effects, this source of error will not be eliminated. For an in-depth discussion of this and other sources of error as well as methods for dealing with the error, please refer to Dingman (1994).

The variable PCPSIM in the input control code (.cod) file identifies the method used to obtain precipitation data. To read in daily precipitation data, the variable is set to 1 and the names of the precipitation data files and the number of precipitation records stored in the files are defined in the control input/output (file.cio) file. To generate daily precipitation values, PCPSIM is set to 2. The equations used to generate precipitation data in SWAT are reviewed in Chapter 4. SWAT input variables that pertain to precipitation are summarized in Table 3-1.

Table 3-1: SWAT input variables used in precipitation calculations.

Variable name	Definition	File Name
PCPSIM	Precipitation input code: 1-measured, 2-generated	.cod
NRGAGE	Number of precipitation gage files (.pcp) used (required if PCPSIM = 1)	file.cio
NRTOT	Total number of precipitation records used in simulation (required if PCPSIM = 1)	file.cio
NRGFIL	Number of precipitation records in each .pcp file (required if PCPSIM = 1)	file.cio
RFILE	Name of measured precipitation input file(s) (.pcp) (required if PCPSIM = 1)	file.cio
IRGAGE	Number of precipitation record used within the subbasin (required if PCPSIM = 1)	file.cio
see description of .pcp file in the User's Manual for input and format requirements if measured daily precipitation data is being used		

3.2 MAXIMUM HALF-HOUR RAINFALL

The maximum half-hour rainfall is required by SWAT to calculate the peak runoff rate. The maximum half-hour rainfall is reported as a fraction of the total daily rainfall, $\alpha_{0.5}$. If sub-daily precipitation data is used in the model, SWAT will calculate the maximum half-hour rainfall fraction directly from the precipitation data. If daily precipitation data is used, SWAT generates a value for $\alpha_{0.5}$ using the equations summarized in Chapter 4.

3.3 WATER VAPOR

Relative humidity is required by SWAT if the Penman-Monteith or Priestley-Taylor equation is used to estimate potential evapotranspiration. The Penman-Monteith equation includes terms that quantify the effect of the amount of water vapor in the air near the evaporative surface on evaporation. Both Penman-Monteith and Priestley-Taylor require the actual vapor pressure, which is calculated from the relative humidity.

Relative humidity is the ratio of an air volume's actual vapor pressure to its saturation vapor pressure:

$$R_h = \frac{e}{e^o} \qquad 3.3.1$$

where R_h is the relative humidity on a given day, e is the actual vapor pressure on a given day (kPa), and e^o is the saturation vapor pressure on a given day (kPa).

The saturation vapor pressure is the maximum vapor pressure that is thermodynamically stable and is a function of the air temperature. SWAT calculates saturation vapor pressure using an equation presented by Tetens (1930) and Murray (1967):

$$e^o = \exp\left[\frac{16.78 \cdot \overline{T}_{av} - 116.9}{\overline{T}_{av} + 237.3}\right] \qquad 3.3.2$$

where e^o is the saturation vapor pressure on a given day (kPa) and $\overline{T}_{av}$ is the mean daily air temperature (°C). When relative humidity is known, the actual vapor pressure can be calculated by rearranging equation 3.3.1:

$$e = R_h \cdot e^o \qquad 3.3.3$$

The saturation vapor pressure curve is obtained by plotting equation 3.3.2. The slope of the saturation vapor pressure curve can be calculated by differentiating equation 3.3.2:

$$\Delta = \frac{4098 \cdot e^o}{\left(\overline{T}_{av} + 237.3\right)^2} \qquad 3.3.4$$

where Δ is the slope of the saturation vapor pressure curve (kPa $°C^{-1}$), e^o is the saturation vapor pressure on a given day (kPa) and $\overline{T}_{av}$ is the mean daily air temperature (°C).

The rate of evaporation is proportional to the difference between the vapor pressure of the surface layer and the vapor pressure of the overlying air. This difference is termed the vapor pressure deficit:

$$vpd = e^o - e \qquad 3.3.5$$

where vpd is the vapor pressure deficit (kPa), e^o is the saturation vapor pressure on a given day (kPa), and e is the actual vapor pressure on a given day (kPa). The greater the value of vpd the higher the rate of evaporation.

The latent heat of vaporization, λ, is the quantity of heat energy that must be absorbed to break the hydrogen bonds between water molecules in the liquid state to convert them to gas. The latent heat of vaporization is a function of temperature and can be calculated with the equation (Harrison, 1963):

$$\lambda = 2.501 - 2.361\times10^{-3} \cdot \overline{T}_{av} \qquad 3.3.6$$

where λ is the latent heat of vaporization (MJ kg^{-1}) and $\overline{T}_{av}$ is the mean daily air temperature (°C).

Evaporation involves the exchange of both latent heat and sensible heat between the evaporating body and the air. The psychrometric constant, γ, represents a balance between the sensible heat gained from air flowing past a wet bulb thermometer and the sensible heat converted to latent heat (Brunt, 1952) and is calculated:

$$\gamma = \frac{c_p \cdot P}{0.622 \cdot \lambda} \qquad 3.3.7$$

where γ is the psychrometric constant (kPa $°C^{-1}$), c_p is the specific heat of moist air at constant pressure (1.013×10^{-3} MJ kg^{-1} $°C^{-1}$), P is the atmospheric pressure (kPa), and λ is the latent heat of vaporization (MJ kg^{-1}).

Calculation of the psychrometric constant requires a value for atmospheric pressure. SWAT estimates atmospheric pressure using an equation developed by Doorenbos and Pruitt (1977) from mean barometric pressure data at a number of East African sites:

$$P = 101.3 - 0.01152 \cdot EL + 0.544\times10^{-6} \cdot EL^2 \qquad 3.3.8$$

where P is the atmospheric pressure (kPa) and EL is the elevation (m).

The daily relative humidity data required by SWAT may be read from an input file or generated by the model. The variable RHSIM in the input control code (.cod) file identifies the method used to obtain relative humidity data. To read in daily relative humidity data, the variable is set to 1 and the name of the relative humidity data file and the number of different records stored in the file are set in the control input/output (file.cio) file. To generate daily relative humidity values, RHSIM is set to 2. The equations used to generate relative humidity data in SWAT are reviewed in Chapter 4.

Table 3-2: SWAT input variables used in relative humidity calculations.

Variable name	Definition	File Name
RHD	R_h: daily average relative humidity	.hmd
TMP_MX	T_{mx}: maximum temperature for day (°C)	.tmp
TMP_MN	T_{mn}: minimum temperature for day (°C)	.tmp
ELEV	*EL*: elevation (m)	.sub
RHSIM	Relative humidity input code: 1-measured, 2-generated	.cod
NHTOT	Number of relative humidity records within the .hmd file (required if RHSIM = 1)	file.cio
RHFILE	Name of measured relative humidity input file (.hmd) (required if RHSIM = 1)	file.cio
IHGAGE	Number of relative humidity record used within the subbasin (required if RHSIM = 1)	file.cio
see description of .hmd file in the User's Manual for input and format requirements if measured relative humidity data is being used		

3.4 SNOW COVER

SWAT classifies precipitation as rain or freezing rain/snow by the mean daily air temperature. The boundary temperature, T_{s-r}, used to categorize precipitation as rain or snow is defined by the user. If the mean daily air temperature is less than the boundary temperature, then the precipitation within the HRU is classified as snow and the water equivalent of the snow precipitation is added to the snow pack.

Snowfall is stored at the ground surface in the form of a snow pack. The amount of water stored in the snow pack is reported as a snow water equivalent. The snow pack will increase with additional snowfall or decrease with snow melt or sublimation. The mass balance for the snow pack is:

$$SNO = SNO + R_{day} - E_{sub} - SNO_{mlt} \qquad 3.4.1$$

where SNO is the water content of the snow pack on a given day (mm H_2O), R_{day} is the amount of precipitation on a given day (added only if $\overline{T}_{av} \leq T_{s-r}$) (mm H_2O), E_{sub} is the amount of sublimation on a given day (mm H_2O), and SNO_{mlt} is the amount of snow melt on a given day (mm H_2O). The amount of snow is expressed as depth over the total HRU area.

Due to variables such as drifting, shading and topography, the snow pack in a subbasin will rarely be uniformly distributed over the total area. This results in a fraction of the subbasin area that is bare of snow. This fraction must be quantified to accurately compute snow melt in the subbasin.

The factors that contribute to variable snow coverage are usually similar from year to year, making it possible to correlate the areal coverage of snow with the amount of snow present in the subbasin at a given time. This correlation is expressed as an areal depletion curve, which is used to describe the seasonal growth and recession of the snow pack as a function of the amount of snow present in the subbasin (Anderson, 1976).

The areal depletion curve requires a threshold depth of snow, SNO_{100}, to be defined above which there will always be 100% cover. The threshold depth will depend on factors such as vegetation distribution, wind loading of snow, wind scouring of snow, interception and aspect, and will be unique to the watershed of interest.

The areal depletion curve is based on a natural logarithm. The areal depletion curve equation is:

$$sno_{\mathrm{cov}} = \frac{SNO}{SNO_{100}} \cdot \left(\frac{SNO}{SNO_{100}} + \exp\left(cov_1 - cov_2 \cdot \frac{SNO}{SNO_{100}} \right) \right)^{-1} \qquad 3.4.2$$

where sno_{cov} is the fraction of the HRU area covered by snow, SNO is the water content of the snow pack on a given day (mm H_2O), SNO_{100} is the threshold depth of snow at 100% coverage (mm H_2O), cov_1 and cov_2 are coefficients that define the shape of the curve. The values used for cov_1 and cov_2 are determined by solving equation 3.4.2 using two known points: 95% coverage at 95% SNO_{100}; and 50% coverage at a user specified fraction of SNO_{100}.

Example areal depletion curves for various fractions of SNO_{100} at 50% coverage are shown in the following figures.

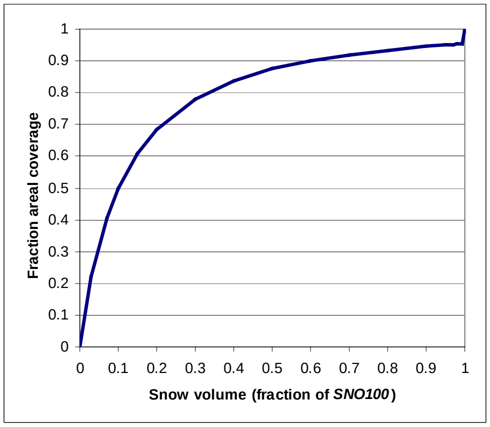

Figure 3-1:10% SNO_{100} = 50% coverage

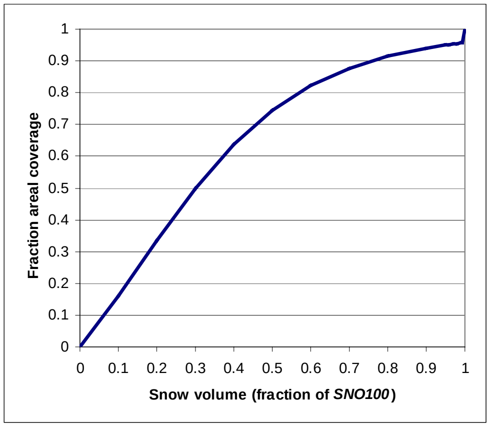

Figure 3-2: 30% SNO_{100} = 50% coverage

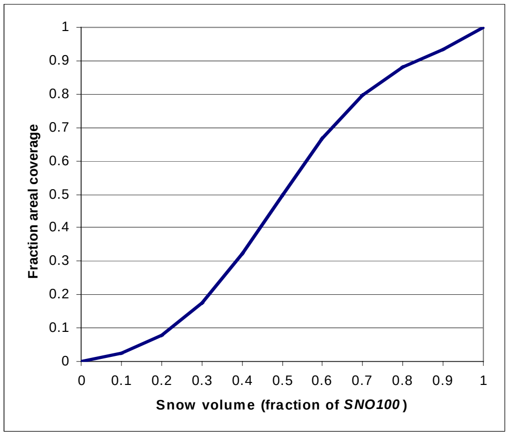

Figure 3-3: 50% SNO_{100} = 50% coverage

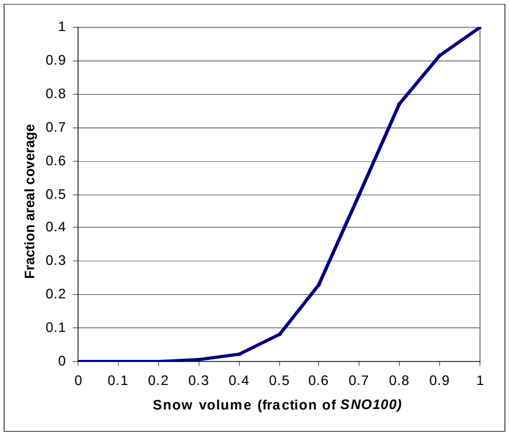

Figure 3-4: 70% SNO_{100} = 50% coverage

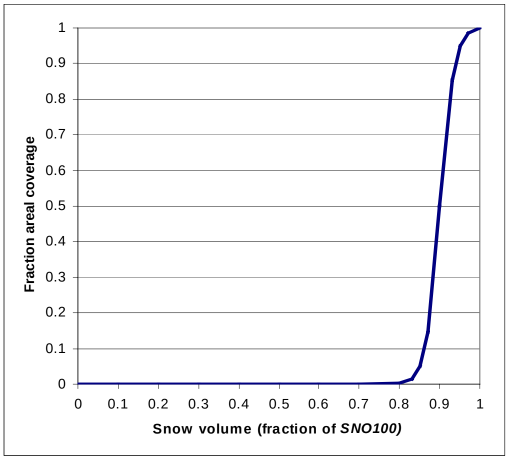

Figure 3-5: 90% SNO_{100} = 50% coverage

It is important to remember that once the volume of water held in the snow pack exceeds SNO_{100} the depth of snow over the HRU is assumed to be uniform, i.e. sno_{cov} = 1.0. The areal depletion curve affects snow melt only when the snow pack water content is between 0.0 and SNO_{100}. Consequently if SNO_{100} is set to a very small value, the impact of the areal depletion curve on snow melt will be minimal. As the value for SNO_{100} increases, the influence of the areal depletion curve will assume more importance in snow melt processes.

Table 3-3: SWAT input variables used in snow cover calculations.

Variable name	Definition	File Name
SFTMP	$T_{s\text{-}r}$: Mean air temperature at which precipitation is equally likely to be rain as snow/freezing rain (°C)	.bsn
SNOCOVMX	SNO_{100}: Threshold depth of snow, above which there is 100% cover	.bsn
SNO50COV	Fraction of SNOCOVMX that provides 50% cover	.bsn
SNO_SUB	Initial snow water content in subbasin (mm H_2O)	.sub
SNOEB	Initial snow water content in subbasin elevation band (mm H_2O)	.sub

3.5 SNOW MELT

Snow melt is controlled by the air and snow pack temperature, the melting rate, and the areal coverage of snow.

Snow melt is included with rainfall in the calculations of runoff and percolation. When SWAT calculates erosion, the rainfall energy of the snow melt fraction of the water is set to zero. The water released from snow melt is assumed to be evenly distributed over the 24 hours of the day.

3.5.1 SNOW PACK TEMPERATURE

The snow pack temperature is a function of the mean daily temperature during the preceding days and varies as a dampened function of air temperature (Anderson, 1976). The influence of the previous day's snow pack temperature on the current day's snow pack temperature is controlled by a lagging factor, ℓ_{sno}. The lagging factor inherently accounts for snow pack density, snow pack depth, exposure and other factors affecting snow pack temperature. The equation used to calculate the snow pack temperature is:

$$T_{snow(d_n)} = T_{snow(d_n-1)} \cdot \left(1 - \ell_{sno}\right) + \overline{T}_{av} \cdot \ell_{sno} \qquad 3.5.1$$

where $T_{snow(d_n)}$ is the snow pack temperature on a given day (°C), $T_{snow(d_n-1)}$ is the snow pack temperature on the previous day (°C), ℓ_{sno} is the snow temperature lag factor, and $\overline{T}_{av}$ is the mean air temperature on the current day (°C). As ℓ_{sno} approaches 1.0, the mean air temperature on the current day exerts an increasingly greater influence on the snow pack temperature and the snow pack temperature from the previous day exerts less and less influence.

The snow pack will not melt until the snow pack temperature exceeds a threshold value, T_{mlt}. This threshold value is specified by the user.

3.5.2 SNOW MELT EQUATION

The snow melt in SWAT is calculated as a linear function of the difference between the average snow pack-maximum air temperature and the base or threshold temperature for snow melt:

$$SNO_{mlt} = b_{mlt} \cdot sno_{\text{cov}} \cdot \left[\frac{T_{snow} + T_{mx}}{2} - T_{mlt} \right] \qquad 3.5.2$$

where SNO_{mlt} is the amount of snow melt on a given day (mm H_2O), b_{mlt} is the melt factor for the day (mm H_2O/day-°C), sno_{cov} is the fraction of the HRU area covered by snow, T_{snow} is the snow pack temperature on a given day (°C), T_{mx} is the maximum air temperature on a give day (°C), and T_{mlt} is the base temperature above which snow melt is allowed (°C).

The melt factor is allowed a seasonal variation with maximum and minimum values occurring on summer and winter solstices:

$$b_{mlt} = \frac{(b_{mlt6} + b_{mlt12})}{2} + \frac{(b_{mlt6} - b_{mlt12})}{2} \cdot \sin\left(\frac{2\pi}{365} \cdot (d_n - 81) \right) \qquad 3.5.3$$

where b_{mlt} is the melt factor for the day (mm H_2O/day-°C), b_{mlt6} is the melt factor for June 21 (mm H_2O/day-°C), b_{mlt12} is the melt factor for December 21 (mm H_2O/day-°C), and d_n is the day number of the year.

In rural areas, the melt factor will vary from 1.4 to 6.9 mm H_2O/day-°C (Huber and Dickinson, 1988). In urban areas, values will fall in the higher end of the range due to compression of the snow pack by vehicles, pedestrians, etc.

Urban snow melt studies in Sweden (Bengston, 1981; Westerstrom, 1981) reported melt factors ranging from 3.0 to 8.0 mm H_2O/day-°C. Studies of snow melt on asphalt (Westerstrom, 1984) gave melt factors of 1.7 to 6.5 mm H_2O/day-°C.

Table 3-4: SWAT input variables used in snow melt calculations.

Variable name	Definition	File Name
TIMP	ℓ_{sno} : Snow temperature lag factor	.bsn
SMTMP	T_{mlt}: Threshold temperature for snow melt (°C)	.bsn
SMFMX	b_{mlt6}: Melt factor on June 21 (mm H_2O/day-°C)	.bsn
SMFMN	b_{mlt12}: Melt factor on December 21 (mm H_2O/day-°C)	.bsn

3.6 NOMENCLATURE

E_{sub}	Amount of sublimation on a given day (mm H_2O)
EL	Elevation (m)
P	Atmospheric pressure (kPa)
R_{day}	Amount of rainfall on a given day (mm H_2O)
R_h	Average relative humidity for the day
SNO	Water content of snow cover on current day (mm H_2O)
SNO_{100}	Amount of snow above which there is 100% cover (mm H_2O)
SNO_{mlt}	Amount of snow melt on a given day (mm H_2O)
T_{mlt}	Threshold temperature for snow melt (°C)
T_{mx}	Maximum air temperature for day (°C)
$T_{s\text{-}r}$	Rain/snow boundary temperature (°C)
T_{snow}	Snow pack temperature on a given day (°C)
$\overline{T}_{av}$	Average air temperature for day (°C)

b_{mlt}	Melt factor for the day (mm H_2O/day-°C)
b_{mlt6}	Melt factor for June 21 (mm H_2O/day-°C)
b_{mlt12}	Melt factor for December 21 (mm H_2O/day-°C)
c_p	Specific heat of moist air at constant pressure (1.013×10^{-3} MJ kg^{-1} °C^{-1})
cov_1	Snow cover areal depletion curve shape coefficient
cov_2	Snow cover areal depletion curve shape coefficient
d_n	Day number of year, 1 on January 1 and 365 on December 31
e	Actual vapor pressure on a given day (kPa)
e^o	Saturation vapor pressure on a given day (kPa)
sno_{cov}	Fraction of the HRU area covered by snow
vpd	Vapor pressure deficit (kPa)

$\alpha_{0.5}$	Maximum half-hour rainfall expressed as a fraction of daily rainfall
Δ	Slope of the saturation vapor pressure curve (kPa °C^{-1})
γ	Psychrometric constant (kPa °C^{-1})
λ	Latent heat of vaporization (MJ kg^{-1})
ℓ_{sno}	Snow temperature lag factor

3.7 REFERENCES

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CHAPTER 4

EQUATIONS: WEATHER GENERATOR

SWAT requires daily values of precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed. The user may choose to read these inputs from a file or generate the values using monthly average data summarized over a number of years.

SWAT includes the WXGEN weather generator model (Sharpley and Williams, 1990) to generate climatic data or to fill in gaps in measured records. This weather generator was developed for the contiguous U.S. If the user prefers a different weather generator, daily input values for the different weather parameters may be generated with an alternative model and formatted for input to SWAT.

The occurrence of rain on a given day has a major impact on relative humidity, temperature and solar radiation for the day. The weather generator first independently generates precipitation for the day. Maximum temperature, minimum temperature, solar radiation and relative humidity are then generated based on the presence or absence of rain for the day. Finally, wind speed is generated independently.

4.1 PRECIPITATION

The precipitation generator is a Markov chain-skewed (Nicks, 1974) or Markov chain-exponential model (Williams, 1995). A first-order Markov chain is used to define the day as wet or dry. When a wet day is generated, a skewed distribution or exponential distribution is used to generate the precipitation amount. Table 4.1 lists SWAT input variables that are used in the precipitation generator.

4.1.1 OCCURRENCE OF WET OR DRY DAY

With the first-order Markov-chain model, the probability of rain on a given day is conditioned on the wet or dry status of the previous day. A wet day is defined as a day with 0.1 mm of rain or more.

The user is required to input the probability of a wet day on day i given a wet day on day i – 1, $P_i(W/W)$, and the probability of a wet day on day i given a dry day on day i – 1, $P_i(W/D)$, for each month of the year. From these inputs the remaining transition probabilities can be derived:

$$P_i\left(D/W\right) = 1 - P_i\left(W/W\right) \qquad 4.1.1$$

$$P_i\left(D/D\right) = 1 - P_i\left(W/D\right) \qquad 4.1.2$$

where $P_i(D/W)$ is the probability of a dry day on day i given a wet day on day i – 1 and $P_i(D/D)$ is the probability of a dry day on day i given a dry day on day i – 1.

To define a day as wet or dry, SWAT generates a random number between 0.0 and 1.0. This random number is compared to the appropriate wet-dry probability, $P_i(W/W)$ or $P_i(W/D)$. If the random number is equal to or less than the wet-dry probability, the day is defined as wet. If the random number is greater than the wet-dry probability, the day is defined as dry.

4.1.2 AMOUNT OF PRECIPITATION

Numerous probability distribution functions have been used to describe the distribution of rainfall amounts. SWAT provides the user with two options: a skewed distribution and an exponential distribution.

The skewed distribution was proposed by Nicks (1974) and is based on a skewed distribution used by Fiering (1967) to generate representative streamflow. The equation used to calculate the amount of precipitation on a wet day is:

$$R_{day} = \mu_{mon} + 2 \cdot \sigma_{mon} \cdot \left(\frac{\left[\left(SND_{day} - \frac{g_{mon}}{6} \right) \cdot \left(\frac{g_{mon}}{6} \right) + 1 \right]^3 - 1}{g_{mon}} \right) \qquad 4.1.3$$

where R_{day} is the amount of rainfall on a given day (mm H_2O), μ_{mon} is the mean daily rainfall (mm H_2O) for the month, σ_{mon} is the standard deviation of daily rainfall (mm H_2O) for the month, SND_{day} is the standard normal deviate calculated for the day, and g_{mon} is the skew coefficient for daily precipitation in the month.

The standard normal deviate for the day is calculated:

$$SND_{day} = \cos(6.283 \cdot rnd_2) \cdot \sqrt{-2\ln(rnd_1)} \qquad 4.1.4$$

where rnd_1 and rnd_2 are random numbers between 0.0 and 1.0.

The exponential distribution is provided as an alternative to the skewed distribution. This distribution requires fewer inputs and is most commonly used in areas where limited data on precipitation events is available. Daily precipitation is calculated with the exponential distribution using the equation:

$$R_{day} = \mu_{mon} \cdot (-\ln(rnd_1))^{r\exp} \qquad 4.1.5$$

where R_{day} is the amount of rainfall on a given day (mm H_2O), μ_{mon} is the mean daily rainfall (mm H_2O) for the month, rnd_1 is a random number between 0.0 and 1.0, and *rexp* is an exponent that should be set between 1.0 and 2.0. As the value of *rexp* is increased, the number of extreme rainfall events during the year will increase. Testing of this equation at locations across the U.S. have shown that a value of 1.3 gives satisfactory results.

Table 4-1: SWAT input variables that pertain to generation of precipitation.

Variable name	Definition	File Name
PCPSIM	Precipitation input code: 1-measured, 2-generated	.cod
PR_W(1,mon)	$P_i(W/D)$: probability of a wet day following a dry day in month	.wgn
PR_W(2,mon)	$P_i(W/W)$: probability of a wet day following a wet day in month	.wgn
IDIST	Rainfall distribution code: 0-skewed, 1-exponential	.cod
REXP	*rexp*: value of exponent (required if IDIST = 1)	.cod
PCPMM(mon)	average amount of precipitation falling in month (mm H_2O)	.wgn
PCPD(mon)	average number of days of precipitation in month (μ_{mon} = PCPMM / PCPD)	.wgn
PCPSTD(mon)	σ_{mon}: standard deviation for daily precipitation in month (mm H_2O)	.wgn
PCPSKW(mon)	g_{mon}: skew coefficient for daily precipitation in month	.wgn

4.2 SOLAR RADIATION & TEMPERATURE

The procedure used to generate daily values for maximum temperature, minimum temperature and solar radiation (Richardson, 1981; Richardson and Wright, 1984) is based on the weakly stationary generating process presented by Matalas (1967).

4.2.1 DAILY RESIDUALS

Residuals for maximum temperature, minimum temperature and solar radiation are required for calculation of daily values. The residuals must be serially correlated and cross-correlated with the correlations being constant at all locations. The equation used to calculate residuals is:

$$\chi_i(j) = A\chi_{i-1}(j) + B\varepsilon_i(j) \qquad 4.2.1$$

where $\chi_i(j)$ is a 3 × 1 matrix for day i whose elements are residuals of maximum temperature (j = 1), minimum temperature (j = 2) and solar radiation (j = 3), $\chi_{i-1}(j)$ is a 3 × 1 matrix of the previous day's residuals, ε_i is a 3 × 1 matrix of independent random components, and A and B are 3 × 3 matrices whose elements are defined such that the new sequences have the desired serial-correlation and cross-correlation coefficients. The A and B matrices are given by

$$A = M_1 \cdot M_0^{-1} \qquad 4.2.2$$

$$B \cdot B^T = M_0 - M_1 \cdot M_0^{-1} \cdot M_1^T \qquad 4.2.3$$

where the superscript –1 denotes the inverse of the matrix and the superscript T denotes the transpose of the matrix. M_0 and M_1 are defined as

$$M_0 = \begin{bmatrix} 1 & \rho_0(1,2) & \rho_0(1,3) \\ \rho_0(1,2) & 1 & \rho_0(2,3) \\ \rho_0(1,3) & \rho_0(2,3) & 1 \end{bmatrix} \qquad 4.2.4$$

$$M_1 = \begin{bmatrix} \rho_1(1,1) & \rho_1(1,2) & \rho_1(1,3) \\ \rho_1(2,1) & \rho_1(2,2) & \rho_1(2,3) \\ \rho_1(3,1) & \rho_1(3,2) & \rho_1(3,3) \end{bmatrix} \qquad 4.2.5$$

$\rho_0(j,k)$ is the correlation coefficient between variables j and k on the same day where j and k may be set to 1 (maximum temperature), 2 (minimum temperature) or 3 (solar radiation) and $\rho_1(j,k)$ is the correlation coefficient between variable j and k with variable k lagged one day with respect to variable j.

Correlation coefficients were determined for 31 locations in the United States using 20 years of temperature and solar radiation data (Richardson, 1982). Using the average values of these coefficients, the M_0 and M_1 matrices become

$$M_0 = \begin{bmatrix} 1.000 & 0.633 & 0.186 \\ 0.633 & 1.000 & -0.193 \\ 0.186 & -0.193 & 1.000 \end{bmatrix} \qquad 4.2.6$$

$$M_1 = \begin{bmatrix} 0.621 & 0.445 & 0.087 \\ 0.563 & 0.674 & -0.100 \\ 0.015 & -0.091 & 0.251 \end{bmatrix} \qquad 4.2.7$$

Using equations 4.2.2 and 4.2.3, the A and B matrices become

$$A = \begin{bmatrix} 0.567 & 0.086 & -0.002 \\ 0.253 & 0.504 & -0.050 \\ -0.006 & -0.039 & 0.244 \end{bmatrix} \qquad 4.2.8$$

$$B = \begin{bmatrix} 0.781 & 0 & 0 \\ 0.328 & 0.637 & 0 \\ 0.238 & -0.341 & 0.873 \end{bmatrix} \qquad 4.2.9$$

The *A* and *B* matrices defined in equations 4.2.8 and 4.2.9 are used in conjunction with equation 4.2.1 to generate daily sequences of residuals of maximum temperature, minimum temperature and solar radiation.

4.2.2 GENERATED VALUES

The daily generated values are determined by multiplying the residual elements generated with equation 4.2.1 by the monthly standard deviation and adding the monthly average value.

$$T_{mx} = \mu mx_{mon} + \chi_i(1) \cdot \sigma mx_{mon} \qquad 4.2.10$$

$$T_{mn} = \mu mn_{mon} + \chi_i(2) \cdot \sigma mn_{mon} \qquad 4.2.11$$

$$H_{day} = \mu rad_{mon} + \chi_i(3) \cdot \sigma rad_{mon} \qquad 4.2.12$$

where T_{mx} is the maximum temperature for the day (°C), μmx_{mon} is the average daily maximum temperature for the month (°C), $\chi_i(1)$ is the residual for maximum temperature on the given day, σmx_{mon} is the standard deviation for daily maximum temperature during the month (°C), T_{mn} is the minimum temperature for the day (°C), μmn_{mon} is the average daily minimum temperature for the month (°C), $\chi_i(2)$ is the residual for minimum temperature on the given day, σmn_{mon} is the standard deviation for daily minimum temperature during the month (°C), H_{day} is the solar radiation for the day (MJ m^{-2}), μrad_{mon} is the average daily solar radiation for the month (MJ m^{-2}), $\chi_i(3)$ is the residual for solar radiation on the given day, and σrad_{mon} is the standard deviation for daily solar radiation during the month (MJ m^{-2}).

The user is required to input standard deviation for maximum and minimum temperature. For solar radiation the standard deviation is estimated as ¼ of the difference between the extreme and mean value for each month.

$$\sigma rad_{mon} = \frac{H_{mx} - \mu rad_{mon}}{4} \qquad 4.2.13$$

where σrad_{mon} is the standard deviation for daily solar radiation during the month (MJ m^{-2}), H_{mx} is the maximum solar radiation that can reach the earth's surface on a given day (MJ m^{-2}), and μrad_{mon} is the average daily solar radiation for the month (MJ m^{-2}).

4.2.3 ADJUSTMENT FOR CLEAR/OVERCAST CONDITIONS

Maximum temperature and solar radiation will be lower on overcast days than on clear days. To incorporate the influence of wet/dry days on generated values of maximum temperature and solar radiation, the average daily maximum temperature, μmx_{mon}, and average daily solar radiation, μrad_{mon}, in equations 4.2.10 and 4.2.12 are adjusted for wet or dry conditions.

4.2.3.1 MAXIMUM TEMPERATURE

The continuity equation relates average daily maximum temperature adjusted for wet or dry conditions to the average daily maximum temperature for the month:

$$\mu mx_{mon} \cdot days_{tot} = \mu Wmx_{mon} \cdot days_{wet} + \mu Dmx_{mon} \cdot days_{dry} \qquad 4.2.14$$

where μmx_{mon} is the average daily maximum temperature for the month (°C), $days_{tot}$ are the total number of days in the month, μWmx_{mon} is the average daily maximum temperature of the month on wet days (°C), $days_{wet}$ are the number of wet days in the month, μDmx_{mon} is the average daily maximum temperature of the month on dry days (°C), and $days_{dry}$ are the number of dry days in the month.

The wet day average maximum temperature is assumed to be less than the dry day average maximum temperature by some fraction of (μmx_{mon} - μmn_{mon}):

$$\mu Wmx_{mon} = \mu Dmx_{mon} - b_T \cdot \left(\mu mx_{mon} - \mu mn_{mon}\right) \qquad 4.2.15$$

where μWmx_{mon} is the average daily maximum temperature of the month on wet days (°C), μDmx_{mon} is the average daily maximum temperature of the month on dry days (°C), b_T is a scaling factor that controls the degree of deviation in temperature caused by the presence or absence of precipitation, μmx_{mon} is the average daily maximum temperature for the month (°C), and μmn_{mon} is the average daily minimum temperature for the month (°C). The scaling factor, b_T, is set to 0.5 in SWAT.

To calculate the dry day average maximum temperature, equations 4.2.14 and 4.2.15 are combined and solved for μDmx_{mon}:

$$\mu Dmx_{mon} = \mu mx_{mon} + b_T \cdot \frac{days_{wet}}{days_{tot}} \cdot \left(\mu mx_{mon} - \mu mn_{mon} \right) \qquad 4.2.16$$

Incorporating the modified values into equation 4.2.10, SWAT calculates the maximum temperature for a wet day using the equation:

$$T_{mx} = \mu Wmx_{mon} + \chi_i(1) \cdot \sigma mx_{mon} \qquad 4.2.17$$

and the maximum temperature for a dry day using the equation:

$$T_{mx} = \mu Dmx_{mon} + \chi_i(1) \cdot \sigma mx_{mon} \qquad 4.2.18$$

4.2.3.2 SOLAR RADIATION

The continuity equation relates average daily solar radiation adjusted for wet or dry conditions to the average daily solar radiation for the month:

$$\mu rad_{mon} \cdot days_{tot} = \mu Wrad_{mon} \cdot days_{wet} + \mu Drad_{mon} \cdot days_{dry} \qquad 4.2.19$$

where μrad_{mon} is the average daily solar radiation for the month (MJ m^{-2}), $days_{tot}$ are the total number of days in the month, $\mu Wrad_{mon}$ is the average daily solar radiation of the month on wet days (MJ m^{-2}), $days_{wet}$ are the number of wet days in the month, $\mu Drad_{mon}$ is the average daily solar radiation of the month on dry days (MJ m^{-2}), and $days_{dry}$ are the number of dry days in the month.

The wet day average solar radiation is assumed to be less than the dry day average solar radiation by some fraction:

$$\mu Wrad_{mon} = b_R \cdot \mu Drad_{mon} \qquad 4.2.20$$

where $\mu Wrad_{mon}$ is the average daily solar radiation of the month on wet days (MJ m^{-2}), $\mu Drad_{mon}$ is the average daily solar radiation of the month on dry days (MJ m^{-2}), and b_R is a scaling factor that controls the degree of deviation in solar radiation caused by the presence or absence of precipitation. The scaling factor, b_R, is set to 0.5 in SWAT.

To calculate the dry day average solar radiation, equations 4.2.19 and 4.2.20 are combined and solved for $\mu Drad_{mon}$:

$$\mu Drad_{mon} = \frac{\mu rad_{mon} \cdot days_{tot}}{b_R \cdot days_{wet} + days_{dry}} \qquad 4.2.21$$

Incorporating the modified values into equation 4.2.12, SWAT calculated the solar radiation on a wet day using the equation:

$$H_{day} = \mu Wrad_{mon} + \chi_i(3) \cdot \sigma rad_{mon} \qquad 4.2.22$$

and the solar radiation on a dry day using the equation:

$$H_{day} = \mu Drad_{mon} + \chi_i(3) \cdot \sigma rad_{mon} \qquad 4.2.23$$

Table 4-2: SWAT input variables that pertain to generation of temperature and solar radiation.

Variable name	Definition	File Name
TMPSIM	Temperature input code: 1-measured, 2-generated	.cod
SLRSIM	Solar radiation input code: 1-measured, 2-generated	.cod
TMPMX(mon)	μmx_{mon}: average maximum air temperature for month (°C)	.wgn
TMPSTDMX(mon)	σmx_{mon}: standard deviation for maximum air temperature in month (°C)	.wgn
TMPMN(mon)	μmn_{mon}: average minimum air temperature for month (°C)	.wgn
TMPSTDMN(mon)	σmn_{mon}: standard deviation for minimum air temperature in month (°C)	.wgn
SOLARAV(mon)	μrad_{mon}: average daily solar radiation for month (MJ m^{-2})	.wgn
PCPD(mon)	$days_{wet}$: average number of days of precipitation in month	.wgn

4.3 RELATIVE HUMIDITY

Relative humidity is required by SWAT when the Penman-Monteith equation is used to calculate potential evapotranspiration. Daily average relative humidity values are calculated from a triangular distribution using average monthly relative humidity.

4.3.1 MEAN MONTHLY RELATIVE HUMIDITY

Relative humidity is defined as the ratio of the actual vapor pressure to the saturation vapor pressure at a given temperature:

$$R_{hmon} = \frac{e_{mon}}{e^o_{mon}} \qquad 4.3.1$$

where R_{hmon} is the average relative humidity for the month, e_{mon} is the actual vapor pressure at the mean monthly temperature (kPa), and e^o_{mon} is the saturation vapor pressure at the mean monthly temperature (kPa). The saturation vapor pressure, e^o_{mon}, is related to the mean monthly air temperature with the equation:

$$e^o_{mon} = \exp\left[\frac{16.78 \cdot \mu tmp_{mon} - 116.9}{\mu tmp_{mon} + 237.3}\right] \qquad 4.3.2$$

where e^o_{mon} is the saturation vapor pressure at the mean monthly temperature (kPa), and μtmp_{mon} is the mean air temperature for the month (°C). The mean air temperature for the month is calculated by averaging the mean maximum monthly temperature, μmx_{mon}, and the mean minimum monthly temperature, μmn_{mon}.

The dew point temperature is the temperature at which the actual vapor pressure present in the atmosphere is equal to the saturation vapor pressure. Therefore, by substituting the dew point temperature in place of the average monthly temperature in equation 4.3.2, the actual vapor pressure may be calculated:

$$e_{mon} = \exp\left[\frac{16.78 \cdot \mu dew_{mon} - 116.9}{\mu dew_{mon} + 237.3}\right] \qquad 4.3.3$$

where e_{mon} is the actual vapor pressure at the mean month temperature (kPa), and μdew_{mon} is the average dew point temperature for the month (°C).

4.3.2 GENERATED DAILY VALUE

The triangular distribution used to generate daily relative humidity values requires four inputs: mean monthly relative humidity, maximum relative humidity value allowed in month, minimum relative humidity value allowed in month, and a random number between 0.0 and 1.0.

The maximum relative humidity value, or upper limit of the triangular distribution, is calculated from the mean monthly relative humidity with the equation:

$$R_{hUmon} = R_{hmon} + (1 - R_{hmon}) \cdot \exp(R_{hmon} - 1) \qquad 4.3.4$$

where R_{hUmon} is the largest relative humidity value that can be generated on a given day in the month, and R_{hmon} is the average relative humidity for the month.

The minimum relative humidity value, or lower limit of the triangular distribution, is calculated from the mean monthly relative humidity with the equation:

$$R_{hLmon} = R_{hmon} \cdot (1 - \exp(-R_{hmon})) \qquad 4.3.5$$

where R_{hLmon} is the smallest relative humidity value that can be generated on a given day in the month, and R_{hmon} is the average relative humidity for the month.

The triangular distribution uses one of two sets of equations to generate a relative humidity value for the day. If $rnd_1 \le \left(\frac{R_{hmon} - R_{hLmon}}{R_{hUmon} - R_{hLmon}} \right)$ then

$$R_h = R_{hLmon} + [rnd_1 \cdot (R_{hUmon} - R_{hLmon}) \cdot (R_{hmon} - R_{hLmon})]^{0.5} \qquad 4.3.6$$

If $rnd_1 > \left(\frac{R_{hmon} - R_{hLmon}}{R_{hUmon} - R_{hLmon}} \right)$ then

$$R_h = R_{hUmon} - (R_{hUmon} - R_{hmon}) \cdot \left[\frac{R_{hUmon}(1 - rnd_1) - R_{hLmon}(1 - rnd_1)}{R_{hUmon} - R_{hmon}} \right]^{0.5} \qquad 4.3.7$$

where R_h is the average relative humidity calculated for the day, rnd_1 is a random number generated by the model each day, R_{hmon} is the average relative humidity for the month, R_{hLmon} is the smallest relative humidity value that can be generated on a given day in the month, and R_{hUmon} is the largest relative humidity value that can be generated on a given day in the month.

4.3.3 ADJUSTMENT FOR CLEAR/OVERCAST CONDITIONS

To incorporate the effect of clear and overcast weather on generated values of relative humidity, monthly average relative humidity values can be adjusted for wet or dry conditions.

The continuity equation relates average relative humidity adjusted for wet or dry conditions to the average relative humidity for the month:

$$R_{hmon} \cdot days_{tot} = R_{hWmon} \cdot days_{wet} + R_{hDmon} \cdot days_{dry} \qquad 4.3.8$$

where R_{hmon} is the average relative humidity for the month, $days_{tot}$ are the total number of days in the month, R_{hWmon} is the average relative humidity for the month on wet days, $days_{wet}$ are the number of wet days in the month, R_{hDmon} is the average relative humidity of the month on dry days, and $days_{dry}$ are the number of dry days in the month.

The wet day average relative humidity is assumed to be greater than the dry day average relative humidity by some fraction:

$$R_{hWmon} = R_{hDmon} + b_H \cdot \left(1 - R_{hDmon}\right) \qquad 4.3.9$$

where R_{hWmon} is the average relative humidity of the month on wet days, R_{hDmon} is the average relative humidity of the month on dry days, and b_H is a scaling factor that controls the degree of deviation in relative humidity caused by the presence or absence of precipitation. The scaling factor, b_H, is set to 0.9 in SWAT.

To calculate the dry day relative humidity, equations 4.3.8 and 4.3.9 are combined and solved for R_{hDmon}:

$$R_{hDmon} = \left(R_{hmon} - b_H \cdot \frac{days_{wet}}{days_{tot}}\right) \cdot \left(1.0 - b_H \cdot \frac{days_{wet}}{days_{tot}}\right)^{-1} \qquad 4.3.10$$

To reflect the impact of wet or dry conditions, SWAT will replace R_{hmon} with R_{hWmon} on wet days or R_{hDmon} on dry days in equations 4.3.4 through 4.3.7.

Table 4-3: SWAT input variables that pertain to generation of relative humidity.

Variable name	**Definition**	**File Name**
RHSIM	Relative humidity input code: 1-measured, 2-generated	.cod
TMPMN(mon)	μmn_{mon}: average minimum air temperature for month (°C)	.wgn
TMPMX(mon)	μmx_{mon}: average maximum air temperature for month (°C)	.wgn
DEWPT(mon)	μdew_{mon}: average dew point temperature for month (°C)	.wgn
PCPD(mon)	$days_{wet}$: average number of days of precipitation in month	.wgn

4.4 MAXIMUM HALF-HOUR RAINFALL

Maximum half-hour rainfall is required by SWAT to calculate the peak flow rate for runoff. When daily precipitation data is used by the model, the maximum half-hour rainfall is calculated from a triangular distribution using monthly maximum half-hour rainfall data. The maximum half-hour rainfall is calculated only on days where surface runoff has been generated.

4.4.1 MONTHLY MAXIMUM HALF-HOUR RAIN

For each month, users provide the maximum half-hour rain observed over the entire period of record. These extreme values are used to calculate representative monthly maximum half-hour rainfall fractions.

Prior to calculating the representative maximum half-hour rainfall fraction for each month, the extreme half-hour rainfall values are smoothed by calculating three month average values:

$$R_{0.5sm(mon)} = \frac{R_{0.5x(mon-1)} + R_{0.5x(mon)} + R_{0.5x(mon+1)}}{3} \qquad 4.4.1$$

where $R_{0.5sm(mon)}$ is the smoothed maximum half-hour rainfall for a given month (mm H_2O) and $R_{0.5x}$ is the extreme maximum half-hour rainfall for the specified month (mm H_2O). Once the smoothed maximum half-hour rainfall is known, the representative half-hour rainfall fraction is calculated using the equation:

$$\alpha_{0.5mon} = adj_{0.5\alpha} \cdot \left[1 - \exp\left(\frac{R_{0.5sm(mon)}}{\mu_{mon} \cdot \ln\left(\frac{0.5}{yrs \cdot days_{wet}} \right)} \right) \right] \qquad 4.4.2$$

where $\alpha_{0.5mon}$ is the average half-hour rainfall fraction for the month, $adj_{0.5\alpha}$ is an adjustment factor, $R_{0.5sm}$ is the smoothed half-hour rainfall amount for the month (mm H_2O), μ_{mon} is the mean daily rainfall (mm H_2O) for the month, yrs is the number of years of rainfall data used to obtain values for monthly extreme half-hour rainfalls, and $days_{wet}$ are the number of wet days in the month. The adjustment factor is included to allow users to modify estimations of half-hour rainfall fractions and peak flow rates for runoff.

4.4.2 GENERATED DAILY VALUE

The triangular distribution used to generate the maximum half-hour rainfall fraction requires four inputs: average monthly half-hour rainfall fraction, maximum value for half-hour rainfall fraction allowed in month, minimum value for half-hour rainfall fraction allowed in month, and a random number between 0.0 and 1.0.

The maximum half-hour rainfall fraction, or upper limit of the triangular distribution, is calculated from the daily amount of rainfall with the equation:

$$\alpha_{0.5U} = 1 - \exp\left(\frac{-125}{R_{day} + 5}\right) \qquad 4.4.3$$

where $\alpha_{0.5U}$ is the largest half-hour fraction that can be generated on a given day, and R_{day} is the precipitation on a given day (mm H_2O).

The minimum half-hour fraction, or lower limit of the triangular distribution, $\alpha_{0.5L}$, is set at 0.02083.

The triangular distribution uses one of two sets of equations to generate a maximum half-hour rainfall fraction for the day. If $rnd_1 \leq \left(\frac{\alpha_{0.5mon} - \alpha_{0.5L}}{\alpha_{0.5U} - \alpha_{0.5L}}\right)$ then

$$\alpha_{0.5} = \alpha_{0.5L} + \left[rnd_1 \cdot (\alpha_{0.5U} - \alpha_{0.5L}) \cdot (\alpha_{0.5mon} - \alpha_{0.5L})\right]^{0.5} \qquad 4.4.4$$

If $rnd_1 > \left(\frac{\alpha_{0.5mon} - \alpha_{0.5L}}{\alpha_{0.5U} - \alpha_{0.5L}}\right)$ then

$$\alpha_{0.5} = \alpha_{0.5U} - (\alpha_{0.5U} - \alpha_{0.5mon}) \cdot \left[\frac{\alpha_{0.5U}(1 - rnd_1) - \alpha_{0.5L}(1 - rnd_1)}{\alpha_{0.5U} - \alpha_{0.5mon}}\right]^{0.5} \qquad 4.4.5$$

where $\alpha_{0.5}$ is the maximum half-hour rainfall fraction for the day, $\alpha_{0.5mon}$ is the average maximum half-hour rainfall fraction for the month, rnd_1 is a random number generated by the model each day, $\alpha_{0.5L}$ is the smallest half-hour rainfall fraction that can be generated, and $\alpha_{0.5U}$ is the largest half-hour fraction that can be generated.

Table 4-4: SWAT input variables that pertain to generation of maximum half-hour rainfall.

Variable name	Definition	File Name
RAINHHMX(mon)	$R_{0.5x}$: extreme half-hour rainfall for month (mm H_2O)	.wgn
APM	$adj_{0.5\alpha}$: peak rate adjustment factor	.bsn
PCPMM(mon)	average amount of precipitation falling in month (mm H_2O)	.wgn
PCPD(mon)	$days_{wet}$: average number of days of precipitation in month (μ_{mon} = PCPMM / PCPD)	.wgn
RAIN_YRS	yrs: number of years of data used to obtain values for RAINHHMX	.wgn
PRECIPITATION	R_{day}: amount of rain falling on a given day (mm H_2O)	.pcp

4.5 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:

$$\mu_{10m} = \mu wnd_{mon} \cdot \left(-\ln\left(rnd_1\right)\right)^{0.3} \qquad 4.5.1$$

where μ_{10m} is the mean wind speed for the day (m s^{-1}), μwnd_{mon} is the average wind speed for the month (m s^{-1}), and rnd_1 is a random number between 0.0 and 1.0.

Table 4-5: SWAT input variables that pertain to generation of wind speed.

Variable name	Definition	File Name
WNDSIM	Wind speed input code: 1-measured, 2-generated	.cod
WNDAV(mon)	μwnd_{mon}: Average wind speed in month (m/s)	.wgn

4.6 NOMENCLATURE

A	3×3 matrix of elements defined to ensure serial and cross correlation of generated temperature and radiation values $A = M_1 \cdot M_0^{-1}$
B	3×3 matrix of elements defined to ensure serial and cross correlation of generated temperature and radiation values $B \cdot B^T = M_0 - M_1 \cdot M_0^{-1} \cdot M_1^T$
H_{day}	Solar radiation reaching ground on current day of simulation (MJ m^{-2} d^{-1})
H_{MX}	Maximum possible solar radiation (MJ m^{-2} d^{-1})
M_0	3×3 matrix of correlation coefficients between maximum temperature, minimum temperature and solar radiation on same day
M_1	3×3 matrix of correlation coefficients between maximum temperature, minimum temperature and solar radiation on consecutive days
$P_i(D/D)$	Probability of a dry day on day i given a dry day on day $i - 1$
$P_i(D/W)$	Probability of a dry day on day i given a wet day on day $i - 1$
$P_i(W/D)$	Probability of a wet day on day i given a dry day on day $i - 1$
$P_i(W/W)$	Probability of a wet day on day i given a wet day on day $i - 1$
$R_{0.5sm}$	Smoothed maximum half-hour rainfall for a given month (mm H_2O)
$R_{0.5x}$	Extreme maximum half-hour rainfall for the specified month (mm H_2O)
R_{day}	Amount of rainfall on a given day (mm H_2O)
R_h	Average relative humidity for the day
R_{hDmon}	Average relative humidity of the month on dry days

R_{hLmon}	Smallest relative humidity value that can be generated on a given day in the month
R_{hUmon}	Largest relative humidity value that can be generated on a given day in the month
R_{hWmon}	Average relative humidity for the month on wet days
R_{hmon}	Average relative humidity for the month
SND_{day}	Standard normal deviate for the day
T_{mn}	Minimum air temperature for day (°C)
T_{mx}	Maximum air temperature for day (°C)

$adj_{0.5\alpha}$	Peak rate adjustment factor
b_H	Scaling factor that controls the degree of deviation in relative humidity caused by the presence or absence of precipitation
b_R	Scaling factor that controls the degree of deviation in solar radiation caused by the presence or absence of precipitation
b_T	Scaling factor that controls the degree of deviation in temperature caused by the presence or absence of precipitation
$days_{dry}$	Number of dry days in the month
$days_{tot}$	Total number of days in the month
$days_{wet}$	Number of wet days in the month
e_{mon}	Actual vapor pressure at the mean monthly temperature (kPa)
e^o_{mon}	Saturation vapor pressure at the mean monthly temperature (kPa)
g_{mon}	Skew coefficient for daily precipitation in the month
$rexp$	Exponent for exponential precipitation distribution
rnd_1	Random number between 0.0 and 1.0
rnd_2	Random number between 0.0 and 1.0
yrs	Number of years of rainfall data used to obtain values for monthly extreme half-hour rainfalls

$\alpha_{0.5}$	Maximum half-hour rainfall expressed as a fraction of daily rainfall
$\alpha_{0.5L}$	Smallest half-hour rainfall fraction that can be generated on a given day
$\alpha_{0.5mon}$	Average maximum half-hour rainfall fraction for the month
$\alpha_{0.5U}$	Largest half-hour rainfall fraction that can be generated on a given day
ε_i	3×1 matrix of independent random components
σ_{mon}	Standard deviation of daily rainfall (mm H_2O) for the month
σmn_{mon}	Standard deviation for daily minimum temperature during the month (°C)
σmx_{mon}	Standard deviation for daily maximum temperature during the month (°C)
σrad_{mon}	Standard deviation for daily solar radiation during the month (MJ m^{-2})
$\rho_0(j,k)$	Correlation coefficient between variables *j* and *k* on the same day where *j* and *k* may be set to 1 (maximum temperature), 2 (minimum temperature) or 3 (solar radiation)
$\rho_1(j,k)$	Correlation coefficient between variable *j* and *k* with variable *k* lagged one day with respect to variable *j*
μ_{mon}	Mean daily rainfall (mm H_2O) for the month
μDmx_{mon}	Average daily maximum temperature of the month on dry days (°C)
$\mu Drad_{mon}$	Average daily solar radiation of the month on dry days (MJ m^{-2})

μWmx_{mon}	Average daily maximum temperature of the month on wet days (°C)
$\mu Wrad_{mon}$	Average daily solar radiation of the month on wet days (MJ m^{-2})
μdew_{mon}	Average dew point temperature for the month (°C)
μmn_{mon}	Average daily minimum temperature for the month (°C)
μmx_{mon}	Average daily maximum temperature for the month (°C)
μrad_{mon}	Average daily solar radiation for the month (MJ m^{-2})
μtmp_{mon}	Mean air temperature for the month (°C)
μwnd_{mon}	Average wind speed for the month (m s^{-1})
μ_{10m}	Mean wind speed for the day at height of 10 meters (m s^{-1})
$\chi_i(j)$	3×1 matrix for day i whose elements are residuals of maximum temperature (j = 1), minimum temperature (j = 2) and solar radiation (j = 3),

4.7 REFERENCES

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CHAPTER 5

EQUATIONS: CLIMATE CUSTOMIZATION

SWAT is capable of simulating orographic impacts on temperature and precipitation for watersheds in mountainous regions. The model will also modify climate inputs for simulations that are looking at the impact of climatic change in a given watershed.

5.1 ELEVATION BANDS

Orographic precipitation is a significant phenomenon in certain areas of the world. To account for orographic effects on both precipitation and temperature, SWAT allows up to 10 elevation bands to be defined in each subbasin. Precipitation and maximum and minimum temperatures are calculated for each band as a function of the respective lapse rate and the difference between the gage elevation and the average elevation specified for the band. For precipitation,

$$R_{band} = R_{day} + \left(EL_{band} - EL_{gage}\right) \cdot \frac{plaps}{1000} \qquad \text{when } R_{day} > 0.01 \qquad 5.1.1$$

where R_{band} is the precipitation falling in the elevation band (mm H_2O), R_{day} is the precipitation recorded at the gage or generated from gage data (mm H_2O), EL_{band} is the mean elevation in the elevation band (m), EL_{gage} is the elevation at the recording gage (m), $plaps$ is the precipitation lapse rate (mm H_2O/km), and 1000 is a factor needed to convert meters to kilometers. For temperature,

$$T_{mx,band} = T_{mx} + \left(EL_{band} - EL_{gage}\right) \cdot \frac{tlaps}{1000} \qquad 5.1.2$$

$$T_{mn,band} = T_{mn} + \left(EL_{band} - EL_{gage}\right) \cdot \frac{tlaps}{1000} \qquad 5.1.3$$

$$\overline{T}_{av,band} = \overline{T}_{av} + \left(EL_{band} - EL_{gage}\right) \cdot \frac{tlaps}{1000} \qquad 5.1.4$$

where $T_{mx,band}$ is the maximum daily temperature in the elevation band (°C), $T_{mn,band}$ is the minimum daily temperature in the elevation band (°C), $\overline{T}_{av,band}$ is the mean daily temperature in the elevation band (°C), T_{mx} is the maximum daily temperature recorded at the gage or generated from gage data (°C), T_{mn} is the minimum daily temperature recorded at the gage or generated from gage data (°C), $\overline{T}_{av}$ is the mean daily temperature recorded at the gage or generated from gage data (°C), EL_{band} is the mean elevation in the elevation band (m), EL_{gage} is the elevation at the recording gage (m), $tlaps$ is the temperature lapse rate (°C/km), and 1000 is a factor needed to convert meters to kilometers.

Once the precipitation and temperature values have been calculated for each elevation band in the subbasin, new average subbasin precipitation and temperature values are calculated:

$$R_{day} = \sum_{bnd=1}^{b} R_{band} \cdot fr_{bnd} \tag{5.1.5}$$

$$T_{mx} = \sum_{bnd=1}^{b} T_{mx,band} \cdot fr_{bnd} \tag{5.1.6}$$

$$T_{mn} = \sum_{bnd=1}^{b} T_{mn,band} \cdot fr_{bnd} \tag{5.1.7}$$

$$\overline{T}_{av} = \sum_{bnd=1}^{b} \overline{T}_{av,band} \cdot fr_{bnd} \tag{5.1.8}$$

where R_{day} is the daily average precipitation adjusted for orographic effects (mm H_2O), T_{mx} is the daily maximum temperature adjusted for orographic effects (°C), T_{mn} is the daily minimum temperature adjusted for orographic effects (°C), $\overline{T}_{av}$ is the daily mean temperature adjusted for orographic effects (°C), R_{band} is the precipitation falling in elevation band bnd (mm H_2O), $T_{mx,band}$ is the maximum daily temperature in elevation band bnd (°C), $T_{mn,band}$ is the minimum daily temperature in elevation band bnd (°C), $\overline{T}_{av,band}$ is the mean daily temperature in elevation band bnd (°C), fr_{bnd} is the fraction of subbasin area within the elevation band, and b is the total number of elevation bands in the subbasin.

The only processes modeled separately for each individual elevation band are the accumulation, sublimation and melting of snow. As with the initial precipitation and temperature data, after amounts of sublimation and snow melt are determined for each elevation band, subbasin average values are calculated. These average values are the values that are used in the remainder of the simulation and reported in the output files.

Table 5-1: SWAT input variables that pertain to orographic effects.

Variable Name	Definition	Input File
ELEVB	EL_{band}: Elevation at center of the elevation band (m)	.sub
ELEVB_FR	fr_{bnd}: Fraction of subbasin area within the elevation band.	.sub
WELEV	EL_{gage}: Elevation of recording gage whose data is used to calculate values in .wgn file (m)	.wgn
ELEVATION	EL_{gage}: Elevation of precipitation recording gage (m)	.pcp
ELEVATION	EL_{gage}: Elevation of temperature recording gage (m)	.tmp
PLAPS	*plaps*: Precipitation lapse rate (mm H_2O/km)	.sub
TLAPS	*tlaps*: Temperature lapse rate (°C/km)	.sub
PRECIPITATION	R_{day}: Daily precipitation (mm H_2O)	.pcp
MAX TEMP	T_{mx}: Daily maximum temperature (°C)	.tmp
MIN TEMP	T_{mn}: Daily minimum temperature (°C)	.tmp

5.2 CLIMATE CHANGE

The impact of global climate change on water supply is a major area of research. Climate change can be simulated with SWAT by manipulating the climatic input that is read into the model (precipitation, temperature, solar radiation, relative humidity, wind speed, potential evapotranspiration and weather generator parameters). A less time-consuming method is to set adjustment factors for the various climatic inputs.

SWAT will allow users to adjust precipitation, temperature, solar radiation, relative humidity, and carbon dioxide levels in each subbasin. The alteration of precipitation, temperature, solar radiation and relative humidity are straightforward:

$$R_{day} = R_{day} \cdot \left(1 + \frac{adj_{pcp}}{100}\right) \qquad 5.2.1$$

where R_{day} is the precipitation falling in the subbasin on a given day (mm H_2O), and adj_{pcp} is the % change in rainfall.

$$T_{mx} = T_{mx} + adj_{tmp} \qquad 5.2.2$$

where T_{mx} is the daily maximum temperature (°C), and adj_{tmp} is the change in temperature (°C).

$$T_{mn} = T_{mn} + adj_{tmp} \qquad 5.2.3$$

where T_{mn} is the daily minimum temperature (°C), and adj_{tmp} is the change in temperature (°C).

$$\overline{T}_{av} = \overline{T}_{av} + adj_{tmp} \qquad 5.2.4$$

where $\overline{T}_{av}$ is the daily mean temperature (°C), and adj_{tmp} is the change in temperature (°C).

$$H_{day} = H_{day} + adj_{rad} \qquad 5.2.5$$

where H_{day} is the daily solar radiation reaching the earth's surface (MJ m^{-2}), and adj_{rad} is the change in radiation (MJ m^{-2} d^{-1}).

$$R_h = R_h + adj_{hmd} \qquad 5.2.6$$

where R_h is the relative humidity for the day expressed as a fraction, and adj_{hmd} is the change in relative humidity expressed as a fraction.

SWAT allows the adjustment terms to vary from month to month so that the user is able to simulate seasonal changes in climatic conditions.

Changes in carbon dioxide levels impact plant growth. As carbon dioxide levels increase, plant productivity increases and plant water requirements go down. The equations used to account for the impact of carbon dioxide levels on plant water requirements are reviewed in Chapters 7 and 18. When carbon dioxide climate change effects are being simulated, the Penman-Monteith equation must be used to calculate potential evapotranspiration. This method has been modified to account for CO_2 impacts on potential evapotranspiration levels.

Table 5-2: SWAT input variables that pertain to climate change.

Variable Name	**Definition**	**Input File**
RFINC(mon)	adj_{pcp}: % change in rainfall for month	.sub
TMPINC(mon)	adj_{tmp}: increase or decrease in temperature for month (°C)	.sub
RADINC(mon)	adj_{rad}: increase or decrease in solar radiation reaching earth's surface for month (MJ m^{-2})	.sub
HUMINC(mon)	adj_{hmd}: increase or decrease in relative humidity for month	.sub
CO2	CO_2: carbon dioxide level in subbasin (ppmv)	.sub
IPET	Potential evapotranspiration method	.cod

5.3 NOMENCLATURE

CO_2	Concentration of carbon dioxide in the atmosphere (ppmv)
EL_{band}	Mean elevation in the elevation band (m)
EL_{gage}	Elevation at the precipitation, temperature, or weather generator data recording gage (m)
H_{day}	Solar radiation reaching ground on current day of simulation (MJ m^{-2} d^{-1})
R_{band}	Precipitation falling in the elevation band (mm H_2O)
R_{day}	Amount of rainfall on a given day (mm H_2O)
R_h	Average relative humidity for the day
T_{mn}	Minimum air temperature for day (°C)
$T_{mn,band}$	Minimum daily temperature in the elevation band (°C)
T_{mx}	Maximum air temperature for day (°C)
$T_{mx,band}$	Maximum daily temperature in the elevation band (°C)
$\bar{T}_{av}$	Mean air temperature for day (°C)
$\bar{T}_{av,band}$	Mean daily temperature in the elevation band (°C)

adj_{hmd}	Change in relative humidity expressed as a fraction
adj_{pcp}	% change in rainfall
adj_{rad}	Change in radiation (MJ m^{-2} d^{-1})
adj_{tmp}	Change in temperature (°C)
fr_{bnd}	Fraction of subbasin area within the elevation band
$plaps$	Precipitation lapse rate (mm H_2O/km)
$tlaps$	Temperature lapse rate (°C/km)

HYDROLOGY

The land phase of the hydrologic cycle is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content (mm H_2O), t is the time (days), R_{day} is the 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 flow 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).

CHAPTER 6

EQUATIONS: SURFACE RUNOFF

Surface runoff occurs whenever the rate of water application to the ground surface exceeds the rate of infiltration. When water is initially applied to a dry soil, the application rate and infiltration rates may be similar. However, the infiltration rate will decrease as the soil becomes wetter. When the application rate is higher than the infiltration rate, surface depressions begin to fill. If the application rate continues to be higher than the infiltration rate once all surface depressions have filled, surface runoff will commence.

SWAT provides two methods for estimating surface runoff: the SCS curve number procedure (SCS, 1972) and the Green & Ampt infiltration method (1911).

6.1 RUNOFF VOLUME: SCS CURVE NUMBER PROCEDURE

The SCS runoff equation is an empirical model that came into common use in the 1950s. It was the product of more than 20 years of studies involving rainfall-runoff relationships from small rural watersheds across the U.S. The model was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types (Rallison and Miller, 1981).

The SCS curve number equation is (SCS, 1972):

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)} \tag{6.1.1}$$

where Q_{surf} is the accumulated runoff or rainfall excess (mm H_2O), R_{day} is the rainfall depth for the day (mm H_2O), I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm H_2O), and S is the retention parameter (mm H_2O). The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{6.1.2}$$

where CN is the curve number for the day. The initial abstractions, I_a, is commonly approximated as $0.2S$ and equation 6.1.1 becomes

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)} \tag{6.1.3}$$

Runoff will only occur when $R_{day} > I_a$. A graphical solution of equation 6.1.3 for different curve number values is presented in Figure 6-1.

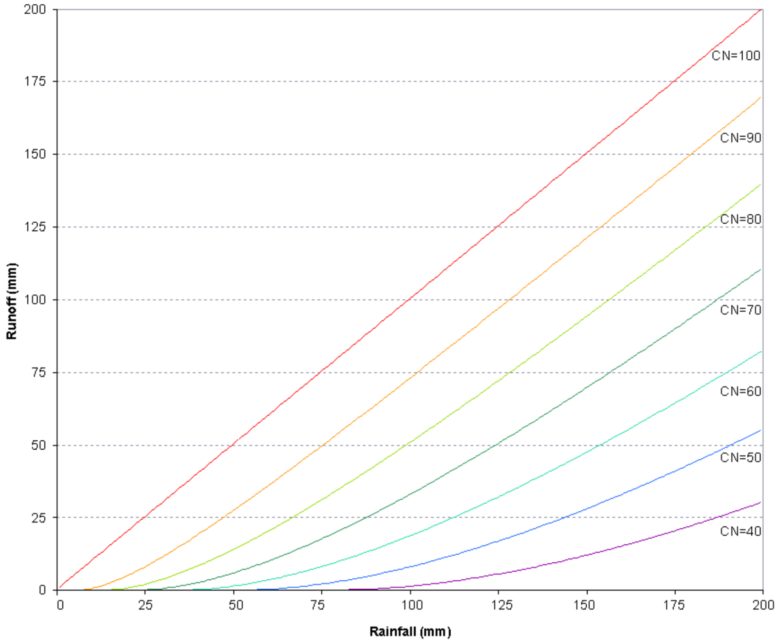

Figure 6-1: Relationship of runoff to rainfall in SCS curve number method.

6.1.1 SCS CURVE NUMBER

The SCS curve number is a function of the soil's permeability, land use and antecedent soil water conditions. Typical curve numbers for moisture condition II are listed in tables 6-1, 6-2 and 6-3 for various land covers and soil types (SCS Engineering Division, 1986). These values are appropriate for a 5% slope.

Table 6-1: Runoff curve numbers for cultivated agricultural lands (from SCS Engineering Division, 1986)

Cover			Hydrologic Soil Group			
Land Use	**Treatment or practice**	**Hydrologic condition**	**A**	**B**	**C**	**D**
Fallow	Bare soil	- - - -	77	86	91	94
	Crop residue cover[*]	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Straight row w/ residue	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured w/ residue	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced	Poor	66	74	80	82
		Good	62	71	78	81
	Contoured & terraced w/ residue	Poor	65	73	79	81
		Good	61	70	77	80
Small grains	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Straight row w/ residue	Poor	64	75	83	86

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[*] Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

Table 6-1, cont.: Runoff curve numbers for cultivated agricultural lands

Cover			Hydrologic Soil Group			
Land Use	**Treatment or practice**	**Hydrologic condition**	**A**	**B**	**C**	**D**
		Good	60	72	80	84
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Contoured w/ residue	Poor	62	73	81	84
		Good	60	72	80	83
	Contoured & terraced	Poor	61	72	79	82
		Good	59	70	78	81
	Contoured & terraced w/ residue	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation	Straight row	Poor	66	77	85	89
		Good	58	72	81	85
	Contoured	Poor	64	75	83	85
		Good	55	69	78	83
	Contoured & terraced	Poor	63	73	80	83
		Good	51	67	76	80

Table 6-2: Runoff curve numbers for other agricultural lands (from SCS Engineering Division, 1986)

Cover		Hydrologic Soil Group			
Cover Type	**Hydrologic condition**	**A**	**B**	**C**	**D**
Pasture, grassland, or range—continuous forage for grazing[1]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay	- - - -	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element[2]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30	48	65	73
Woods—grass combination (orchard or tree farm)	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods[3]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	- - - -	59	74	82	86

Table 6-3: Runoff curve numbers for urban areas (from SCS Engineering Divison, 1986)

Cover			Hydrologic Soil Group			
Cover Type	**Hydrologic condition**	**Average % impervious area**	**A**	**B**	**C**	**D**
Fully developed urban areas						
Open spaces (lawns, parks, golf courses, cemeteries, etc.)[†]	Poor		68	79	86	89
	Fair		49	69	79	84
	Good		39	61	74	80
Impervious areas:						
Paved parking lots, roofs, driveways, etc. (excl. right-of-way)	- - - -		98	98	98	98
Paved streets and roads; open ditches (incl. right-of-way)	- - - -		83	89	92	93
Gravel streets and roads (including right-of-way)	- - - -		76	85	89	91
Dirt streets and roads (including right-of way)	- - - -		72	82	87	89

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[1] *Poor:* < 50% ground cover or heavily grazed with no mulch; *Fair:* 50 to 75% ground cover and not heavily grazed; *Good*: > 75% ground cover and lightly or only occasionally grazed

[2] *Poor:* < 50% ground cover; *Fair:* 50 to 75% ground cover; Good: > 75% ground cover

[3] *Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning; *Fair:* Woods are grazed but not burned, and some forest litter covers the soil; *Good:* Woods are protected from grazing, and litter and brush adequately cover the soil.

[§] SWAT will automatically adjust curve numbers for impervious areas when IURBAN and URBLU are defined in the .hru file. Curve numbers from Table 6-3 should ***not*** be used in this instance.

[†] *Poor:* grass cover < 50%; *Fair:* grass cover 50 to 75%; *Good:* grass cover > 75%

Table 6-3, continued: Runoff curve number for urban areas

Cover			**Hydrologic Soil Group**			
Cover Type	**Hydrologic condition**	**Average % impervious area**	**A**	**B**	**C**	**D**
Urban districts:						
Commercial and business		85%	89	92	94	95
Industrial		72%	81	88	91	93
Residential Districts by average lot size:						
1/8 acre (0.05 ha) or less (town houses)		65%	77	85	90	92
1/4 acre (0.10 ha)		38%	61	75	83	87
1/3 acre (0.13 ha)		30%	57	72	81	86
1/2 acre (0.20 ha)		25%	54	70	80	85
1 acre (0.40 ha)		20%	51	68	79	84
2 acres (0.81 ha)		12%	46	65	77	82
Developing urban areas:						
Newly graded areas (pervious areas only, no vegetation)			77	86	91	94

6.1.1.1 SOIL HYDROLOGIC GROUPS

The U.S. Natural Resource Conservation Service (NRCS) classifies soils into four hydrologic groups based on infiltration characteristics of the soils. NRCS Soil Survey Staff (1996) defines a hydrologic group as a group of soils having similar runoff potential under similar storm and cover conditions. Soil properties that influence runoff potential are those that impact the minimum rate of infiltration for a bare soil after prolonged wetting and when not frozen. These properties are depth to seasonally high water table, saturated hydraulic conductivity, and depth to a very slowly permeable layer. Soil may be placed in one of four groups, A, B, C, and D, or three dual classes, A/D, B/D, and C/D. Definitions of the classes are:

A: (Low runoff potential). The soils have a high infiltration rate even when thoroughly wetted. They chiefly consist of deep, well drained to excessively drained sands or gravels. They have a high rate of water transmission.

B: The soils have a moderate infiltration rate when thoroughly wetted. They chiefly are moderately deep to deep, moderately well-drained to well-drained soils that have moderately fine to moderately coarse textures. They have a moderate rate of water transmission.

C: The soils have a slow infiltration rate when thoroughly wetted. They chiefly have a layer that impedes downward movement of water or have moderately fine to fine texture. They have a slow rate of water transmission.

D. (High runoff potential). The soils have a very slow infiltration rate when thoroughly wetted. They chiefly consist of clay soils that have a high swelling potential, soils that have a permanent water table, soils that have a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. They have a very slow rate of water transmission.

Dual hydrologic groups are given for certain wet soils that can be adequately drained. The first letter applies to the drained condition, the second to the undrained. Only soils that are rated D in their natural condition are assigned to dual classes. A summary of U.S. soils and their hydrologic group is given in Appendix D.

6.1.1.2 ANTECEDENT SOIL MOISTURE CONDITION

SCS defines three antecedent moisture conditions: I—dry (wilting point), II—average moisture, and III—wet (field capacity). The moisture condition I curve number is the lowest value the daily curve number can assume in dry conditions. The curve numbers for moisture conditions I and III are calculated with the equations:

$$CN_1 = CN_2 - \frac{20 \cdot (100 - CN_2)}{(100 - CN_2 + \exp[2.533 - 0.0636 \cdot (100 - CN_2)])} \qquad 6.1.4$$

$$CN_3 = CN_2 \cdot \exp[0.00673 \cdot (100 - CN_2)] \qquad 6.1.5$$

where CN_1 is the moisture condition I curve number, CN_2 is the moisture condition II curve number, and CN_3 is the moisture condition III curve number.

The retention parameter varies with soil profile water content according to the following equation:

$$S = S_{\max} \cdot \left(1 - \frac{SW}{[SW + \exp(w_1 - w_2 \cdot SW)]}\right) \qquad 6.1.6$$

where S is the retention parameter for a given moisture content (mm), S_{max} is the maximum value the retention parameter can achieve on any given day (mm), SW is the soil water content of the entire profile excluding the amount of water held in the profile at wilting point (mm H_2O), and w_1 and

w_2 are shape coefficients. The maximum retention parameter value, S_{max}, is calculated by solving equation 6.1.2 using CN_1.

The shape coefficients are determined by solving equation 6.1.6 assuming that

1) the retention parameter for moisture condition I curve number corresponds to wilting point soil profile water content,
2) the retention parameter for moisture condition III curve number corresponds to field capacity soil profile water content, and
3) the soil has a curve number of 99 (S = 2.54) when completely saturated.

$$w_1 = \ln\left[\frac{FC}{1 - S_3 \cdot S_{\max}{}^{-1}} - FC\right] + w_2 \cdot FC \qquad 6.1.7$$

$$w_2 = \frac{\left(\ln\left[\frac{FC}{1 - S_3 \cdot S_{\max}{}^{-1}} - FC\right] - \ln\left[\frac{SAT}{1 - 2.54 \cdot S_{\max}{}^{-1}} - SAT\right]\right)}{(SAT - FC)} \qquad 6.1.8$$

where w_1 is the first shape coefficient, w_2 is the second shape coefficient, FC is the amount of water in the soil profile at field capacity (mm H_2O), S_3 is the retention parameter for the moisture condition III curve number, S_{max} is the retention parameter for the moisture condition I curve number, SAT is the amount of water in the soil profile when completely saturated (mm H_2O), and 2.54 is the retention parameter value for a curve number of 99.

When the top layer of the soil is frozen, the retention parameter is modified using the following equation:

$$S_{frz} = S_{\max} \cdot [1 - \exp(-0.000862 \cdot S)] \qquad 6.1.9$$

where S_{frz} is the retention parameter adjusted for frozen conditions (mm), S_{max} is the maximum value the retention parameter can achieve on any given day (mm), and S is the retention parameter for a given moisture content calculated with equation 6.1.6 (mm).

The daily curve number value adjusted for moisture content is calculated by rearranging equation 6.1.2 and inserting the retention parameter calculated for that moisture content:

$$CN = \frac{25400}{\left(S + 254\right)} \qquad 6.1.10$$

where CN is the curve number on a given day and S is the retention parameter calculated for the moisture content of the soil on that day.

6.1.1.3 SLOPE ADJUSTMENTS

The moisture condition II curve numbers provided in the tables are assumed to be appropriate for 5% slopes. Williams (1995) developed an equation to adjust the curve number to a different slope:

$$CN_{2s} = \frac{\left(CN_3 - CN_2\right)}{3} \cdot \left[1 - 2 \cdot \exp\left(-13.86 \cdot slp\right)\right] + CN_2 \qquad 6.1.11$$

where CN_{2s} is the moisture condition II curve number adjusted for slope, CN_3 is the moisture condition III curve number for the default 5% slope, CN_2 is the moisture condition II curve number for the default 5% slope, and slp is the average percent slope of the subbasin. SWAT does not adjust curve numbers for slope. If the user wishes to adjust the curve numbers for slope effects, the adjustment must be done prior to entering the curve numbers in the management input file.

Table 6-1: SWAT input variables that pertain to surface runoff calculated with the SCS curve number method.

Variable Name	Definition	Input File
IEVENT	Rainfall, runoff, routing option.	.cod
PRECIPITATION	R_{day}: Daily precipitation (mm H_2O)	.pcp
CN2	CN_2: Moisture condition II curve number	.mgt
CNOP	CN_2: Moisture condition II curve number	.mgt

6.2 RUNOFF VOLUME: GREEN & AMPT INFILTRATION METHOD

The Green & Ampt equation was developed to predict infiltration assuming excess water at the surface at all times (Green & Ampt, 1911). The equation assumes that the soil profile is homogenous and antecedent moisture is uniformly distributed in the profile. As water infiltrates into the soil, the model assumes the soil above the wetting front is completely saturated and there is a sharp break in moisture content at the wetting front. Figure 6-2 graphically illustrates the difference between the moisture distribution with depth modeled by the Green & Ampt equation and what occurs in reality.

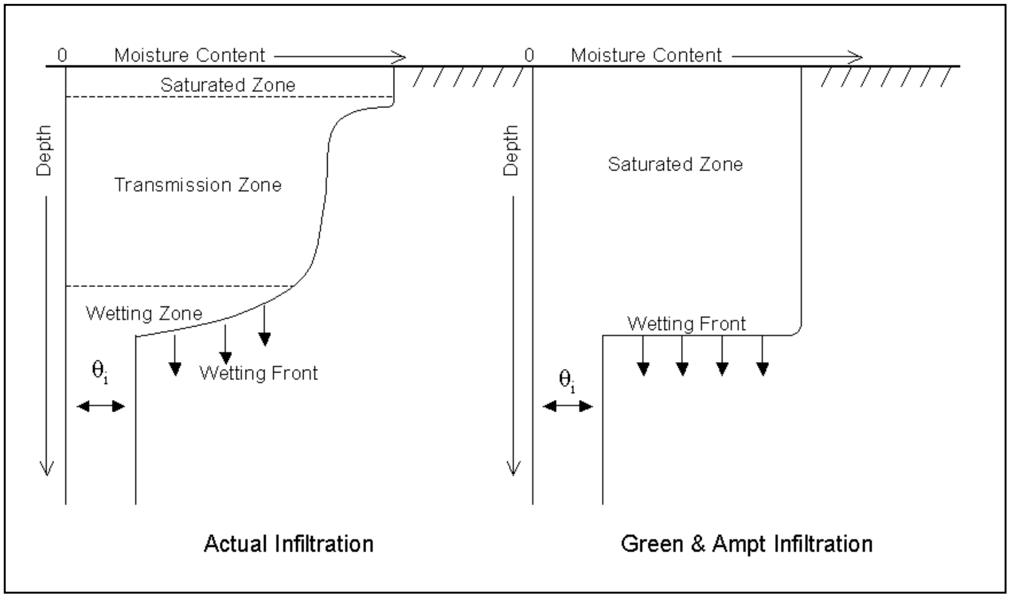

Figure 6-2: Comparison of moisture content distribution modeled by Green & Ampt and a typical observed distribution.

Mein and Larson (1973) developed a methodology for determining ponding time with infiltration using the Green & Ampt equation. The Green-Ampt Mein-Larson excess rainfall method was incorporated into SWAT to provide an alternative option for determining surface runoff. This method requires sub-daily precipitation data supplied by the user.

The Green-Ampt Mein-Larson infiltration rate is defined as:

$$f_{inf,t} = K_e \cdot \left(1 + \frac{\Psi_{wf} \cdot \Delta\theta_v}{F_{inf,t}} \right) \qquad 6.2.1$$

where f_{inf} is the infiltration rate at time t (mm/hr), K_e is the effective hydraulic conductivity (mm/hr), Ψ_{wf} is the wetting front matric potential (mm), $\Delta\theta_v$ is the change in volumetric moisture content across the wetting front (mm/mm) and F_{inf} is the cumulative infiltration at time t (mm H_2O).

When the rainfall intensity is less than the infiltration rate, all the rainfall will infiltrate during the time period and the cumulative infiltration for that time period is calculated:

$$F_{inf,t} = F_{inf,t-1} + R_{\Delta t} \qquad 6.2.2$$

where and $F_{inf,t}$ is the cumulative infiltration for a given time step (mm H_2O), $F_{inf,t-1}$ is the cumulative infiltration for the previous time step (mm H_2O), and $R_{\Delta t}$ is the amount of rain falling during the time step (mm H_2O).

The infiltration rate defined by equation 6.2.1 is a function of the infiltrated volume, which in turn is a function of the infiltration rates in previous time steps. To avoid numerical errors over long time steps, f_{inf} is replaced by dF_{inf}/dt in equation 6.2.1 and integrated to obtain

$$F_{inf,t} = F_{inf,t-1} + K_e \cdot \Delta t + \Psi_{wf} \cdot \Delta\theta_v \cdot \ln\left[\frac{F_{inf,t} + \Psi_{wf} \cdot \Delta\theta_v}{F_{inf,t-1} + \Psi_{wf} \cdot \Delta\theta_v}\right] \qquad 6.2.3$$

Equation 6.2.3 must be solved iteratively for $F_{inf,t}$, the cumulative infiltration at the end of the time step. A successive substitution technique is used.

The Green-Ampt effective hydraulic conductivity parameter, K_e, is approximately equivalent to one-half the saturated hydraulic conductivity of the soil, K_{sat} (Bouwer, 1969). Nearing et al. (1996) developed an equation to calculate the effective hydraulic conductivity as a function of saturated hydraulic conductivity and curve number. This equation incorporates land cover impacts into the calculated effective hydraulic conductivity. The equation for effective hydraulic conductivity is:

$$K_e = \frac{56.82 \cdot K_{sat}^{\ 0.286}}{1 + 0.051 \cdot \exp(0.062 \cdot CN)} - 2 \qquad 6.2.4$$

where K_e is the effective hydraulic conductivity (mm/hr), K_{sat} is the saturated hydraulic conductivity (mm/hr), and CN is the curve number.

Wetting front matric potential, Ψ_{wf}, is calculated as a function of porosity, percent sand and percent clay (Rawls and Brakensiek, 1985):

$$\Psi_{wf} = 10 \cdot \exp\left[6.5309 - 7.32561 \cdot \phi_{soil} + 0.001583 \cdot m_c^{\ 2} + 3.809479 \cdot \phi_{soil}^{\ 2} + 0.000344 \cdot m_s \cdot m_c - 0.049837 \cdot m_s \cdot \phi_{soil} + 0.001608 \cdot m_s^{\ 2} \cdot \phi_{soil}^{\ 2} + 0.001602 \cdot m_c^{\ 2} \cdot \phi_{soil}^{\ 2} - 0.0000136 \cdot m_s^{\ 2} \cdot m_c - 0.003479 \cdot m_c^{\ 2} \cdot \phi_{soil} - 0.000799 \cdot m_s^{\ 2} \cdot \phi_{soil}\right] \qquad 6.2.5$$

where ϕ_{soil} is the porosity of the soil (mm/mm), m_c is the percent clay content, and m_s is the percent sand content.

For each time step, SWAT calculates the amount of water entering the soil. The water that does not infiltrate into the soil becomes surface runoff.

Table 6-2: SWAT input variables that pertain to Green & Ampt infiltration calculations.

Variable Name	Definition	Input File
IEVENT	Rainfall, runoff, routing option.	.cod
IDT	Length of time step (min): Δt=IDT/60	.cod
PRECIPITATION	$R_{\Delta t}$: Precipitation during time step (mm H_2O)	.pcp
SOL_K	K_{sat}: Saturated hydraulic conductivity of first layer (mm/hr)	.sol
CN2	CN: Moisture condition II curve number	.mgt
CNOP	CN: Moisture condition II curve number	.mgt
SOL_BD	ρ_b: Moist bulk density (Mg/m^3): ϕ_{soil}=1 - ρ_b / 2.65	.sol
CLAY	m_c: % clay content	.sol
SAND	m_s: % sand content	.sol

6.3 PEAK RUNOFF RATE

The peak runoff rate is the maximum runoff flow rate that occurs with a given rainfall event. The peak runoff rate is an indicator of the erosive power of a storm and is used to predict sediment loss. SWAT calculates the peak runoff rate with a modified rational method.

The rational method is widely used in the design of ditches, channels and storm water control systems. The rational method is based on the assumption that if a rainfall of intensity i begins at time $t = 0$ and continues indefinitely, the rate of runoff will increase until the time of concentration, $t = t_{conc}$, when the entire subbasin area[*] is contributing to flow at the outlet. The rational formula is:

$$q_{peak} = \frac{C \cdot i \cdot Area}{3.6} \qquad 6.3.1$$

where q_{peak} is the peak runoff rate (m^3 s^{-1}), C is the runoff coefficient, i is the rainfall intensity (mm/hr), $Area$ is the subbasin area (km^2) and 3.6 is a unit conversion factor.

6.3.1 TIME OF CONCENTRATION

The time of concentration is the amount of time from the beginning of a rainfall event until the entire subbasin area is contributing to flow at the outlet. In other words, the time of concentration is the time for a drop of water to flow from the remotest point in the subbasin to the subbasin outlet. The time of concentration is calculated by summing the overland flow time (the time it takes for flow from the remotest point in the subbasin to reach the channel) and the channel flow time (the time it takes for flow in the upstream channels to reach the outlet):

$$t_{conc} = t_{ov} + t_{ch} \qquad 6.3.2$$

where t_{conc} is the time of concentration for a subbasin (hr), t_{ov} is the time of concentration for overland flow (hr), and t_{ch} is the time of concentration for channel flow (hr).

6.3.1.1 OVERLAND FLOW TIME OF CONCENTRATION

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

$$t_{ov} = \frac{L_{slp}}{3600 \cdot v_{ov}} \qquad 6.3.3$$

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[*] The equations in section 6.3 use the subbasin area rather than the HRU area. Unlike HRUs, subbasins are geographically contiguous areas. Using the subbasin area makes the equations for time of concentration and peak runoff rate easier to conceptualize.

In the model, these calculations are performed at the HRU level. Two modifications are made to adapt the equations to HRUs. First, the area of the subbasin is replaced by the area of the HRU. Second, the channel length term, L, used in the channel flow time of concentration calculation is multiplied by the fraction of the subbasin area with the HRU of interest.

where L_{slp} is the subbasin slope length (m), v_{ov} is the overland flow velocity (m s^{-1}) and 3600 is a unit conversion factor.

The overland flow velocity can be estimated from Manning's equation by considering a strip 1 meter wide down the sloping surface:

$$v_{ov} = \frac{q_{ov}{}^{0.4} \cdot slp^{0.3}}{n^{0.6}} \qquad 6.3.4$$

where q_{ov} is the average overland flow rate (m^3 s^{-1}), slp is the average slope in the subbasin (m m^{-1}), and n is Manning's roughness coefficient for the subbasin. Assuming an average flow rate of 6.35 mm/hr and converting units

$$v_{ov} = \frac{0.005 \cdot L_{slp}{}^{0.4} \cdot slp^{0.3}}{n^{0.6}} \qquad 6.3.5$$

Substituting equation 6.3.5 into equation 6.3.3 gives

$$t_{ov} = \frac{L_{slp}{}^{0.6} \cdot n^{0.6}}{18 \cdot slp^{0.3}} \qquad 6.3.6$$

Table 6-3: Values of Manning's roughness coefficient, *n*, for overland flow (Engman, 1983).

Characteristics of Land Surface	**Median**	**Range**
Fallow, no residue	0.010	0.008-0.012
Conventional tillage, no residue	0.090	0.060-0.120
Conventional tillage, residue	0.190	0.160-0.220
Chisel plow, no residue	0.090	0.060-0.120
Chisel plow, residue	0.130	0.100-0.160
Fall disking, residue	0.400	0.300-0.500
No till, no residue	0.070	0.040-0.100
No till, 0.5-1 t/ha residue	0.120	0.070-0.170
No till, 2-9 t/ha residue	0.300	0.170-0.470
Rangeland, 20% cover	0.600	
Short grass prairie	0.150	0.100-0.200
Dense grass	0.240	0.170-0.300
Bermudagrass	0.410	0.300-0.480

6.3.1.2 CHANNEL FLOW TIME OF CONCENTRATION

The channel flow time of concentration, t_{ch}, can be computed using the equation:

$$t_{ch} = \frac{L_c}{3.6 \cdot v_c} \qquad 6.3.7$$

where L_c is the average flow channel length for the subbasin (km), v_c is the average channel velocity (m s^{-1}), and 3.6 is a unit conversion factor.

The average channel flow length can be estimated using the equation

$$L_c = \sqrt{L \cdot L_{cen}} \qquad 6.3.8$$

where L is the channel length from the most distant point to the subbasin outlet (km), and L_{cen} is the distance along the channel to the subbasin centroid (km). Assuming $L_{cen} = 0.5 \cdot L$, the average channel flow length is

$$L_c = 0.71 \cdot L \qquad 6.3.9$$

The average velocity can be estimated from Manning's equation assuming a trapezoidal channel with 2:1 side slopes and a 10:1 bottom width-depth ratio.

$$v_c = \frac{0.489 \cdot q_{ch}^{\ 0.25} \cdot slp_{ch}^{\ 0.375}}{n^{0.75}} \qquad 6.3.10$$

where v_c is the average channel velocity (m s^{-1}), q_{ch} is the average channel flow rate (m^3 s^{-1}), slp_{ch} is the channel slope (m m^{-1}), and n is Manning's roughness coefficient for the channel. To express the average channel flow rate in units of mm/hr, the following expression is used

$$q_{ch} = \frac{q_{ch}^{*} \cdot Area}{3.6} \qquad 6.3.11$$

where q_{ch}^{*} is the average channel flow rate (mm hr^{-1}), $Area$ is the subbasin area (km^2), and 3.6 is a unit conversion factor. The average channel flow rate is related to the unit source area flow rate (unit source area = 1 ha)

$$q_{ch}^{*} = q_0^{*} \cdot \left(100 \cdot Area\right)^{-0.5} \qquad 6.3.12$$

where q_0^{*} is the unit source area flow rate (mm hr^{-1}), $Area$ is the subbasin area (km^2), and 100 is a unit conversion factor. Assuming the unit source area flow rate is 6.35 mm/hr and substituting equations 6.3.11 and 6.3.12 into 6.3.10 gives

$$v_c = \frac{0.317 \cdot Area^{0.125} \cdot slp_{ch}^{\ 0.375}}{n^{0.75}} \qquad 6.3.13$$

Substituting equations 6.3.9 and 6.3.13 into 6.3.7 gives

$$t_{ch} = \frac{0.62 \cdot L \cdot n^{0.75}}{Area^{0.125} \cdot slp_{ch}^{0.375}} \qquad 6.3.14$$

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 Manning's roughness coefficient for the channel, $Area$ is the subbasin area (km^2), and slp_{ch} is the channel slope (m m^{-1}).

Table 6-4: Values of Manning's roughness coefficient, n, for channel flow (Chow, 1959).[1]

Characteristics of Channel	Median	Range
Excavated or dredged		
Earth, straight and uniform	0.025	0.016-0.033
Earth, winding and sluggish	0.035	0.023-0.050
Not maintained, weeds and brush	0.075	0.040-0.140
Natural streams		
Few trees, stones or brush	0.050	0.025-0.065
Heavy timber and brush	0.100	0.050-0.150

[1] Chow (1959) has a very extensive list of Manning's roughness coefficients. These values represent only a small portion of those he lists in his book.

Although some of the assumptions used in developing equations 6.3.6 and 6.3.14 may appear liberal, the time of concentration values obtained generally give satisfactory results for homogeneous subbasins. Since equations 6.3.6 and 6.3.14 are based on hydraulic considerations, they are more reliable than purely empirical equations.

6.3.2 RUNOFF COEFFICIENT

The runoff coefficient is the ratio of the inflow rate, $i \cdot Area$, to the peak discharge rate, q_{peak}. The coefficient will vary from storm to storm and is calculated with the equation:

$$C = \frac{Q_{surf}}{R_{day}} \qquad 6.3.15$$

where Q_{surf} is the surface runoff (mm H_2O) and R_{day} is the rainfall for the day (mm H_2O).

6.3.3 RAINFALL INTENSITY

The rainfall intensity is the average rainfall rate during the time of concentration. Based on this definition, it can be calculated with the equation:

$$i = \frac{R_{tc}}{t_{conc}} \qquad 6.3.16$$

where i is the rainfall intensity (mm/hr), R_{tc} is the amount of rain falling during the time of concentration (mm H_2O), and t_{conc} is the time of concentration for the subbasin (hr).

An analysis of rainfall data collected by Hershfield (1961) for different durations and frequencies showed that the amount of rain falling during the time of concentration was proportional to the amount of rain falling during the 24-hr period.

$$R_{tc} = \alpha_{tc} \cdot R_{day} \qquad 6.3.17$$

where R_{tc} is the amount of rain falling during the time of concentration (mm H_2O), α_{tc} is the fraction of daily rainfall that occurs during the time of concentration, and R_{day} is the amount of rain falling during the day (mm H_2O).

For short duration storms, all or most of the rain will fall during the time of concentration, causing α_{tc} to approach its upper limit of 1.0. The minimum value of α_{tc} would be seen in storms of uniform intensity ($i_{24} = i$). This minimum value can be defined by substituting the products of time and rainfall intensity into equation 6.3.17

$$\alpha_{tc,\min} = \frac{R_{tc}}{R_{day}} = \frac{i \cdot t_{conc}}{i_{24} \cdot 24} = \frac{t_{conc}}{24} \qquad 6.3.18$$

Thus, α_{tc} falls in the range $t_{conc}/24 \leq \alpha_{tc} \leq 1.0$.

SWAT estimates the fraction of rain falling in the time of concentration as a function of the fraction of daily rain falling in the half-hour of highest intensity rainfall.

$$\alpha_{tc} = 1 - \exp\left[2 \cdot t_{conc} \cdot \ln\left(1 - \alpha_{0.5}\right)\right] \qquad 6.3.19$$

where $\alpha_{0.5}$ is the fraction of daily rain falling in the half-hour highest intensity rainfall, and t_{conc} is the time of concentration for the subbasin (hr). The determination of a value for $\alpha_{0.5}$ is discussed in Chapters 3 and 4.

6.3.4 MODIFIED RATIONAL FORMULA

The modified rational formula used to estimate peak flow rate is obtained by substituting equations 6.3.15, 6.3.16, and 6.3.17 into equation 6.3.1

$$q_{peak} = \frac{\alpha_{tc} \cdot Q_{surf} \cdot Area}{3.6 \cdot t_{conc}} \qquad 6.3.20$$

where q_{peak} is the peak runoff rate (m^3 s^{-1}), α_{tc} is the fraction of daily rainfall that occurs during the time of concentration, Q_{surf} is the surface runoff (mm H_2O), $Area$ is the subbasin area (km^2), t_{conc} is the time of concentration for the subbasin (hr) and 3.6 is a unit conversion factor.

Table 6-5: SWAT input variables that pertain to peak rate calculations.

Variable Name	Definition	Input File
DA_KM	Area of the watershed (km^2)	.bsn
HRU_FR	Fraction of total watershed area contained in HRU	.hru
SLSUBBSN	L_{slp}: Average slope length (m)	.hru
SLOPE	slp: Average slope steepness (m/m)	.hru
OV_N	n: Manning's "n" value for overland flow	.hru
CH_L(1)	L: Longest tributary channel length in subbasin (km)	.sub
CH_S(1)	slp_{ch}: Average slope of tributary channels (m/m)	.sub
CH_N(1)	n: Manning's "n" value for tributary channels	.sub

6.4 SURFACE RUNOFF LAG

In large subbasins with a time of concentration greater than 1 day, only a portion of the surface runoff will reach the main channel on the day it is generated. SWAT incorporates a surface runoff storage feature to lag a portion of the surface runoff release to the main channel.

Once surface runoff is calculated with the curve number or Green & Ampt method, the amount of surface runoff released to the main channel is calculated:

$$Q_{surf} = \left(Q'_{surf} + Q_{stor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 6.4.1$$

where Q_{surf} is the amount of surface runoff discharged to the main channel on a given day (mm H_2O), Q'_{surf} is the amount of surface runoff generated in the subbasin on a given day (mm H_2O), $Q_{stor,i-1}$ is the surface runoff stored or lagged from the previous day (mm H_2O), $surlag$ is the surface runoff lag coefficient, and t_{conc} is the time of concentration for the subbasin (hrs).

The expression $\left(1-\exp\left[\frac{-surlag}{t_{conc}}\right]\right)$ in equation 6.4.1 represents the fraction of the total available water that will be allowed to enter the reach on any one day. Figure 6-3 plots values for this expression at different values for $surlag$ and t_{conc}.

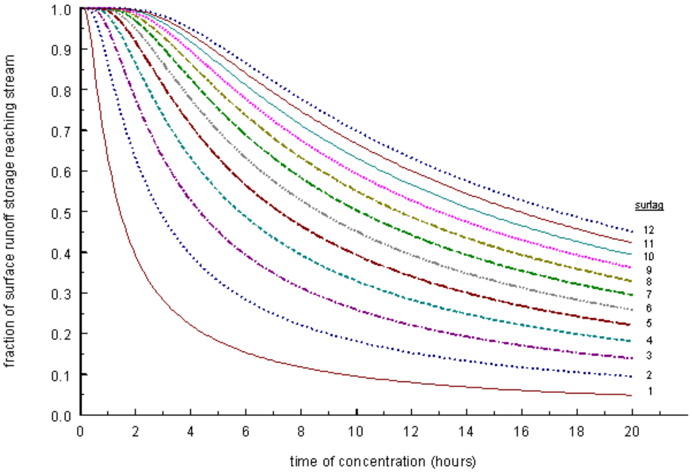

Figure 6-3: Influence of $surlag$ and t_{conc} on fraction of surface runoff released.

Note that for a given time of concentration, as $surlag$ decreases in value more water is held in storage. The delay in release of surface runoff will smooth the streamflow hydrograph simulated in the reach.

Table 6-6: SWAT input variables that pertain to surface runoff lag calculations.

Variable Name	Definition	Input File
SURLAG	*surlag*: surface runoff lag coefficient	.bsn

6.5 TRANSMISSION LOSSES

Many semiarid and arid watersheds have ephemeral channels that abstract large quantities of streamflow (Lane, 1982). The abstractions, or transmission losses, reduce runoff volume as the flood wave travels downstream. Chapter 19 of the SCS Hydrology Handbook (Lane, 1983) describes a procedure for estimating transmission losses for ephemeral streams which has been incorporated into

SWAT. This method was developed to estimate transmission losses in the absence of observed inflow-outflow data and assumes no lateral inflow or out-of-bank flow contributions to runoff.

The prediction equation for runoff volume after transmission losses is

$$vol_{Qsurf,f} = \begin{cases} 0 & vol_{Qsurf,i} \le vol_{thr} \\ a_x + b_x \cdot vol_{Qsurf,i} & vol_{Qsurf,i} > vol_{thr} \end{cases} \qquad 6.5.1$$

where $vol_{Qsurf,f}$ is the volume of runoff after transmission losses (m^3), a_x is the regression intercept for a channel of length L and width W (m^3), b_x is the regression slope for a channel of length L and width W, $vol_{Qsurf,i}$ is the volume of runoff prior to transmission losses (m^3), and vol_{thr} is the threshold volume for a channel of length L and width W (m^3). The threshold volume is

$$vol_{thr} = -\frac{a_x}{b_x} \qquad 6.5.2$$

The corresponding equation for peak runoff rate is

$$q_{peak,f} = \frac{1}{\left(3600 \cdot dur_{flw}\right)} \cdot \left[a_x - \left(1 - b_x\right) \cdot vol_{Qsurf,i}\right] + b_x \cdot q_{peak,i} \qquad 6.5.3$$

where $q_{peak,f}$ is the peak rate after transmission losses (m^3/s), dur_{flw} is the duration of flow (hr), a_x is the regression intercept for a channel of length L and width W (m^3), b_x is the regression slope for a channel of length L and width W, $vol_{Qsurf,i}$ is the volume of runoff prior to transmission losses (m^3), $q_{peak,i}$ is the peak rate before accounting for transmission losses (m^3/s). The duration of flow is calculated with the equation:

$$dur_{flw} = \frac{Q_{surf} \cdot Area}{3.6 \cdot q_{peak}} \qquad 6.5.4$$

where dur_{flw} is the duration of runoff flow (hr), Q_{surf} is the surface runoff (mm H_2O), $Area$ is the area of the subbasin (km^2), q_{peak} is the peak runoff rate (m^3/s), and 3.6 is a conversion factor.

In order to calculate the regression parameters for channels of differing lengths and widths, the parameters of a unit channel are needed. A unit channel is defined as a channel of length L = 1 km and width W = 1 m. The unit channel parameters are calculated with the equations:

$$k_r = -2.22 \cdot \ln\left[1 - 2.6466 \cdot \frac{K_{ch} \cdot dur_{flw}}{vol_{Qsurf,i}}\right] \qquad 6.5.5$$

$$a_r = -0.2258 \cdot K_{ch} \cdot dur_{flw} \qquad 6.5.6$$

$$b_r = \exp\left[-0.4905 \cdot k_r\right] \qquad 6.5.7$$

where k_r is the decay factor (m^{-1} km^{-1}), a_r is the unit channel regression intercept (m^3), b_r is the unit channel regression slope, K_{ch} is the effective hydraulic conductivity of the channel alluvium (mm/hr), dur_{flw} is the duration of runoff flow (hr), and $vol_{Qsurf,i}$ is the initial volume of runoff (m^3). The regression parameters are

$$b_x = \exp\left[-k_r \cdot L \cdot W\right] \qquad 6.5.8$$

$$a_x = \frac{a_r}{(1 - b_r)} \cdot (1 - b_x) \qquad 6.5.9$$

where a_x is the regression intercept for a channel of length L and width W (m^3), b_x is the regression slope for a channel of length L and width W, k_r is the decay factor (m^{-1} km^{-1}), L is the channel length from the most distant point to the subbasin outlet (km), W is the average width of flow, i.e. channel width (m) a_r is the unit channel regression intercept (m^3), and b_r is the unit channel regression slope.

Transmission losses from surface runoff are assumed to percolate into the shallow aquifer.

Table 6-7: SWAT input variables that pertain to transmission loss calculations.

Variable Name	Definition	Input File
DA_KM	Area of the watershed (km^2)	.bsn
HRU_FR	Fraction of total watershed area contained in HRU	.hru
CH_K(1)	K_{ch}: effective hydraulic conductivity (mm/hr)	.sub
CH_W(1)	W: average width of tributary channel (m)	.sub
CH_L(1)	L: Longest tributary channel length in subbasin (km)	.sub

6.6 NOMENCLATURE

$Area$	Subbasin area (km^2)
C	Runoff coefficient in peak runoff rate calculation
CN	Curve number
CN_1	Moisture condition I curve number
CN_2	Moisture condition II curve number
CN_{2s}	Moisture condition II curve number adjusted for slope
CN_3	Moisture condition III curve number
F_{inf}	Cumulative infiltration at time t (mm H_2O)
FC	Water content of soil profile at field capacity (mm H_2O)
I_a	Initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm H_2O)
K_{ch}	Effective hydraulic conductivity of the channel alluvium (mm/hr)
K_e	Effective hydraulic conductivity (mm/hr)
K_{sat}	Saturated hydraulic conductivity (mm/hr)
L	Channel length from the most distant point to the subbasin outlet (km)
L_c	Average flow channel length for the subbasin (km)
L_{cen}	Distance along the channel to the subbasin centroid (km)
L_{slp}	Subbasin slope length (m)
Q_{stor}	Surface runoff stored or lagged (mm H_2O)
Q_{surf}	Accumulated runoff or rainfall excess (mm H_2O)
$R_{\Delta t}$	Amount of rain falling during the time step (mm H_2O)
R_{day}	Amount of rainfall on a given day (mm H_2O)
R_{tc}	Amount of rain falling during the time of concentration (mm H_2O)
S	Retention parameter in SCS curve number equation (mm)
S_3	Retention parameter for the moisture condition III curve number
S_{frz}	Retention parameter adjusted for frozen conditions (mm)
S_{max}	Maximum value the retention parameter can achieve on any given day (mm)
SAT	Amount of water in the soil profile when completely saturated (mm H_2O),
SW	Amount of water in soil profile (mm H_2O)
W	Average width of flow, i.e. channel width (m)

a_r	Unit channel regression intercept (m^3)
a_x	Regression intercept for a channel of length L and width W (m^3)
b_r	Unit channel regression slope
b_x	Regression slope for a channel of length L and width W
dur_{flw}	Duration of flow (hr)
f_{inf}	Infiltration rate (mm/hr)
i	Rainfall intensity (mm/hr)
k_r	Decay factor (m^{-1} km^{-1})
m_c	Percent clay content
m_s	Percent sand content
n	Manning's roughness coefficient for the subbasin or channel
q_0^*	Unit source area flow rate (mm hr^{-1})

q_{ch}	Average channel flow rate (m^3 s^{-1})
q^*_{ch}	Average channel flow rate (mm hr^{-1})
q_{ov}	Average overland flow rate (m^3 s^{-1})
q_{peak}	Peak runoff rate (m^3/s)
$q_{peak,f}$	Peak rate after transmission losses (m^3/s)
$q_{peak,i}$	Peak rate before accounting for transmission losses (m^3/s)
slp	Average slope of the subbasin (% or m/m)
slp_{ch}	Average channel slope (m m^{-1})
$surlag$	Surface runoff lag coefficient
t_{ch}	Time of concentration for channel flow (hr)
t_{conc}	Time of concentration for a subbasin (hr)
t_{ov}	Time of concentration for overland flow (hr)
v_c	Average channel velocity (m s^{-1})
v_{ov}	Overland flow velocity (m s^{-1})
$vol_{Qsurf,f}$	Volume of runoff after transmission losses (m^3)
$vol_{Qsurf,i}$	Volume of runoff prior to transmission losses (m^3)
vol_{thr}	Threshold volume for a channel of length L and width W (m^3)
w_1	Shape coefficient in retention parameter adjustments for soil moisture content
w_2	Shape coefficient in retention parameter adjustments for soil moisture content

$\alpha_{0.5}$	Fraction of daily rain falling in the half-hour highest intensity rainfall,
α_{tc}	Fraction of daily rainfall that occurs during the time of concentration
ϕ_{soil}	Porosity of the soil (mm/mm)
Ψ_{wf}	Wetting front matric potential (mm)
θ_v	Volumetric moisture content (mm/mm)

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CHAPTER 7

EQUATIONS: EVAPOTRANSPIRATION

Evapotranspiration is a collective term that includes all processes by which water at the earth's surface is converted to water vapor. It includes evaporation from the plant canopy, transpiration, sublimation and evaporation from the soil.

Evapotranspiration is the primary mechanism by which water is removed from a watershed. Roughly 62% of the precipitation that falls on the continents is evapotranspired. Evapotranspiration exceeds runoff in most river basins and on all continents except Antarctica (Dingman, 1994).

The difference between precipitation and evapotranspiration is the water available for human use and management. An accurate estimation of evapotranspiration is critical in the asssessment of water resources and the impact of climate and land use change on those resources.

7.1 CANOPY STORAGE

The plant canopy can significantly affect infiltration, surface runoff and evapotranspiration. As rain falls, canopy interception reduces the erosive energy of droplets and traps a portion of the rainfall within the canopy. The influence the canopy exerts on these processes is a function of the density of plant cover and the morphology of the plant species.

When calculating surface runoff, the SCS curve number method lumps canopy interception in the term for initial abstractions. This variable also includes surface storage and infiltration prior to runoff and is estimated as 20% of the retention parameter value for a given day (see Chapter 6). When the Green and Ampt infiltration equation is used to calculate surface runoff and infiltration, the interception of rainfall by the canopy must be calculated separately.

SWAT allows the maximum amount of water that can be held in canopy storage to vary from day to day as a function of the leaf area index:

$$can_{day} = can_{mx} \cdot \frac{LAI}{LAI_{mx}} \qquad 7.1.1$$

where can_{day} is the maximum amount of water that can be trapped in the canopy on a given day (mm H_2O), can_{mx} is the maximum amount of water that can be trapped in the canopy when the canopy is fully developed (mm H_2O), LAI is the leaf area index for a given day, and LAI_{mx} is the maximum leaf area index for the plant.

When precipitation falls on any given day, the canopy storage is filled before any water is allowed to reach the ground:

$$R_{INT(f)} = R_{INT(i)} + R'_{day} \quad \text{and} \quad R_{day} = 0$$

$$\text{when } R'_{day} \leq can_{day} - R_{INT(i)} \qquad 7.1.2$$

$$R_{INT(f)} = can_{day} \text{ and } R_{day} = R'_{day} - \left(can_{day} - R_{INT(i)}\right)$$

$$\text{when } R'_{day} > can_{day} - R_{INT(i)} \qquad 7.1.3$$

where $R_{INT(i)}$ is the initial amount of free water held in the canopy on a given day (mm H_2O), $R_{INT(f)}$ is the final amount of free water held in the canopy on a given day (mm H_2O), R'_{day} is the amount of precipitation on a given day before canopy interception is removed (mm H_2O), R_{day} is the amount of precipitation on a given day that reaches the soil surface (mm H_2O), and can_{day} is the maximum amount of water that can be trapped in the canopy on a given day (mm H_2O).

Table 7-1: SWAT input variables used in canopy storage calculations.

Variable name	Definition	File Name
CANMX	can_{mx}: maximum canopy storage	.hru

7.2 POTENTIAL EVAPOTRANSPIRATION

Potential evapotranspiration (PET) was a concept originally introduced by Thornthwaite (1948) as part of a climate classification scheme. He defined PET is the rate at which evapotranspiration would occur from a large area uniformly covered with growing vegetation that has access to an unlimited supply of soil water and that was not exposed to advection or heat storage effects. Because the evapotranspiration rate is strongly influenced by a number of vegetative surface characteristics, Penman (1956) redefined PET as “the amount of water transpired ... by a short green crop, completely shading the ground, of uniform height and never short of water”. Penman used grass as his reference crop, but later researchers (Jensen, et al., 1990) have suggested that alfalfa at a height of 30 to 50 cm may be a more appropriate choice.

Numerous methods have been developed to estimate PET. Three of these methods have been incorporated into SWAT: 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 model will also read in daily PET values if the user prefers to apply a different potential evapotranspiration method.

The three PET methods included in SWAT vary in the amount of required inputs. The Penman-Monteith method requires solar radiation, air temperature, relative humidity and wind speed. The Priestley-Taylor method requires solar radiation, air temperature and relative humidity. The Hargreaves method requires air temperature only.

7.2.1 PENMAN-MONTEITH METHOD

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:

$$\lambda E = \frac{\Delta \cdot (H_{net} - G) + \rho_{air} \cdot c_p \cdot \left[e_z^o - e_z\right]/r_a}{\Delta + \gamma \cdot (1 + r_c/r_a)} \qquad 7.2.1$$

where λE is the latent heat flux density (MJ m^{-2} d^{-1}), E is the depth rate evaporation (mm d^{-1}), Δ is the slope of the saturation vapor pressure-temperature curve, de/dT (kPa ˚C^{-1}), H_{net} is the net radiation (MJ m^{-2} d^{-1}), G is the heat flux density to the ground (MJ m^{-2} d^{-1}), ρ_{air} is the air density (kg m^{-3}), c_p is the specific heat at constant pressure (MJ kg^{-1} ˚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 ˚C^{-1}), r_c is the plant canopy resistance (s m^{-1}), and r_a is the diffusion resistance of the air layer (aerodynamic resistance) (s m^{-1}).

For well-watered plants under neutral atmospheric stability and assuming logarithmic wind profiles, the Penman-Monteith equation may be written (Jensen et al., 1990):

$$\lambda E_t = \frac{\Delta \cdot (H_{net} - G) + \gamma \cdot K_1 \cdot (0.622 \cdot \lambda \cdot \rho_{air}/P) \cdot (e_z^o - e_z)/r_a}{\Delta + \gamma \cdot (1 + r_c/r_a)} \qquad 7.2.2$$

where λ is the latent heat of vaporization (MJ kg^{-1}), E_t is the maximum transpiration rate (mm d^{-1}), K_1 is a dimension coefficient needed to ensure the two terms in the numerator have the same units (for u_z in m s^{-1}, $K_1 = 8.64 \times 10^4$), and P is the atmospheric pressure (kPa).

The calculation of net radiation, H_{net}, is reviewed in Chapter 2. The calculations for the latent heat of vaporization, λ, the slope of the saturation vapor pressure-temperature curve, Δ, the psychrometric constant, γ, and the saturation and actual vapor pressure, e_z^o and e_z, are reviewed in Chapter 3. The remaining undefined terms are the soil heat flux, G, the combined term $K_1 0.622 \lambda \rho / P$, the aerodynamic resistance, r_a, and the canopy resistance, r_c.

7.2.1.1 SOIL HEAT FLUX

Soil heat storage or release can be significant over a few hours, but is usually small from day to day because heat stored as the soil warms early in the day is lost when the soil cools late in the day or at night. Since the magnitude of daily soil heat flux over a 10- to 30-day period is small when the soil is under a crop cover, it can normally be ignored for most energy balance estimates. SWAT assumes the daily soil heat flux, G, is always equal to zero.

7.2.1.2 AERODYNAMIC RESISTANCE

The aerodynamic resistance to sensible heat and vapor transfer, r_a, is calculated:

$$r_a = \frac{\ln\left[(z_w - d)/z_{om}\right]\ln\left[(z_p - d)/z_{ov}\right]}{k^2 u_z} \qquad 7.2.3$$

where z_w is the height of the wind speed measurement (cm), z_p is the height of the humidity (psychrometer) and temperature measurements (cm), d is the zero plane displacement of the wind profile (cm), z_{om} is the roughness length for momentum transfer (cm), z_{ov} is the roughness length for vapor transfer (cm), k is the von Kármán constant, and u_z is the wind speed at height z_w (m s^{-1}).

The von Kármán constant is considered to be a universal constant in turbulent flow. Its value has been calculated to be near 0.4 with a range of 0.36 to 0.43 (Jensen et al., 1990). A value of 0.41 is used by SWAT for the von Kármán constant.

Brutsaert (1975) determined that the surface roughness parameter, z_o, is related to the mean height (h_c) of the plant canopy by the relationship

$h_c/z_o = 3e$ or 8.15 where e is the natural log base. Based on this relationship, the roughness length for momentum transfer is estimated as:

$$z_{om} = h_c/8.15 = 0.123 \cdot h_c \qquad h_c \leq 200cm \qquad 7.2.4$$

$$z_{om} = 0.058 \cdot (h_c)^{1.19} \qquad h_c > 200cm \qquad 7.2.5$$

where mean height of the plant canopy (h_c) is reported in centimeters.

The roughness length for momentum transfer includes the effects of bluff-body forces. These forces have no impact on heat and vapor transfer, and the roughness length for vapor transfer is only a fraction of that for momentum transfer. To estimate the roughness length for vapor transfer, Stricker and Brutsaert (1978) recommended using:

$$z_{ov} = 0.1 \cdot z_{om} \qquad 7.2.6$$

The displacement height for a plant can be estimated using the following relationship (Monteith, 1981; Plate, 1971):

$$d = 2/3 \cdot h_c \qquad 7.2.7$$

The height of the wind speed measurement, z_w, and the height of the humidity (psychrometer) and temperature measurements, z_p, are always assumed to be 170 cm.

7.2.1.3 CANOPY RESISTANCE

Studies in canopy resistance have shown that the canopy resistance for a well-watered reference crop can be estimated by dividing the minimum surface resistance for a single leaf by one-half of the canopy leaf area index (Jensen et. al, 1990):

$$r_c = r_\ell/(0.5 \cdot LAI) \qquad 7.2.8$$

where r_c is the canopy resistance (s m^{-1}), r_ℓ is the minimum effective stomatal resistance of a single leaf (s m^{-1}), and LAI is the leaf area index of the canopy.

The distribution of stomates on a plant leaf will vary between species. Typically, stomates are distributed unequally on the top and bottom of plant leaves. Plants with stomates located on only one side are classified as hypostomatous while plants with an equal number of stomates on both sides of the leaf are termed amphistomatous. The effective leaf stomatal resistance is determined by considering the stomatal resistance of the top (adaxial) and bottom (abaxial) sides to be connected in parallel (Rosenburg, et al., 1983). When there are unequal numbers of stomates on the top and bottom, the effective stomatal resistance is calculated:

$$r_\ell = \frac{r_{\ell-ad} \cdot r_{\ell-ab}}{r_{\ell-ab} + r_{\ell-ad}} \qquad 7.2.9$$

where r_ℓ is the minimum effective stomatal resistance of a single leaf (s m^{-1}), $r_{\ell-ad}$ is the minimum adaxial stomatal leaf resistance (s m^{-1}), and $r_{\ell-ab}$ is the minimum abaxial stomatal leaf resistance (s m^{-1}). For amphistomatous leaves, the effective stomatal resistance is:

$$r_\ell = \frac{r_{\ell-ad}}{2} = \frac{r_{\ell-ab}}{2} \qquad 7.2.10$$

For hypostomatous leaves the effective stomatal resistance is:

$$r_\ell = r_{\ell-ad} = r_{\ell-ab} \qquad 7.2.11$$

Leaf conductance is defined as the inverse of the leaf resistance:

$$g_\ell = \frac{1}{r_\ell} \qquad 7.2.12$$

where g_ℓ is the maximum effective leaf conductance (m s^{-1}). When the canopy resistance is expressed as a function of leaf conductance instead of leaf resistance, equation 7.2.8 becomes:

$$r_c = \left(0.5 \cdot g_\ell \cdot LAI\right)^{-1} \qquad 7.2.13$$

where r_c is the canopy resistance (s m^{-1}), g_ℓ is the maximum conductance of a single leaf (m s^{-1}), and LAI is the leaf area index of the canopy.

For climate change simulations, the canopy resistance term can be modified to reflect the impact of change in CO_2 concentration on leaf conductance. The influence of increasing CO_2 concentrations on leaf conductance was reviewed by Morison (1987). Morison found that at CO_2 concentrations between 330 and 660 ppmv, a doubling in CO_2 concentration resulted in a 40% reduction in leaf conductance. Within the specified range, the reduction in conductance is linear (Morison and Gifford, 1983). Easterling et al. (1992) proposed the following modification to the leaf conductance term for simulating carbon dioxide concentration effects on evapotranspiration:

$$g_{\ell,CO_2} = g_\ell \cdot \left[1.4 - 0.4 \cdot \left(CO_2/330\right)\right] \qquad 7.2.14$$

where g_{ℓ,CO_2} is the leaf conductance modified to reflect CO_2 effects (m s^{-1}) and CO_2 is the concentration of carbon dioxide in the atmosphere (ppmv).

Incorporating this modification into equation 7.2.8 gives

$$r_c = r_\ell \cdot \left[\left(0.5 \cdot LAI\right) \cdot \left(1.4 - 0.4 \cdot \frac{CO_2}{330}\right)\right]^{-1} \qquad 7.2.15$$

SWAT will default the value of CO_2 concentration to 330 ppmv if no value is entered by the user. With this default, the term $\left(1.4 - 0.4 \cdot \frac{CO_2}{330}\right)$ reduces to 1.0 and the canopy resistance equation becomes equation 7.2.8.

When calculating actual evapotranspiration, the canopy resistance term is modified to reflect the impact of high vapor pressure deficit on leaf conductance (Stockle et al, 1992). For a plant species, a threshold vapor pressure deficit is defined at which the plant's leaf conductance begins to drop in response to the vapor pressure deficit. The adjusted leaf conductance is calculated:

$$g_\ell = g_{\ell,mx} \cdot \left[1 - \Delta g_{\ell,dcl}\left(vpd - vpd_{thr}\right)\right] \quad \text{if } vpd > vpd_{thr} \qquad 7.2.16$$

$$g_\ell = g_{\ell,mx} \quad \text{if } vpd \le vpd_{thr} \qquad 7.2.17$$

where g_ℓ is the conductance of a single leaf (m s^{-1}), $g_{\ell,mx}$ is the maximum conductance of a single leaf (m s^{-1}), $\Delta g_{\ell,dcl}$ is the rate of decline in leaf conductance per unit increase in vapor pressure deficit (m s^{-1} kPa^{-1}), vpd is the vapor pressure deficit (kPa), and vpd_{thr} is the threshold vapor pressure deficit above which a plant will exhibit reduced leaf conductance (kPa). The rate of decline in leaf conductance per unit increase in vapor pressure deficit is calculated by solving equation 7.2.16 using measured values for stomatal conductance at two different vapor pressure deficits:

$$\Delta g_{\ell,dcl} = \frac{\left(1 - fr_{g,mx}\right)}{\left(vpd_{fr} - vpd_{thr}\right)} \qquad 7.2.18$$

where $\Delta g_{\ell,dcl}$ is the rate of decline in leaf conductance per unit increase in vapor pressure deficit (m s^{-1} kPa^{-1}), $fr_{g,mx}$ is the fraction of the maximum stomatal conductance, $g_{\ell,mx}$, achieved at the vapor pressure deficit vpd_{fr}, and vpd_{thr} is the threshold vapor pressure deficit above which a plant will exhibit reduced leaf conductance (kPa). The threshold vapor pressure deficit is assumed to be 1.0 kPa for all plant species.

7.2.1.4 COMBINED TERM

For wind speed in m s^{-1}, Jensen et al. (1990) provided the following relationship to calculate $K_1 0.622 \lambda \rho / P$:

$$K_1 \cdot 0.622 \cdot \lambda \cdot \rho / P = 1710 - 6.85 \cdot \overline{T}_{av} \qquad 7.2.19$$

where $\overline{T}_{av}$ is the mean air temperature for the day (°C).

To calculate potential evapotranspiration, the Penman-Monteith equation must be solved for a reference crop. SWAT uses alfalfa at a height of 40 cm with a minimum leaf resistance of 100 s m^{-1} for the reference crop. Using this canopy height, the equation for aerodynamic resistance (7.2.3) simplifies to:

$$r_a = \frac{114.}{u_z} \qquad 7.2.20$$

The equation for canopy resistance requires the leaf area index. The leaf area index for the reference crop is estimated using an equation developed by Allen et al. (1989) to calculate *LAI* as a function of canopy height. For nonclipped grass and alfalfa greater than 3 cm in height:

$$LAI = 1.5 \cdot \ln(h_c) - 1.4 \qquad 7.2.21$$

where LAI is the leaf area index and h_c is the canopy height (cm). For alfalfa with a 40 cm canopy height, the leaf area index is 4.1. Using this value, the equation for canopy resistance simplifies to:

$$r_c = 49 \Big/ \left(1.4 - 0.4 \cdot \frac{CO_2}{330}\right) \qquad 7.2.22$$

The most accurate estimates of evapotranspiration with the Penman-Monteith equation are made when evapotranspiration is calculated on an hourly basis and summed to obtain the daily values. Mean daily parameter values have been shown to provide reliable estimates of daily evapotranspiration values and this is the approach used in SWAT. However, the user should be aware that calculating evapotranspiration with the Penman-Monteith equation using mean daily values can potentially lead to significant errors. These errors result from diurnal distributions of wind speed, humidity, and net radiation that in combination create conditions which the daily averages do not replicate.

7.2.2 PRIESTLEY-TAYLOR METHOD

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

$$\lambda E_o = \alpha_{pet} \cdot \frac{\Delta}{\Delta + \gamma} \cdot (H_{net} - G) \qquad 7.2.23$$

where λ is the latent heat of vaporization (MJ kg^{-1}), E_o is the potential evapotranspiration (mm d^{-1}), α_{pet} is a coefficient, Δ is the slope of the saturation vapor pressure-temperature curve, *de/dT* (kPa ˚C^{-1}), γ is the psychrometric constant (kPa ˚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.

7.2.3 HARGREAVES METHOD

The Hargreaves method was originally derived from eight years of cool-season Alta fescue grass lysimeter data from Davis, California (Hargreaves, 1975). Several improvements were made to the original equation (Hargreaves and Samani, 1982 and 1985) and the form used in SWAT was published in 1985 (Hargreaves et al., 1985):

$$\lambda E_o = 0.0023 \cdot H_0 \cdot (T_{mx} - T_{mn})^{0.5} \cdot (\overline{T}_{av} + 17.8) \qquad 7.2.24$$

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 (°C), T_{mn} is the minimum air temperature for a given day (°C), and $\overline{T}_{av}$ is the mean air temperature for a given day (°C).

Table 7-2: SWAT input variables used in potential evapotranspiration calculations summarized in this section.

Variable name	Definition	File Name
IPET	Potential evapotranspiration method	.cod
WND_SP	u_z: Daily wind speed (m/s)	.wnd
CO2	CO_2: Carbon dioxide concentration (ppmv)	.sub
MAX TEMP	T_{mx}: Daily maximum temperature (°C)	.tmp
MIN TEMP	T_{mn}: Daily minimum temperature (°C)	.tmp
GSI	$g_{\ell,mx}$: maximum leaf conductance (m s^{-1})	crop.dat
FRGMAX	$fr_{g,mx}$: Fraction of maximum leaf conductance achieved at the vapor pressure deficit specified by vpd_{fr}	crop.dat
VPDFR	vpd_{fr}: Vapor pressure deficit corresponding to value given for $fr_{g,mx}$ (kPa)	crop.dat

7.3 ACTUAL EVAPOTRANSPIRATION

Once total potential evapotranspiration is determined, actual evaporation must be calculated. SWAT first evaporates any rainfall intercepted by the plant canopy. Next, SWAT calculates the maximum amount of transpiration and the maximum amount of sublimation/soil evaporation using an approach similar to that of Richtie (1972). The actual amount of sublimation and evaporation from the soil is then calculated. If snow is present in the HRU, sublimation will occur. Only when no snow is present will evaporation from the soil take place.

7.3.1 EVAPORATION OF INTERCEPTED RAINFALL

Any free water present in the canopy is readily available for removal by evapotranspiration. The amount of actual evapotranspiration contributed by intercepted rainfall is especially significant in forests where in some instances evaporation of intercepted rainfall is greater than transpiration.

SWAT removes as much water as possible from canopy storage when calculating actual evaporation. If potential evapotranspiration, E_o, is less than the amount of free water held in the canopy, R_{INT}, then

$$E_a = E_{can} = E_o \qquad 7.3.1$$

$$R_{INT(f)} = R_{INT(i)} - E_{can} \qquad 7.3.2$$

where E_a is the actual amount of evapotranspiration occurring in the watershed on a given day (mm H_2O), E_{can} is the amount of evaporation from free water in the canopy on a given day (mm H_2O), E_o is the potential evapotranspiration on a given day (mm H_2O), $R_{INT(i)}$ is the initial amount of free water held in the canopy on a given day (mm H_2O), and $R_{INT(f)}$ is the final amount of free water held in the canopy on a given day (mm H_2O). If potential evapotranspiration, E_o, is greater than the amount of free water held in the canopy, R_{INT}, then

$$E_{can} = R_{INT(i)} \qquad 7.3.3$$

$$R_{INT(f)} = 0 \qquad 7.3.4$$

Once any free water in the canopy has been evaporated, the remaining evaporative water demand ($E'_o = E_o - E_{can}$) is partitioned between the vegetation and snow/soil.

7.3.2 TRANSPIRATION

If the Penman-Monteith equation is selected as the potential evapotranspiration method, transpiration is also calculated with the equations summarized in Section 7.2.1. For the other potential evapotranspiration methods, transpiration is calculated as:

$$E_t = \frac{E'_o \cdot LAI}{3.0} \qquad 0 \le LAI \le 3.0 \qquad 7.3.5$$

$$E_t = E'_o \qquad LAI > 3.0 \qquad 7.3.6$$

where E_t is the maximum transpiration on a given day (mm H_2O), E'_o is the potential evapotranspiration adjusted for evaporation of free water in the canopy (mm H_2O), and LAI is the leaf area index. The value for transpiration calculated by equations 7.3.5 and 7.3.6 is the amount of transpiration that will occur on a given day when the plant is growing under ideal conditions. The actual amount of transpiration may be less than this due to lack of available water in the soil profile. Calculation of actual plant water uptake and transpiration is reviewed in Chapters 18 and 19.

7.3.3 SUBLIMATION AND EVAPORATION FROM THE SOIL

The amount of sublimation and soil evaporation will be impacted by the degree of shading. The maximum amount of sublimation/soil evaporation on a given day is calculated as:

$$E_s = E'_o \cdot cov_{sol} \qquad 7.3.7$$

where E_s is the maximum sublimation/soil evaporation on a given day (mm H_2O), E'_o is the potential evapotranspiration adjusted for evaporation of free water in the canopy (mm H_2O), and cov_{sol} is the soil cover index. The soil cover index is calculated

$$cov_{sol} = \exp\left(-5.0 \times 10^{-5} \cdot CV\right) \qquad 7.3.8$$

where CV is the aboveground biomass and residue (kg ha^{-1}). If the snow water content is greater than 0.5 mm H_2O, the soil cover index is set to 0.5.

The maximum amount of sublimation/soil evaporation is reduced during periods of high plant water use with the relationship:

$$E'_s = \min\left[E_s, \quad \frac{E_s \cdot E'_o}{E_s + E_t}\right] \qquad 7.3.9$$

where E'_s is the maximum sublimation/soil evaporation adjusted for plant water use on a given day (mm H_2O), E_s is the maximum sublimation/soil evaporation on a given day (mm H_2O), E'_o is the potential evapotranspiration adjusted for evaporation of free water in the canopy (mm H_2O), and E_t is the transpiration on a given day (mm H_2O). When E_t is low $E'_s \rightarrow E_s$. However, as E_t approaches E'_o, $E'_s \rightarrow \frac{E_s}{1 + cov_{sol}}$.

7.3.3.1 SUBLIMATION

Once the maximum amount of sublimation/soil evaporation for the day is calculated, SWAT will first remove water from the snow pack to meet the evaporative demand. If the water content of the snow pack is greater than the maximum sublimation/soil evaporation demand, then

$$E_{sub} = E'_s \qquad 7.3.10$$

$$SNO_{(f)} = SNO_{(i)} - E'_s \qquad 7.3.11$$

$$E''_s = 0. \qquad 7.3.12$$

where E_{sub} is the amount of sublimation on a given day (mm H_2O), E'_s is the maximum sublimation/soil evaporation adjusted for plant water use on a given day (mm H_2O), $SNO_{(i)}$ is the amount of water in the snow pack on a given day prior to accounting for sublimation (mm H_2O), $SNO_{(f)}$ is the amount of water in the snow pack on a given day after accounting for sublimation (mm H_2O), and E''_s is the maximum soil water evaporation on a given day (mm H_2O). If the water content of the snow pack is less than the maximum sublimation/soil evaporation demand, then

$$E_{sub} = SNO_{(i)} \tag{7.3.13}$$

$$SNO_{(f)} = 0. \tag{7.3.14}$$

$$E''_s = E'_s - E_{sub} \tag{7.3.15}$$

7.3.3.2 SOIL WATER EVAPORATION

When an evaporation demand for soil water exists, SWAT must first partition the evaporative demand between the different layers. The depth distribution used to determine the maximum amount of water allowed to be evaporated is:

$$E_{soil,z} = E''_s \cdot \frac{z}{z + \exp(2.374 - 0.00713 \cdot z)} \tag{7.3.16}$$

where $E_{soil,z}$ is the evaporative demand at depth z (mm H_2O), E''_s is the maximum soil water evaporation on a given day (mm H_2O), and z is the depth below the surface. The coefficients in this equation were selected so that 50% of the evaporative demand is extracted from the top 10 mm of soil and 95% of the evaporative demand is extracted from the top 100 mm of soil.

The amount of evaporative demand for a soil layer is determined by taking the difference between the evaporative demands calculated at the upper and lower boundaries of the soil layer:

$$E_{soil,ly} = E_{soil,zl} - E_{soil,zu} \tag{7.3.16}$$

where $E_{soil,ly}$ is the evaporative demand for layer ly (mm H_2O), $E_{soil,zl}$ is the evaporative demand at the lower boundary of the soil layer (mm H_2O), and $E_{soil,zu}$ is the evaporative demand at the upper boundary of the soil layer (mm H_2O).

Figure 7-1 graphs the depth distribution of the evaporative demand for a soil that has been partitioned into 1 mm layers assuming a total soil evaporation demand of 100 mm.

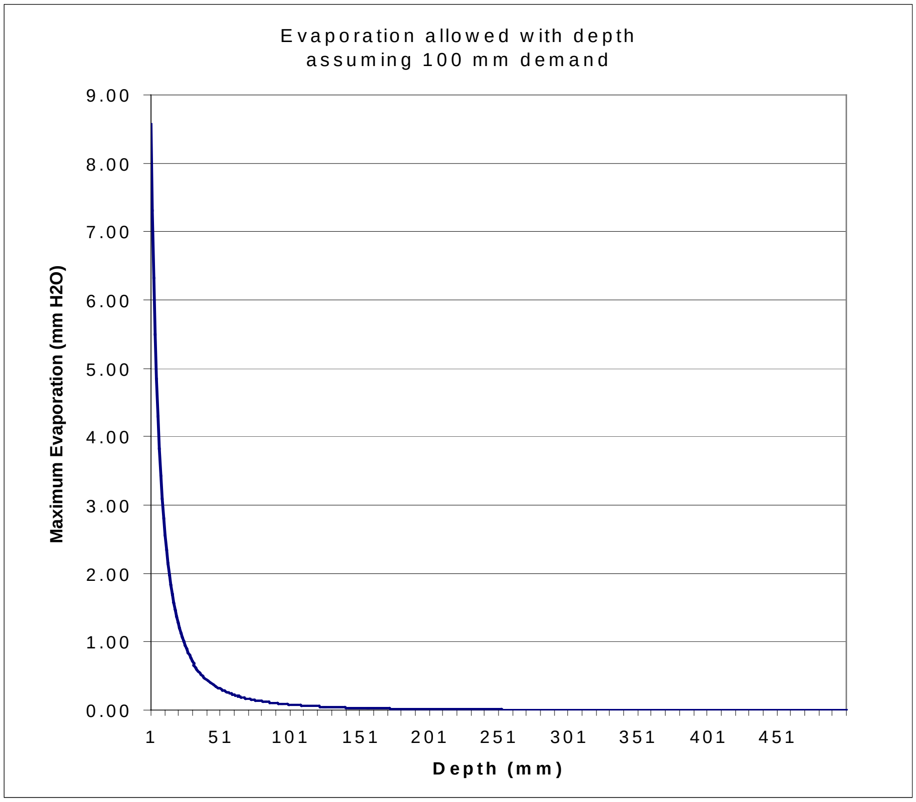

Figure 7-1: Soil evaporative demand distribution with depth.

As mentioned previously, the depth distribution assumes 50% of the evaporative demand is met by soil water stored in the top 10 mm of the soil profile. With our example of a 100 mm total evaporative demand, 50 mm of water is 50%. This is a demand that the top layer cannot satisfy.

SWAT does not allow a different layer to compensate for the inability of another layer to meet its evaporative demand. The evaporative demand not met by a soil layer results in a reduction in actual evapotranspiration for the HRU.

A coefficient has been incorporated into equation 7.3.16 to allow the user to modify the depth distribution used to meet the soil evaporative demand. The modified equation is:

$$E_{soil,ly} = E_{soil,zl} - E_{soil,zu} \cdot esco \qquad 7.3.17$$

where $E_{soil,ly}$ is the evaporative demand for layer ly (mm H_2O), $E_{soil,zl}$ is the evaporative demand at the lower boundary of the soil layer (mm H_2O), $E_{soil,zu}$ is the evaporative demand at the upper boundary of the soil layer (mm H_2O), and *esco* is the soil evaporation compensation coefficient. Solutions to this equation for different values of *esco* are graphed in Figure 7-2. The plot for *esco* = 1.0 is that shown in Figure 7-1.

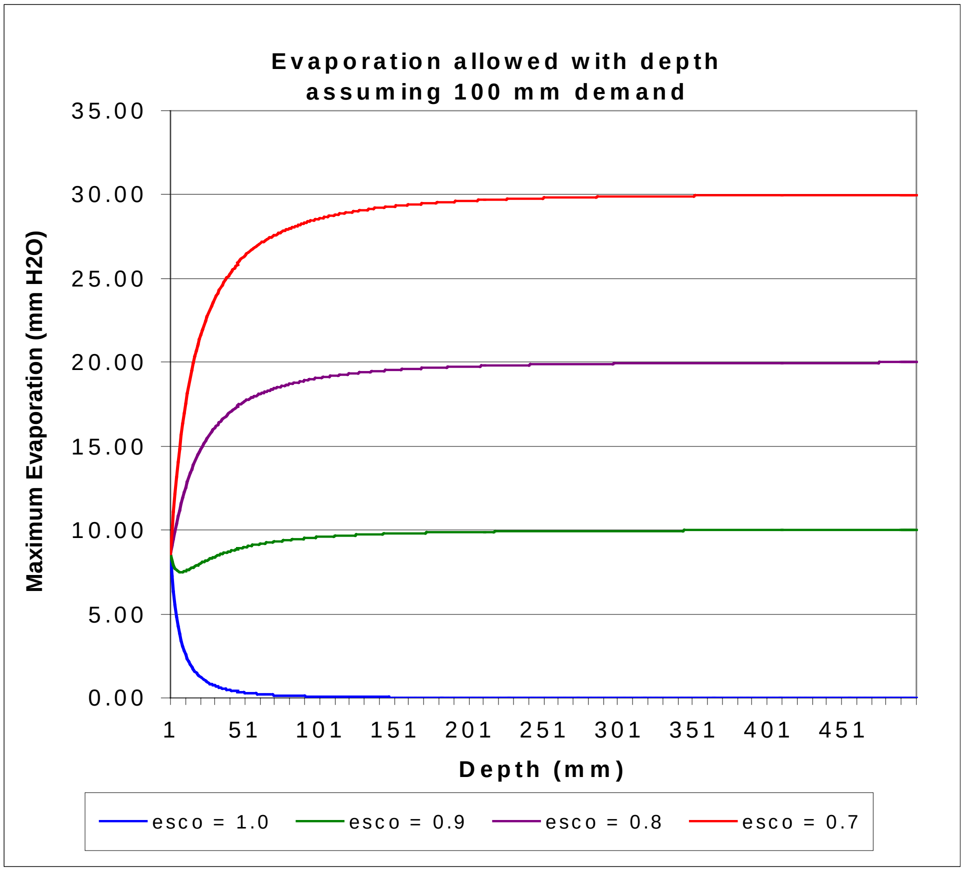

Figure 7-2: Soil evaporative demand distribution with depth

As the value for *esco* is reduced, the model is able to extract more of the evaporative demand from lower levels.

When the water content of a soil layer is below field capacity, the evaporative demand for the layer is reduced according to the following equations:

$$E'_{soil,ly} = E_{soil,ly} \cdot \exp\left(\frac{2.5 \cdot \left(SW_{ly} - FC_{ly}\right)}{FC_{ly} - WP_{ly}}\right) \quad \text{when } SW_{ly} < FC_{ly} \qquad 7.3.18$$

$$E'_{soil,ly} = E_{soil,ly} \quad \text{when } SW_{ly} \geq FC_{ly} \qquad 7.3.19$$

where $E'_{soil,ly}$ is the evaporative demand for layer *ly* adjusted for water content (mm H_2O), $E_{soil,ly}$ is the evaporative demand for layer *ly* (mm

H_2O), SW_{ly} is the soil water content of layer ly (mm H_2O), FC_{ly} is the water content of layer ly at field capacity (mm H_2O), and WP_{ly} is the water content of layer ly at wilting point (mm H_2O).

In addition to limiting the amount of water removed by evaporation in dry conditions, SWAT defines a maximum value of water that can be removed at any time. This maximum value is 80% of the plant available water on a given day where the plant available water is defined as the total water content of the soil layer minus the water content of the soil layer at wilting point (-1.5 MPa).

$$E''_{soil,ly} = \min\left(E'_{soil,ly} \quad 0.8 \cdot (SW_{ly} - WP_{ly})\right) \qquad 7.3.20$$

where $E''_{soil,ly}$ is the amount of water removed from layer ly by evaporation (mm H_2O), $E'_{soil,ly}$ is the evaporative demand for layer ly adjusted for water content (mm H_2O), SW_{ly} is the soil water content of layer ly (mm H_2O), and WP_{ly} is the water content of layer ly at wilting point (mm H_2O).

Table 7-3: SWAT input variables used in soil evaporation calculations.

Variable name	Definition	File Name
ESCO	*esco*: soil evaporation compensation coefficient	.bsn, .hru

7.4 NOMENCLATURE

CO_2	Concentration of carbon dioxide in the atmosphere (ppmv)
CV	Total aboveground biomass and residue present on current day (kg ha^{-1})
E	Depth rate evaporation (mm d^{-1})
E_a	Actual amount of evapotranspiration on a given day (mm H_2O)
E_{can}	Amount of evaporation from free water in the canopy on a given day (mm H_2O)
E_o	Potential evapotranspiration (mm d^{-1})
E'_o	Potential evapotranspiration adjusted for evaporation of free water in the canopy (mm H_2O)
E_s	Maximum sublimation/soil evaporation on a given day (mm H_2O)
E'_s	Maximum sublimation/soil evaporation adjusted for plant water use on a given day (mm H_2O)
E''_s	Maximum soil water evaporation on a given day (mm H_2O)
$E_{soil,ly}$	Evaporative demand for layer ly (mm H_2O)

$E'_{soil,ly}$	Evaporative demand for layer *ly* adjusted for water content (mm H_2O)
$E''_{soil,ly}$	Amount of water removed from layer *ly* by evaporation (mm H_2O)
$E_{soil,z}$	Evaporative demand at depth *z* (mm H_2O)
E_{sub}	Amount of sublimation on a given day (mm H_2O)
E_t	Transpiration rate (mm d^{-1})
FC_{ly}	Water content of layer *ly* at field capacity (mm H_2O)
G	Heat flux density to the ground (MJ m^{-2} d^{-1})
H_0	Extraterrestrial daily irradiation (MJ m^{-2} d^{-1})
H_{net}	Net radiation on day (MJ m^{-2} d^{-1})
K_1	Dimension coefficient in Penman-Monteith equation
LAI	Leaf area index of the canopy
LAI_{mx}	Maximum leaf area index for the plant
P	Atmospheric pressure (kPa)
R_{day}	Amount of rainfall on a given day (mm H_2O)
R'_{day}	Amount of precipitation on a given day before canopy interception is removed (mm H_2O)
R_{INT}	Amount of free water held in the canopy on a given day (mm H_2O)
SNO	Water content of snow cover on current day (mm H_2O)
SW_{ly}	Soil water content of layer *ly* (mm H_2O)
T_{mn}	Minimum air temperature for day (°C)
T_{mx}	Maximum air temperature for day (°C)
$\overline{T}_{av}$	Mean air temperature for day (°C)
WP_{ly}	Water content of layer *ly* at wilting point (mm H_2O).

c_p	Specific heat of moist air at constant pressure (1.013×10^{-3} MJ kg^{-1} $°C^{-1}$)
can_{day}	Maximum amount of water that can be trapped in the canopy on a given day (mm H_2O)
can_{mx}	Maximum amount of water that can be trapped in the canopy when the canopy is fully developed (mm H_2O)
cov_{sol}	Soil cover index
d	Zero plane displacement of the wind profile (cm)
e	Actual vapor pressure on a given day (kPa)
e^o	Saturation vapor pressure on a given day (kPa)
$esco$	Soil evaporation compensation coefficient
$fr_{g,mx}$	Fraction of the maximum stomatal conductance, $g_{\ell,mx}$, achieved at the vapor pressure deficit, vpd_{fr}
g_ℓ	Leaf conductance (m s^{-1})
$g_{\ell,mx}$	Maximum conductance of a single leaf (m s^{-1})
h_c	Canopy height (cm)
k	Von Kármán constant
r_a	Diffusion resistance of the air layer (aerodynamic resistance) (s m^{-1})
r_c	Plant canopy resistance (s m^{-1})
r_ℓ	Minimum effective resistance of a single leaf (s m^{-1})

$r_{\ell-ab}$	Minimum abaxial stomatal leaf resistance (s m^{-1})
$r_{\ell-ad}$	Minimum adaxial stomatal leaf resistance (s m^{-1})
u_z	Wind speed at height z_w (m s^{-1})
vpd	Vapor pressure deficit (kPa)
vpd_{fr}	Vapor pressure deficit corresponding to $fr_{g,mx}$ (kPa)
vpd_{thr}	Threshold vapor pressure deficit above which a plant will exhibit reduced leaf conductance (kPa)
z	Depth below soil surface (mm)
z_{om}	Roughness length for momentum transfer (cm)
z_{ov}	Roughness length for vapor transfer (cm)
z_p	Height of the humidity (psychrometer) and temperature measurements (cm)
z_w	Height of the wind speed measurement (cm)
α_{pet}	Coefficient in Priestley-Taylor equation
Δ	Slope of the saturation vapor pressure curve (kPa °C^{-1})
$\Delta g_{\ell,dcl}$	Rate of decline in leaf conductance per unit increase in vapor pressure deficit (m s^{-1} kPa^{-1})
ρ_{air}	Air density (kg m^{-3})
γ	Psychrometric constant (kPa °C^{-1})
λ	Latent heat of vaporization (MJ kg^{-1})

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CHAPTER 8

EQUATIONS: SOIL WATER

Water that enters the soil may move along one of several different pathways. The water may be removed from the soil by plant uptake or evaporation. It can percolate past the bottom of the soil profile and ultimately become aquifer recharge. A final option is that water may move laterally in the profile and contribute to streamflow. Of these different pathways, plant uptake of water removes the majority of water that enters the soil profile.

8.1 SOIL STRUCTURE

Soil is comprised of three phases—solid, liquid and gas. The solid phase consists of minerals and/or organic matter that forms the matrix or skeleton of the soil. Between the solid particles, soil pores are formed that hold the liquid and gas phases. The soil solution may fill the soil pores completely (saturated) or partially (unsaturated). When the soil is unsaturated, the soil solution is found as thin films along particle surfaces, as annular wedges around contact points of particles and as isolated bodies in narrow pore passages.

The soil's bulk density defines the relative amounts of pore space and soil matrix. Bulk density is calculated:

$$\rho_b = \frac{M_S}{V_T} \qquad 8.1.1$$

where ρ_b is the bulk density (Mg m^{-3}), M_S is the mass of the solids (Mg), and V_T is the total volume (m^3). The total volume is defined as

$$V_T = V_A + V_W + V_S \qquad 8.1.2$$

where V_A is the volume of air (m^3), V_W is the volume of water (m^3), and V_S is the volume of solids (m^3). The relationship between soil porosity and soil bulk density is

$$\phi_{soil} = 1 - \frac{\rho_b}{\rho_s} \qquad 8.1.3$$

where ϕ_{soil} is the soil porosity expressed as a fraction of the total soil volume, ρ_b is the bulk density (Mg m^{-3}), and ρ_s is the particle density (Mg m^{-3}). The particle density, or density of the solid fraction, is a function of the mineral composition of the soil matrix. Based on research, a default value of 2.65 Mg m^{-3} is used for particle density.

Storage, transport and availability of soil solution and soil air are not nearly as dependent on the total amount of porosity as they are on the arrangement of pore space. Soil pores vary in size and shape due to textural and structural arrangement. Based on the diameter of the pore at the narrowest point, the pores may be classified as macropores (narrowest diameter > 100 μm), mesopores (narrowest diameter 30-100 μm), and micropores (narrowest diameter < 30 μm) (Koorevaar et al, 1983). Macropores conduct water only during flooding or ponding rain and drainage of water from these pores is complete soon after cessation of the water supply. Macropores control aeration and drainage processes in the soil. Mesopores conduct water even after macropores have emptied, e.g. during non-ponding rain and redistribution. Micropores retain soil solution or conduct it very slowly.

When comparing soils of different texture, clay soils contain a greater fraction of mesopores and micropores while sand soils contain mostly macropores. This is evident when the hydraulic conductivities of clay and sand soils are compared. The conductivity of a sand soil can be several orders of magnitude greater than that for a clay soil.

The water content of a soil can range from zero when the soil is oven dried to a maximum value (ϕ_{soil}) when the soil is saturated. For plant-soil interactions, two intermediate stages are recognized: field capacity and permanent wilting point. Field capacity is the water content found when a thoroughly wetted soil has drained for approximately two days. Permanent wilting point is the water content found when plants growing in the soil wilt and do not recover if their leaves are kept in a humid atmosphere overnight. To allow these two stages to be quantified more easily, they have been redefined in terms of tensions at which water is held by the soil. Field capacity is the amount of water held in the soil at a tension of 0.033 MPa and the permanent wilting point is the amount of water held in the soil at a tension of 1.5 MPa. The amount of water held in the soil between field capacity and permanent wilting point is considered to be the water available for plant extraction.

Table 8-1: Water contents for various soils at different moisture conditions.

		Water content (fraction total soil volume)		
Texture	Clay Content (% Solids)	Saturation	Field capacity	Permanent wilting point
sand	3 %	0.40	0.06	0.02
loam	22 %	0.50	0.29	0.05
clay	47 %	0.60	0.41	0.20

Table 8-1 lists the water content for three soils as a fraction of the total volume for different moisture conditions. Note that the total porosity, given by the water content at saturation, is lowest for the sand soil and highest for the clay soil.

The sand soil drains more quickly than the loam and clay. Only 15% of the water present in the sand soil at saturation remains at field capacity. 58% of the water present at saturation in the loam remains at field capacity while 68% of the water present at saturation in the clay soil remains at field capacity. The reduction of water loss with increase in clay content is cause by two factors. As mentioned previously, clay soils contain more mesopores and micropores than sand soils. Also, unlike sand and silt particles, clay particles possess a net negative charge. Due to the polar nature of water molecules, clay particles are able to attract and retain water molecules. The higher water retention of clay soils is also seen in the fraction of water present at permanent wilting point. In the soils listed in Table 8-1, the volumetric water content of the clay is 0.20 at the wilting point while the sand and loam have a volumetric water content of 0.02 and 0.05 respectively.

The plant available water, also referred to as the available water capacity, is calculated by subtracting the fraction of water present at permanent wilting point from that present at field capacity.

$$AWC = FC - WP \qquad 8.1.4$$

where AWC is the plant available water content, FC is the water content at field capacity, and WP is the water content at permanent wilting point. For the three soil textures listed in Table 8-1, the sand has an available water capacity of 0.04, the loam has an available water capacity of 0.24 and the clay has an available water capacity of 0.21. Even though the clay contains a greater amount of water than the loam at all three tensions, the loam has a larger amount of water available for plant uptake than the clay. This characteristic is true in general.

SWAT estimates the permanent wilting point volumetric water content for each soil layer as:

$$WP_{ly} = 0.40 \cdot \frac{m_c \cdot \rho_b}{100} \qquad 8.1.5$$

where WP_{ly} is the water content at wilting point expressed as a fraction of the total soil volume, m_c is the percent clay content of the layer (%), and ρ_b is the bulk density for the soil layer (Mg m^{-3}). Field capacity water content is estimated

$$FC_{ly} = WP_{ly} + AWC_{ly} \qquad 8.1.6$$

where FC_{ly} is the water content at field capacity expressed as a fraction of the total soil volume, WP_{ly} is the water content at wilting point expressed as a fraction of the total soil volume, and AWC_{ly} is the available water capacity of the soil layer expressed as a fraction of the total soil volume. AWC_{ly} is input by the user.

Water in the soil can flow under saturated or unsaturated conditions. In saturated soils, flow is driven by gravity and usually occurs in the downward direction. Unsaturated flow is caused by gradients arising due to adjacent areas of high and low water content. Unsaturated flow may occur in any direction.

SWAT directly simulates saturated flow only. The model records the water contents of the different soil layers but assumes that the water is uniformly distributed within a given layer. This assumption eliminates the need to model unsaturated flow in the horizontal direction. Unsaturated flow between layers is indirectly modeled with the depth distribution of plant water uptake (equation 18.2.1) and the depth distribution of soil water evaporation (equation 7.3.16).

Saturated flow occurs when the water content of a soil layer surpasses the field capacity for the layer. Water in excess of the field capacity water content is available for percolation, lateral flow or tile flow drainage unless the temperature of the soil layer is below 0°C. When the soil layer is frozen, no water movement is calculated.

Table 8-1: SWAT input variables used in percolation calculations.

Variable name	**Definition**	**File Name**
CLAY	m_c: Percent clay content	.sol
SOL_BD	ρ_b: Bulk density (Mg m^{-3})	.sol
SOL_AWC	AWC_{ly}: available water capacity	.sol

8.2 PERCOLATION

Percolation is calculated for each soil layer in the profile. Water is allowed to percolate if the water content exceeds the field capacity water content for that layer. When the soil layer is frozen, no water flow out of the layer is calculated.

The volume of water available for percolation in the soil layer is calculated:

$$SW_{ly,excess} = SW_{ly} - FC_{ly} \qquad \text{if} \qquad SW_{ly} > FC_{ly} \qquad 8.2.1$$

$$SW_{ly,excess} = 0 \qquad \text{if} \qquad SW_{ly} \leq FC_{ly} \qquad 8.2.2$$

where $SW_{ly,excess}$ is the drainable volume of water in the soil layer on a given day (mm H_2O), SW_{ly} is the water content of the soil layer on a given day (mm H_2O) and FC_{ly} is the water content of the soil layer at field capacity (mm H_2O).

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:

$$w_{perc,ly} = SW_{ly,excess} \cdot \left(1 - \exp\left[\frac{-\Delta t}{TT_{perc}}\right]\right) \qquad 8.2.3$$

where $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O), $SW_{ly,excess}$ is the drainable volume of water in the soil layer on a given day (mm H_2O), Δt is the length of the time step (hrs), and TT_{perc} is the travel time for percolation (hrs).

The travel time for percolation is unique for each layer. It is calculate

$$TT_{perc} = \frac{SAT_{ly} - FC_{ly}}{K_{sat}} \qquad 8.2.4$$

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 H_2O), FC_{ly} is the water content of the soil layer at field capacity (mm H_2O), and K_{sat} is the saturated hydraulic conductivity for the layer ($\text{mm}\cdot\text{h}^{-1}$).

Water that percolates out of the lowest soil layer enters the vadose zone. The vadose zone is the unsaturated zone between the bottom of the soil profile and the top of the aquifer. Movement of water through the vadose zone and into the aquifers is reviewed in Chapter 9.

Table 8-2: SWAT input variables used in percolation calculations.

Variable name	Definition	File Name
SOL_K	K_{sat}: Saturated hydraulic conductivity (mm/hr)	.sol

8.3 BYPASS FLOW

One of the most unique soil orders is the Vertisols. These soils are characterized by a propensity to shrink when dried and swell when moistened. When the soil is dry, large cracks form at the soil surface. This behavior is a result of the type of soil material present and the climate. Vertisols contain at least 30% clay with the clay fraction dominated by smectitic mineralogy and occur in areas with cyclical wet and dry periods.

Vertisols are found worldwide (Figure 8-1). They have a number of local names, some of which are listed in Table 8-3.

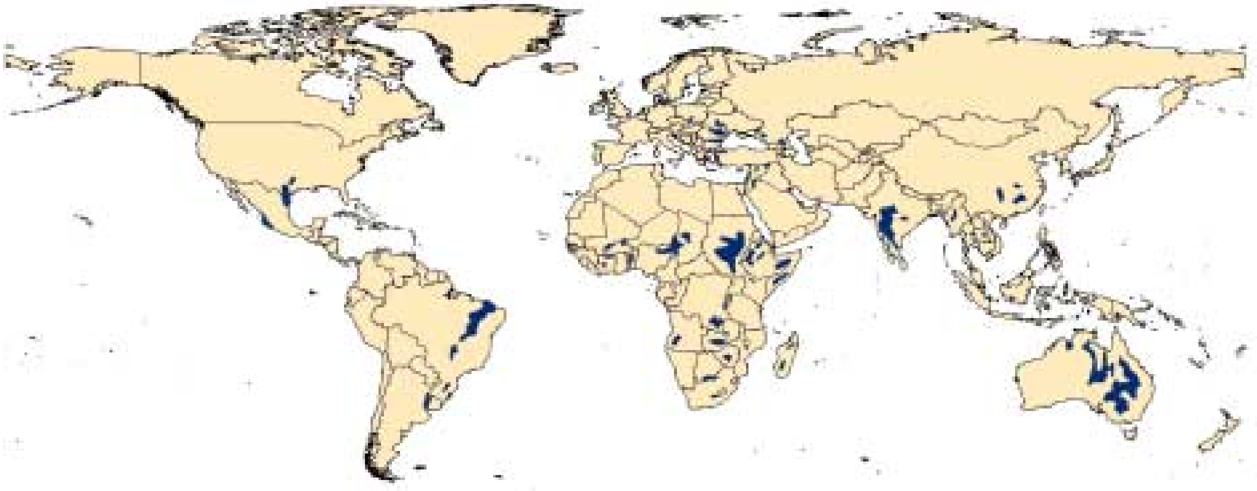

Figure 8-1: Soil associations of Vertisols (After Dudal and Eswaran, 1988)

Table 8-3: Alternative names for Vertisols or soils with Vertic properties (Dudal and Eswaran, 1988).

Names	**Countries**
Names that include the word "black"	
Barros pretos	Portugal
Black clays	South Africa, Australia
Black cotton soils	Africa, India
Black cracking clays	Uganda
Black earths	Australia, Africa
Black turf soils	South Africa
Dark clay soils	United States
Subtropical black clays	Africa
Sols noirs tropicaux	Africa
Terra nera	Italy
Terres noires tropicales	Africa
Terras negras tropicais	Mozambique
Tierras negras de Andalucia	Spain
Tropical black earths	Angola, Ghana
Tropical black clays	Africa
Names that reflect the black color	
Karail	India
Melanites	Ghana
Teen Suda	Sudan
Tropical Chernozems	Africa, India
Impact Chernozems	Russia
Vernacular names	
Adobe soils	United States, Philippines
Badobes	Sudan
Dian Pere	French West Africa
Gilgai soils	Australia
Firki	Nigeria
Mbuga	Tanzania
Kahamba	Congo
Makande	Malawi
Morogan	Romania
Regur	India
Rendzina	United States
Shachiang soils	China
Smolnitza	Bulgaria, Romania
Smonitza	Austria, Yugoslavia
Sols de paluds	France
Tirs	Morocco, North Africa
Vlei grond	South Africa
Sonsocuite	Nicaragua
Coined names	
Densinigra soils	Angola
Gravinigra soils	Angola
Grumusols	United States
Margalite soils	Indonesia
Vertisols	United States

One criteria used to classify a soil as a Vertisol is the formation of shrinkage cracks in the dry season that penetrate to a depth of more than 50 cm and are at least 1 cm wide at 50 cm depth. The cracks can be considerably wider at the surface—30 cm cracks at the surface are not unusual although 6-15 cm cracks are more typical.

To accurately predict surface runoff and infiltration in areas dominated by soils that exhibit Vertic properties, the temporal change in soil volume must be quantified. Bouma and Loveday (1988) identified three soil moisture conditions for which infiltration needs to be defined (Figure 8-2).

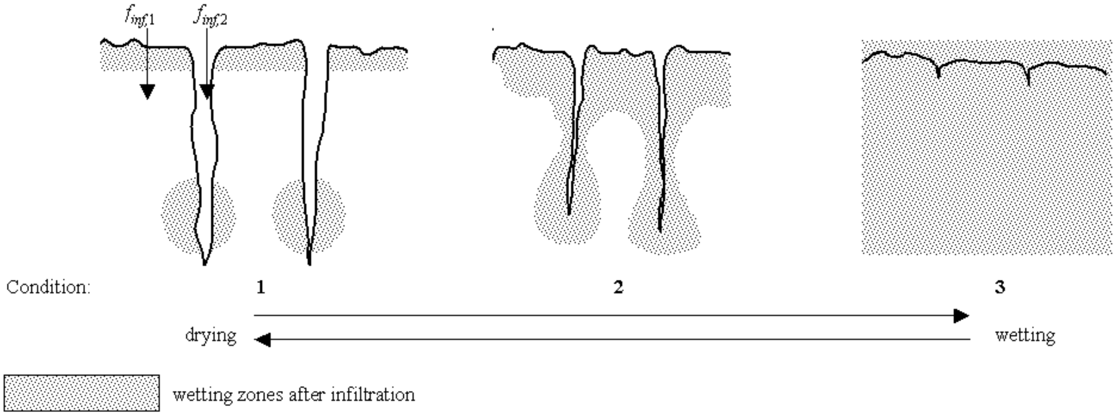

Figure 8-2: Diagram showing the effect of wetting and drying on cracking in Vertisols (After Bouma and Loveday, 1988)

Traditional models of infiltration are applicable to soils in which cracks have been closed by swelling and the soil acts as a relatively homogenous porous medium (Condition 3 in Figure 8-2). Condition 1 in Figure 8-2 represents the driest state with cracks at maximum width, a condition present at the end of the dry season/beginning of the rainy season. Condition 2 in Figure 8-2 represents the crack development typical with an actively growing crop requiring multiple irrigation or rainfall events to sustain growth. Bypass flow, the vertical movement of free water along macropores through unsaturated soil horizons, will occur in conditions 1 and 2. Bypass flow ($f_{inf,2}$ in Figure 8-2) occurs when the rate of rainfall or irrigation exceeds the vertical infiltration rate into the soil peds ($f_{inf,1}$ in Figure 8-2).

When bypass flow is modeled, SWAT calculates the crack volume of the soil matrix for each day of simulation by layer. On days in which precipitation events occur, infiltration and surface runoff is first calculated for the soil peds ($f_{inf,1}$ in Figure 8-2) using the curve number or Green & Ampt method. If any surface runoff is generated, it is allowed to enter the cracks. A volume of water equivalent to the total crack volume for the soil profile may enter the profile as bypass flow. Surface runoff in excess of the crack volume remains overland flow.

Water that enters the cracks fills the soil layers beginning with the lowest layer of crack development. After cracks in one layer are filled, the cracks in the overlying layer are allowed to fill.

The crack volume initially estimated for a layer is calculated:

$$crk_{ly,i} = crk_{max,ly} \cdot \frac{coef_{crk} \cdot FC_{ly} - SW_{ly}}{coef_{crk} \cdot FC_{ly}} \qquad 8.3.1$$

where $crk_{ly,i}$ is the initial crack volume calculated for the soil layer on a given day expressed as a depth (mm), $crk_{max,ly}$ is the maximum crack volume possible for the soil layer (mm), $coef_{crk}$ is an adjustment coefficient for crack flow, FC_{ly} is the water content of the soil layer at field capacity (mm H_2O), and SW_{ly} is the water content of the soil layer on a given day (mm H_2O). The adjustment coefficient for crack flow, $coef_{crk}$, is set to 0.10.

When the moisture content of the entire profile falls below 90% of the field capacity water content for the profile during the drying stage, the crack volume for a given day is a function of the crack volume estimated with equation 8.3.1 and the crack volume of the layer on the previous day. When the soil is wetting and/or when the moisture content of the profile is above 90% of the field capacity water content, the crack volume for a given day is equal to the volume calculated with equation 8.3.1.

$$crk_{ly} = \ell_{crk} \cdot crk_{ly,d-1} + (1.0 - \ell_{crk}) \cdot crk_{ly,i}$$

$$\text{when } SW < 0.90 \cdot FC \text{ and } crk_{ly,i} > crk_{ly,d-1} \qquad 8.3.2$$

$$crk_{ly} = crk_{ly,i}$$

$$\text{when } SW \geq 0.90 \cdot FC \text{ or } crk_{ly,i} \leq crk_{ly,d-1} \qquad 8.3.3$$

where crk_{ly} is the crack volume for the soil layer on a given day expressed as a depth (mm), ℓ_{crk} is the lag factor for crack development during drying, $crk_{ly,d\text{-}1}$ is the crack volume for the soil layer on the previous day (mm), $crk_{ly,i}$ is the initial crack volume calculated for the soil layer on a given day using equation 8.3.1

(mm), SW is the water content of the soil profile on a given day (mm H_2O), and FC is the water content of the soil profile at field capacity (mm H_2O).

As the tension at which water is held by the soil particles increases, the rate of water diffusion slows. Because the rate of water diffusion is analogous to the coefficient of consolidation in classical consolidation theory (Mitchell, 1992), the reduction in diffusion will affect crack formation. The lag factor is introduced during the drying stage to account for the change in moisture redistribution dynamics that occurs as the soil dries. The lag factor, ℓ_{crk}, is set to a value of 0.99.

The maximum crack volume for the layer, $crk_{max,ly}$, is calculated:

$$crk_{max,ly} = 0.916 \cdot crk_{max} \cdot \exp\left[-0.0012 \cdot z_{l,ly}\right] \cdot depth_{ly} \qquad 8.3.4$$

where $crk_{max,ly}$ is the maximum crack volume possible for the soil layer (mm), crk_{max} is the potential crack volume for the soil profile expressed as a fraction of the total volume, $z_{l,ly}$ is the depth from the soil surface to the bottom of the soil layer (mm), and $depth_{ly}$ is the depth of the soil layer (mm). The potential crack volume for the soil profile, crk_{max}, is input by the user. Those needing information on the measurement of this parameter are referred to Bronswijk (1989; 1990).

Once the crack volume for each layer is calculated, the total crack volume for the soil profile is determined.

$$crk = \sum_{ly=1}^{n} crk_{ly} \qquad 8.3.5$$

where crk is the total crack volume for the soil profile on a given day (mm), crk_{ly} is the crack volume for the soil layer on a given day expressed as a depth (mm), ly is the layer, and n is the number of layers in the soil profile.

After surface runoff is calculated for rainfall events using the curve number or Green & Ampt method, the amount of runoff is reduced by the volume of cracks present that day:

$$Q_{surf} = Q_{surf,i} - crk \qquad \text{if } Q_{surf,i} > crk \qquad 8.3.6$$

$$Q_{surf} = 0 \qquad \text{if } Q_{surf,i} \leq crk \qquad 8.3.7$$

where Q_{surf} is the accumulated runoff or rainfall excess for the day (mm H_2O), $Q_{surf,i}$ is the initial accumulated runoff or rainfall excess determined with the Green & Ampt or curve number method (mm H_2O), and crk is the total crack volume for the soil profile on a given day (mm). The total amount of water entering the soil is then calculated:

$$w_{inf} = R_{day} - Q_{surf} \qquad 8.3.8$$

where w_{inf} is the amount of water entering the soil profile on a given day (mm H_2O), R_{day} is the rainfall depth for the day adjusted for canopy interception (mm H_2O), and Q_{surf} is the accumulated runoff or rainfall excess for the day (mm H_2O).

Bypass flow past the bottom of the profile is calculated:

$$w_{crk,btm} = 0.5 \cdot crk \cdot \left(\frac{crk_{ly=nn}}{depth_{ly=nn}} \right) \qquad 8.3.9$$

where $w_{crk,btm}$ is the amount of water flow past the lower boundary of the soil profile due to bypass flow (mm H_2O), crk is the total crack volume for the soil profile on a given day (mm), $crk_{ly=nn}$ is the crack volume for the deepest soil layer ($ly=nn$) on a given day expressed as a depth (mm), and $depth_{ly=nn}$ is the depth of the deepest soil layer ($ly=nn$) (mm).

After $w_{crk,btm}$ is calculated, each soil layer is filled to field capacity water content beginning with the lowest layer and moving upward until the total amount of water entering the soil, w_{inf}, has been accounted for.

Table 8-4: SWAT input variables used in bypass flow calculations.

Variable name	**Definition**	**File Name**
ICRK	Bypass flow code: 0-do not model bypass flow; 1-model bypass flow	.cod
SOL_CRK	crk_{max}: Potential crack volume for soil profile	.sol

8.4 LATERAL FLOW

Lateral flow will be significant in areas with soils having high hydraulic conductivities in surface layers and an impermeable or semipermeable layer at a shallow depth. In such a system, rainfall will percolate vertically until it encounters the impermeable layer. The water then ponds above the impermeable layer forming a saturated zone of water, i.e. a perched water table. This saturated zone is the source of water for lateral subsurface flow.

SWAT incorporates a kinematic storage model for subsurface flow developed by Sloan et al. (1983) and summarized by Sloan and Moore (1984). This model simulates subsurface flow in a two-dimensional cross-section along a flow path down a steep hillslope. The kinematic approximation was used in its derivation.

This model is based on the mass continuity equation, or mass water balance, with the entire hillslope segment used as the control volume. The hillslope segment has a permeable soil surface layer of depth D_{perm} and length L_{hill} with an impermeable soil layer or boundary below it as shown in Figure 8-3. The hillslope segment is oriented at an angle α_{hill} to the horizontal.

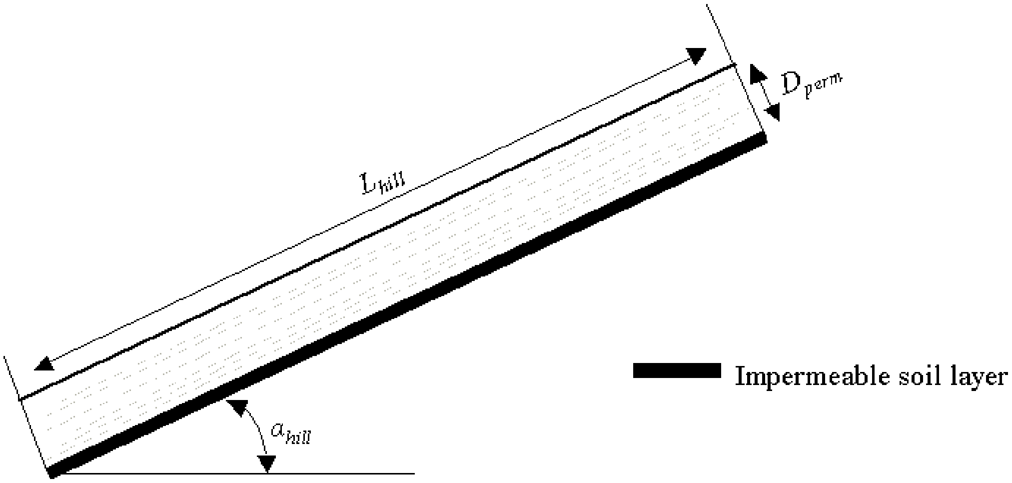

Figure 8-3: Conceptual representation of the hillslope segment.

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.

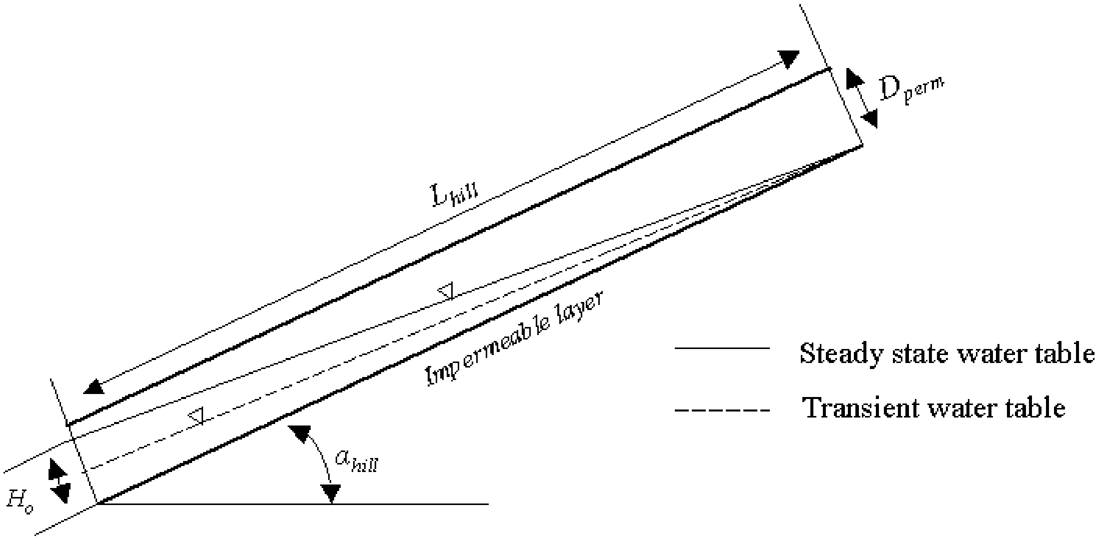

Figure 8-4: Behavior of the water table as assumed in the kinematic storage model.

From Figure 8-4, the drainable volume of water stored in the saturated zone of the hillslope segment per unit area, $SW_{ly,excess}$, is

$$SW_{ly,excess} = \frac{1000 \cdot H_o \cdot \phi_d \cdot L_{hill}}{2} \tag{8.4.1}$$

where $SW_{ly,excess}$ is the drainable volume of water stored in the saturated zone of the hillslope per unit area (mm H_2O), H_o is the saturated thickness normal to the hillslope 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 hillslope length (m), and 1000 is a factor needed to convert meters to millimeters. This equation can be rearranged to solve for H_o:

$$H_o = \frac{2 \cdot SW_{ly,excess}}{1000 \cdot \phi_d \cdot L_{hill}} \tag{8.4.2}$$

The drainable porosity of the soil layer is calculated:

$$\phi_d = \phi_{soil} - \phi_{fc} \tag{8.4.3}$$

where ϕ_d is the drainable porosity of the soil layer (mm/mm), ϕ_{soil} is the total porosity of the soil layer (mm/mm), and ϕ_{fc} is the porosity of the soil layer filled with water when the layer is at field capacity water content (mm/mm).

A soil layer is considered to be saturated whenever the water content of the layer exceeds the layer's field capacity water content. The drainable volume of water stored in the saturated layer is calculated:

$$SW_{ly,excess} = SW_{ly} - FC_{ly} \qquad \text{if} \qquad SW_{ly} > FC_{ly} \qquad 8.4.4$$

$$SW_{ly,excess} = 0 \qquad \text{if} \qquad SW_{ly} \leq FC_{ly} \qquad 8.4.5$$

where SW_{ly} is the water content of the soil layer on a given day (mm H_2O) and FC_{ly} is the water content of the soil layer at field capacity (mm H_2O).

The net discharge at the hillslope outlet, Q_{lat}, is given by

$$Q_{lat} = 24 \cdot H_o \cdot v_{lat} \qquad 8.4.6$$

where Q_{lat} is the water discharged from the hillslope outlet (mm H_2O/day), H_o is the saturated thickness normal to the hillslope at the outlet expressed as a fraction of the total thickness (mm/mm), v_{lat} is the velocity of flow at the outlet (mm·h^{-1}), and 24 is a factor to convert hours to days.

Velocity of flow at the outlet is defined as

$$v_{lat} = K_{sat} \cdot \sin(\alpha_{hill}) \qquad 8.4.7$$

where K_{sat} is the saturated hydraulic conductivity (mm·h^{-1}) and α_{hill} is the slope of the hillslope segment. The slope is input to SWAT as the increase in elevation per unit distance (*slp*) which is equivalent to $\tan(\alpha_{hill})$. Because $\tan(\alpha_{hill}) \cong \sin(\alpha_{hill})$, equation 8.4.3 is modified to use the value for the slope as input to the model:

$$v_{lat} = K_{sat} \cdot \tan(\alpha_{hill}) = K_{sat} \cdot slp \qquad 8.4.8$$

Combining equations 8.4.2 and 8.4.8 with equation 8.4.6 yields the equation

$$Q_{lat} = 0.024 \cdot \left(\frac{2 \cdot SW_{ly,excess} \cdot K_{sat} \cdot slp}{\phi_d \cdot L_{hill}} \right) \qquad 8.4.9$$

where all terms are previously defined.

8.4.1 LATERAL FLOW LAG

In large subbasins with a time of concentration greater than 1 day, only a portion of the lateral flow will reach the main channel on the day it is generated. SWAT incorporates a lateral flow storage feature to lag a portion of lateral flow release to the main channel.

Once lateral flow is calculated, the amount of lateral flow released to the main channel is calculated:

$$Q_{lat} = \left(Q'_{lat} + Q_{latstor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-1}{TT_{lat}}\right]\right) \qquad 8.4.10$$

where Q_{lat} is the amount of lateral flow discharged to the main channel on a given day (mm H_2O), Q'_{lat} is the amount of lateral flow generated in the subbasin on a given day (mm H_2O), $Q_{latstor,i\text{-}1}$ is the lateral flow stored or lagged from the previous day (mm H_2O), and TT_{lag} is the lateral flow travel time (days).

The model will calculate lateral flow travel time or utilize a user-defined travel time. In the majority of cases, the user should allow the model to calculate the travel time. If drainage tiles are present in the HRU, lateral flow travel time is calculated:

$$TT_{lag} = \frac{tile_{lag}}{24} \qquad 8.4.11$$

where TT_{lag} is the lateral flow travel time (days) and $tile_{lag}$ is the drain tile lag time (hrs). In HRUs without drainage tiles, lateral flow travel time is calculated:

$$TT_{lag} = 10.4 \cdot \frac{L_{hill}}{K_{sat,mx}} \qquad 8.4.12$$

where TT_{lag} is the lateral flow travel time (days), L_{hill} is the hillslope length (m), and $K_{sat,mx}$ is the highest layer saturated hydraulic conductivity in the soil profile (mm/hr).

The expression $\left(1 - \exp\left[\frac{-1}{TT_{lag}}\right]\right)$ in equation 8.4.10 represents the fraction of the total available water that will be allowed to enter the reach on any one day. Figure 8-5 plots values for this expression at different values of TT_{lag}.

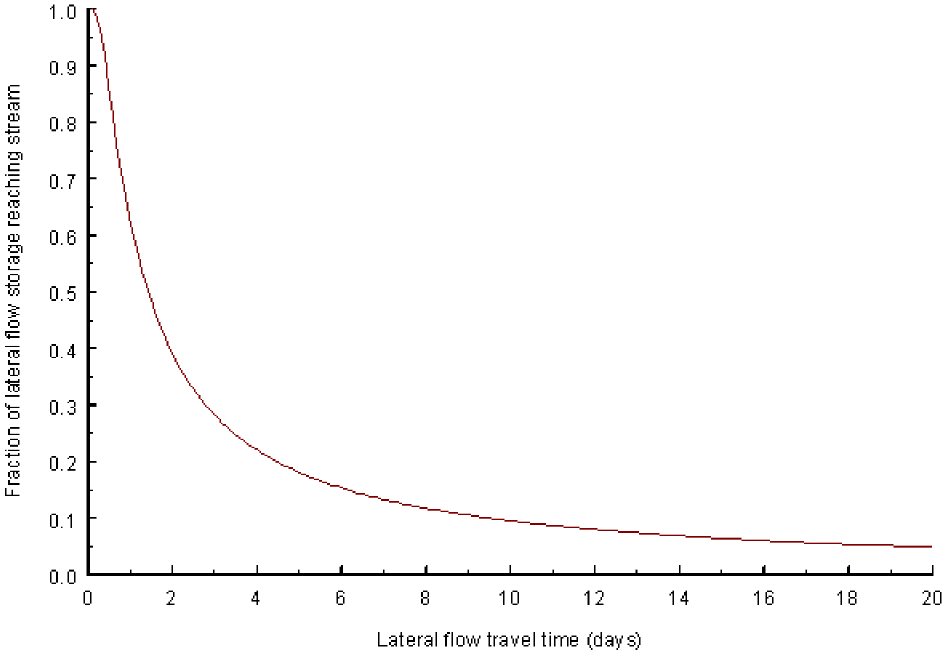

Figure 8-5: Influence of TT_{lag} on fraction of lateral flow released.

The delay in release of lateral flow will smooth the streamflow hydrograph simulated in the reach.

Table 8-5: SWAT input variables used in lateral flow calculations.

Variable name	**Definition**	**File Name**
SLSOIL	L_{hill}: Hillslope length (m)	.hru
SOL_K	K_{sat}: Saturated hydraulic conductivity (mm/hr)	.sol
SLOPE	slp: Average slope of the subbasin (m/m)	.hru
LAT_TTIME	TT_{lag}: Lateral flow travel time (days)	.hru
GDRAIN	$tile_{lag}$: Drain tile lag time (hrs)	.hru

8.5 NOMENCLATURE

AWC	Available water capacity (fraction or mm H_2O)
AWC_{ly}	Available water capacity of soil layer (fraction or mm H_2O)
FC	Water content of soil profile at field capacity (fraction or mm H_2O)
FC_{ly}	Water content of layer ly at field capacity (fraction or mm H_2O)
H_o	Saturated thickness normal to the hillslope at the outlet expressed as a fraction of the total thickness (mm/mm)
K_{sat}	Saturated hydraulic conductivity (mm/hr)
L_{hill}	Hillslope length (m)
M_S	Mass of the solids (Mg)
Q_{lat}	Lateral flow; water discharged from the hillslope outlet (mm H_2O/day)
$Q_{latstor,i-1}$	Lateral flow stored or lagged from the previous day (mm H_2O)
Q_{surf}	Accumulated runoff or rainfall excess (mm H_2O)
R_{day}	Amount of rainfall on a given day (mm H_2O)
SAT_{ly}	Amount of water in the soil layer when completely saturated (mm H_2O)
SW	Amount of water in soil profile (mm H_2O)
SW_{ly}	Soil water content of layer ly (mm H_2O)
$SW_{ly,excess}$	Drainable volume of water stored layer (mm H_2O)
TT_{lag}	Lateral flow travel time (days)
TT_{perc}	Travel time for percolation (hrs)
V_A	Volume of air (m^3)
V_S	Volume of solids (m^3)
V_T	Total soil volume (m^3)
V_W	Volume of water (m^3)
WP	Water content at wilting point (fraction or mm H_2O)
WP_{ly}	Water content of the soil layer at wilting point (fraction or mm H_2O)

$coef_{crk}$	Adjustment coefficient for crack flow
crk	Total crack volume for the soil profile on a given day (mm)
crk_{ly}	Crack volume for the soil layer on a given day expressed as a depth (mm)
$crk_{ly,d-1}$	Crack volume for the soil layer on the previous day (mm)
$crk_{ly,i}$	Initial crack volume calculated for the soil layer on a given day expressed as a depth (mm)
crk_{max}	Potential crack volume for the soil profile expressed as a fraction of the total volume
$crk_{max,ly}$	Maximum crack volume possible for the soil layer (mm)
$depth_{ly}$	Depth of the soil layer (mm)
m_c	Percent clay content
slp	Average slope of the subbasin (% or m/m)
$tile_{lag}$	Drain tile lag time (hrs).
v_{lat}	*V*elocity of flow at the hillslope outlet ($mm \cdot h^{-1}$)
$w_{crk,btm}$	Amount of water flow past the lower boundary of the soil profile due to bypass flow (mm H_2O)
w_{inf}	Amount of water entering the soil profile on a given day (mm H_2O)

$w_{perc,ly}$	Amount of water percolating to the underlying soil layer on a given day (mm H_2O)
$z_{l,ly}$	Depth from the surface to the bottom of the soil layer (mm)
α_{hill}	Slope of the hillslope segment (degrees)
Δt	Length of the time step (hrs)
ℓ_{crk}	Lag factor for crack development during drying
ρ_b	Bulk density (Mg m^{-3})
ρ_s	Particle density (Mg m^{-3})
ϕ_d	Drainable porosity of the soil (mm/mm)
ϕ_{fc}	Porosity of the soil layer filled with water when the layer is at field capacity water content (mm/mm)
ϕ_{soil}	Porosity of the soil (mm/mm)

8.6 REFERENCES

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CHAPTER 9

EQUATIONS: GROUNDWATER

Groundwater is water in the saturated zone of earth materials under pressure greater than atmospheric, i.e. positive pressure. Water enters groundwater storage primarily by infiltration/percolation, although recharge by seepage from surface water bodies may occur. Water leaves groundwater storage primarily by discharge into rivers or lakes, but it is also possible for water to move upward from the water table into the capillary fringe.

9.1 GROUNDWATER SYSTEMS

Within the saturated zone of groundwater, regions of high conductivity and low conductivity will be found. The regions of high conductivity are made up of coarse-grained particles with a large percentage of macropores that allow water to move easily. The regions of low conductivity are made up of fine-grained particles with a large percentage of mesopores and micropores that restrict the rate of water movement.

An aquifer is “a geologic unit that can store enough water and transmit it at a rate fast enough to be hydrologically significant” (Dingman, 1994). An unconfined aquifer is an aquifer whose upper boundary is the water table. The water table is defined as the depth at which the water pressure equals atmospheric pressure. A confined aquifer is an aquifer bounded above and below by geologic formations whose hydraulic conductivity is significantly lower than that of the aquifer. Figure 9-1 illustrates the two types of aquifers.

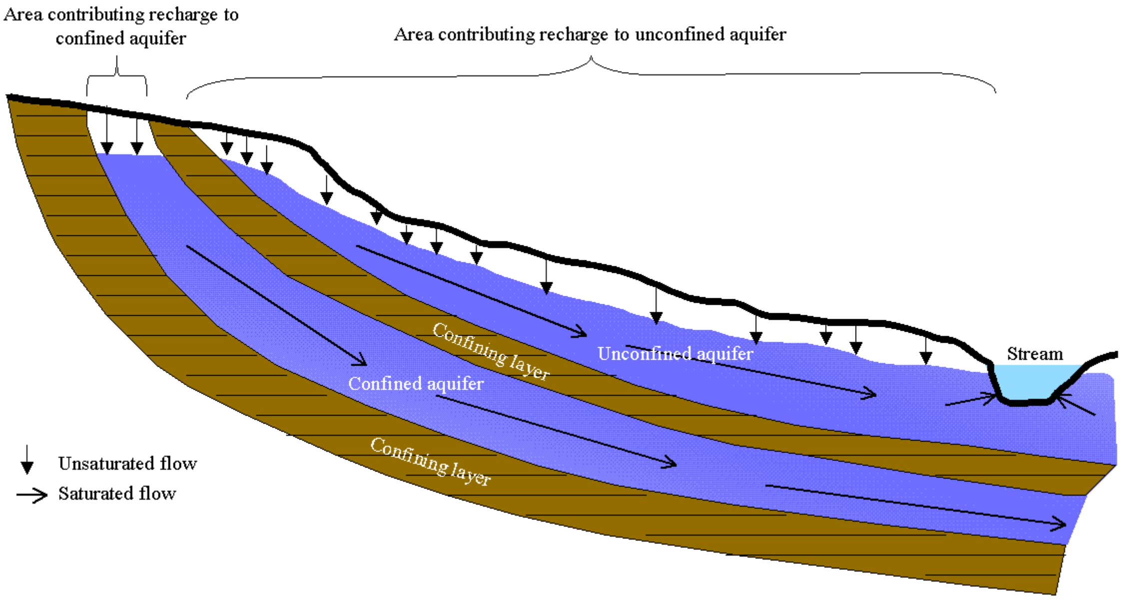

Figure 9-1: Unconfined and confined aquifers (After Dingman, 1994).

Recharge to unconfined aquifers occurs via percolation to the water table from a significant portion of the land surface. In contrast, recharge to confined aquifers by percolation from the surface occurs only at the upstream end of the confined aquifer, where the geologic formation containing the aquifer is exposed at the earth’s surface, flow is not confined, and a water table is present.

Topography exerts an important influence on groundwater flow. The flow of groundwater in an idealized hilly upland area is depicted in Figure 9-2. The landscape can be divided into areas of recharge and areas of discharge. A recharge area is defined as a portion of a drainage basin where ground water flow is directed away from the water table. A discharge area is defined as a portion of the drainage basin where ground water flow is directed toward the water table. The water table is at or near the surface in discharge areas and surface water bodies are normally located in discharge areas.

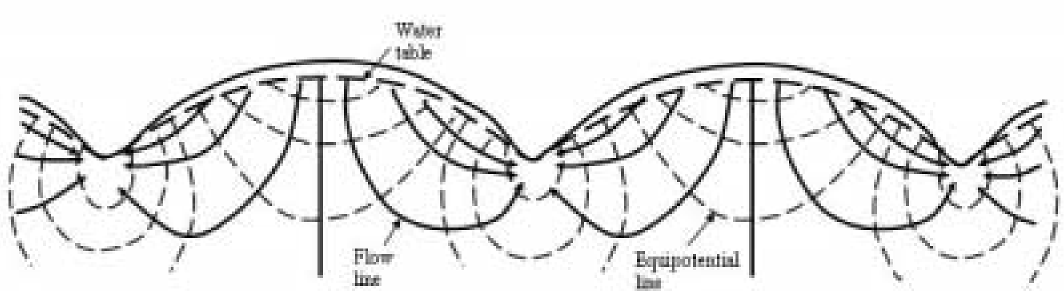

Figure 9-2: Groundwater flow net in an idealized hilly region with homogenous permeable material resting on an impermeable base (After Hubbert, 1940)

Streams may be categorized by their relationship to the groundwater system. A stream located in a discharge area that receives groundwater flow is a gaining or effluent stream (Figure 9-3a). This type of stream is characterized by an increase in discharge downstream. A stream located in a recharge area is a losing or influent stream. This type of stream is characterized by a decrease in discharge downstream. A losing stream may be connected to (Figure 9-3b) or perched above (Figure 9-3c) the groundwater flow area. A stream that simultaneously receives and loses groundwater is a flow-through stream (Figure 9-3d).

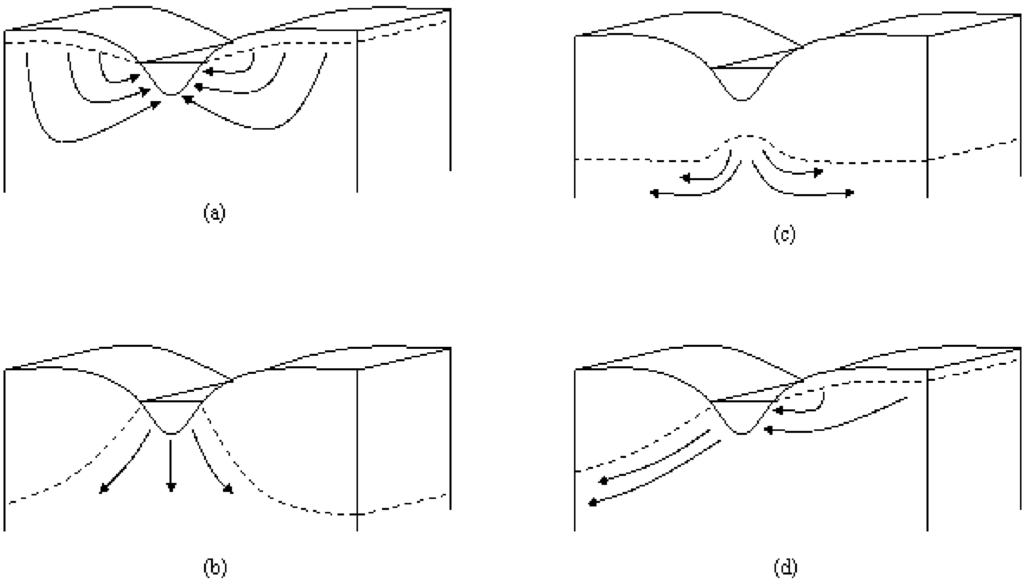

Figure 9-3: Stream-groundwater relationships: a) gaining stream receiving water from groundwater flow; b) losing stream connected to groundwater system; c) losing stream perched above groundwater system; and d) flow-through stream (After Dingman, 1994).

SWAT simulates two aquifers in each subbasin. The shallow aquifer is an unconfined aquifer that contributes to flow in the main channel or reach of the subbasin. The deep aquifer is a confined aquifer. Water that enters the deep aquifer is assumed to contribute to streamflow somewhere outside of the watershed (Arnold et al., 1993).

9.2 SHALLOW AQUIFER

The water balance for the shallow aquifer is:

$$aq_{sh,i} = aq_{sh,i-1} + w_{rchrg} - Q_{gw} - w_{revap} - w_{deep} - w_{pump,sh} \qquad 9.2.1$$

where $aq_{sh,i}$ is the amount of water stored in the shallow aquifer on day i (mm H_2O), $aq_{sh,i\text{-}1}$ is the amount of water stored in the shallow aquifer on day i-1 (mm H_2O), w_{rchrg} is the amount of recharge entering the aquifer on day i (mm H_2O), Q_{gw} is the groundwater flow, or base flow, into the main channel on day i (mm H_2O), w_{revap} is the amount of water moving into the soil zone in response to water deficiencies on day i (mm H_2O), w_{deep} is the amount of water percolating from the shallow aquifer into the deep aquifer on day *i* (mm H_2O), and $w_{pump,sh}$ is the amount of water removed from the shallow aquifer by pumping on day *i* (mm H_2O).

9.2.1 RECHARGE

Water that moves past the lowest depth of the soil profile by percolation or bypass flow enters and flows through the vadose zone before becoming shallow aquifer recharge. The lag between the time that water exits the soil profile and enters the shallow aquifer will depend on the depth to the water table and the hydraulic properties of the geologic formations in the vadose and groundwater zones.

An exponential decay weighting function proposed by Venetis (1969) and used by Sangrey et al. (1984) in a precipitation/groundwater response model is utilized in SWAT to account for the time delay in aquifer recharge once the water exits the soil profile. The delay function accommodates situations where the recharge from the soil zone to the aquifer is not instantaneous, i.e. 1 day or less.

The recharge to the aquifer on a given day is calculated:

$$w_{rchrg,i} = \left(1 - \exp\left[-1/\delta_{gw}\right]\right) \cdot w_{seep} + \exp\left[-1/\delta_{gw}\right] \cdot w_{rchrg,i-1} \qquad 9.2.2$$

where $w_{rchrg,i}$ is the amount of recharge entering the aquifer on day *i* (mm H_2O), δ_{gw} is the delay time or drainage time of the overlying geologic formations (days), w_{seep} is the total amount of water exiting the bottom of the soil profile on day *i* (mm H_2O), and $w_{rchrg,i-1}$ is the amount of recharge entering the aquifer on day *i*-1 (mm H_2O). The total amount of water exiting the bottom of the soil profile on day *i* is calculated:

$$w_{seep} = w_{perc,ly=n} + w_{crk,btm} \qquad 9.2.3$$

where w_{seep} is the total amount of water exiting the bottom of the soil profile on day *i* (mm H_2O), $w_{perc,ly=n}$ is the amount of water percolating out of the lowest layer, *n*, in the soil profile on day *i* (mm H_2O), and $w_{crk,btm}$ is the amount of water flow past the lower boundary of the soil profile due to bypass flow on day *i* (mm H_2O).

The delay time, δ_{gw}, cannot be directly measured. It can be estimated by simulating aquifer recharge using different values for δ_{gw} and comparing the simulated variations in water table level with observed values. Johnson (1977) developed a simple program to iteratively test and statistically evaluate different delay times for a watershed. Sangrey et al. (1984) noted that monitoring wells in the same area had similar values for δ_{gw}, so once a delay time value for a geomorphic area is defined, similar delay times can be used in adjoining watersheds within the same geomorphic province.

9.2.2 GROUNDWATER/BASE FLOW

The shallow aquifer contributes base flow to the main channel or reach within the subbasin. Base flow is allowed to enter the reach only if the amount of water stored in the shallow aquifer exceeds a threshold value specified by the user, $aq_{shthr,q}$.

The steady-state response of groundwater flow to recharge is (Hooghoudt, 1940):

$$Q_{gw} = \frac{8000 \cdot K_{sat}}{L_{gw}^{\ 2}} \cdot h_{wtbl} \qquad 9.2.4$$

where Q_{gw} is the groundwater flow, or base flow, into the main channel on day i (mm H_2O), K_{sat} is the hydraulic conductivity of the aquifer (mm/day), L_{gw} is the distance from the ridge or subbasin divide for the groundwater system to the main channel (m), and h_{wtbl} is the water table height (m).

Water table fluctuations due to non-steady-state response of groundwater flow to periodic recharge is calculated (Smedema and Rycroft, 1983):

$$\frac{dh_{wtbl}}{dt} = \frac{w_{rchrg} - Q_{gw}}{800 \cdot \mu} \qquad 9.2.5$$

where $\frac{dh_{wtbl}}{dt}$ is the change in water table height with time (mm/day), w_{rchrg} is the amount of recharge entering the aquifer on day i (mm H_2O), Q_{gw} is the groundwater flow into the main channel on day i (mm H_2O), and μ is the specific yield of the shallow aquifer (m/m).

Assuming that variation in groundwater flow is linearly related to the rate of change in water table height, equations 9.2.5 and 9.2.4 can be combined to obtain:

$$\frac{dQ_{gw}}{dt} = 10 \cdot \frac{K_{sat}}{\mu \cdot L_{gw}^{\ 2}} \cdot \left(w_{rchrg} - Q_{gw}\right) = \alpha_{gw} \cdot \left(w_{rchrg} - Q_{gw}\right) \qquad 9.2.6$$

where Q_{gw} is the groundwater flow into the main channel on day i (mm H_2O), K_{sat} is the hydraulic conductivity of the aquifer (mm/day), μ is the specific yield of the shallow aquifer (m/m), L_{gw} is the distance from the ridge or subbasin divide for the groundwater system to the main channel (m), w_{rchrg} is the amount of recharge entering the aquifer on day i (mm H_2O) and α_{gw} is the baseflow recession constant or constant of proportionality. Integration of equation 9.2.6 and rearranging to solve for Q_{gw} yields:

$$Q_{gw,i} = Q_{gw,i-1} \cdot \exp\left[-\alpha_{gw} \cdot \Delta t\right] + w_{rchrg} \cdot \left(1 - \exp\left[-\alpha_{gw} \cdot \Delta t\right]\right) \qquad 9.2.7$$

where $Q_{gw,i}$ is the groundwater flow into the main channel on day i (mm H_2O), $Q_{gw,i\text{-}1}$ is the groundwater flow into the main channel on day i-1 (mm H_2O), α_{gw} is the baseflow recession constant, Δt is the time step (1 day), and w_{rchrg} is the amount of recharge entering the aquifer on day i (mm H_2O).

The baseflow recession constant, α_{gw}, is a direct index of groundwater flow response to changes in recharge (Smedema and Rycroft, 1983). Values vary from 0.1-0.3 for land with slow response to recharge to 0.9-1.0 for land with a rapid response. Although the baseflow recession constant may be calculated, the best estimates are obtained by analyzing measured streamflow during periods of no recharge in the watershed.

When the shallow aquifer receives no recharge, equation 9.2.7 simplifies to:

$$Q_{gw} = Q_{gw,0} \cdot \exp\left[-\alpha_{gw} \cdot t\right] \qquad 9.2.8$$

where Q_{gw} is the groundwater flow into the main channel at time t (mm H_2O), $Q_{gw,0}$ is the groundwater flow into the main channel at the beginning of the recession (time t=0) (mm H_2O), α_{gw} is the baseflow recession constant, and t is the time lapsed since the beginning of the recession (days). The baseflow recession constant is measured by rearranging equation 9.2.8.

$$\alpha_{gw} = \frac{1}{N} \cdot \ln\left[\frac{Q_{gw,N}}{Q_{gw,0}}\right] \qquad 9.2.9$$

where α_{gw} is the baseflow recession constant, N is the time lapsed since the start of the recession (days), $Q_{gw,N}$ is the groundwater flow on day N (mm H_2O), $Q_{gw,0}$ is the groundwater flow at the start of the recession (mm H_2O).

It is common to find the baseflow days reported for a stream gage or watershed. This is the number of days for base flow recession to decline through one log cycle. When baseflow days are used, equation 9.2.9 can be further simplified:

$$\alpha_{gw} = \frac{1}{N} \cdot \ln\left[\frac{Q_{gw,N}}{Q_{gw,0}}\right] = \frac{1}{BFD} \cdot \ln[10] = \frac{2.3}{BFD} \qquad 9.2.10$$

where α_{gw} is the baseflow recession constant, and BFD is the number of baseflow days for the watershed.

9.2.3 REVAP

Water may move from the shallow aquifer into the overlying unsaturated zone. In periods when the material overlying the aquifer is dry, water in the capillary fringe that separates the saturated and unsaturated zones will evaporate and diffuse upward. As water is removed from the capillary fringe by evaporation, it is replaced by water from the underlying aquifer. Water may also be removed from the aquifer by deep-rooted plants which are able to uptake water directly from the aquifer.

SWAT models the movement of water into overlying unsaturated layers as a function of water demand for evapotranspiration. To avoid confusion with soil evaporation and transpiration, this process has been termed ‘revap’. This process is significant in watersheds where the saturated zone is not very far below the surface or where deep-rooted plants are growing. Because the type of plant cover will affect the importance of revap in the water balance, the parameters governing revap are usually varied by land use. Revap is allowed to occur only if the amount of water stored in the shallow aquifer exceeds a threshold value specified by the user, $aq_{shthr,rvp}$.

The maximum amount of water than will be removed from the aquifer via 'revap' on a given day is:

$$w_{revap,mx} = \beta_{rev} \cdot E_o \qquad 9.2.11$$

where $w_{revap,mx}$ is the maximum amount of water moving into the soil zone in response to water deficiencies (mm H_2O), β_{rev} is the revap coefficient, and E_o is the potential evapotranspiration for the day (mm H_2O). The actual amount of revap that will occur on a given day is calculated:

$$w_{revap} = 0 \qquad \text{if } aq_{sh} \le aq_{shthr,rvp} \qquad 9.2.12$$

$$w_{revap} = w_{revap,mx} - aq_{shthr,rvp} \qquad \text{if } aq_{shthr,rvp} < aq_{sh} < \left(aq_{shthr,rvp} + w_{revap,mx}\right) \qquad 9.2.13$$

$$w_{revap} = w_{revap,mx} \qquad \text{if } aq_{sh} \ge \left(aq_{shthr,rvp} + w_{revap,mx}\right) \qquad 9.2.14$$

where w_{revap} is the actual amount of water moving into the soil zone in response to water deficiencies (mm H_2O), $w_{revap,mx}$ is the maximum amount of water moving into the soil zone in response to water deficiencies (mm H_2O), aq_{sh} is the amount of water stored in the shallow aquifer at the beginning of day i (mm H_2O) and $aq_{shthr,rvp}$ is the threshold water level in the shallow aquifer for revap or percolation to deep aquifer to occur (mm H_2O).

9.2.4 PERCOLATION TO DEEP AQUIFER

A fraction of the total daily recharge can be routed to the deep aquifer. Percolation to the deep aquifer is allowed to occur only if the amount of water stored in the shallow aquifer exceeds a threshold value specified by the user, $aq_{shthr,rvp}$.

The maximum amount of water than will be removed from the shallow aquifer via percolation to the deep aquifer on a given day is:

$$w_{deep,mx} = \beta_{deep} \cdot w_{rchrg} \qquad 9.2.15$$

where $w_{deep,mx}$ is the maximum amount of water moving into the deep aquifer on day i (mm H_2O), β_{deep} is the aquifer percolation coefficient, and w_{rchrg} is the amount of recharge entering the aquifer on day i (mm H_2O). The actual amount of percolation to the deep aquifer that will occur on a given day is calculated:

$$w_{deep} = 0 \qquad \text{if } aq_{sh} \le aq_{shthr,rvp} \tag{9.2.12}$$

$$w_{deep} = w_{deep,mx} - aq_{shthr,rvp} \qquad \text{if } aq_{shthr,rvp} < aq_{sh} < \left(aq_{shthr,rvp} + w_{revap,mx}\right) \tag{9.2.13}$$

$$w_{deep} = w_{deep,mx} \qquad \text{if } aq_{sh} \ge \left(aq_{shthr,rvp} + w_{revap,mx}\right) \tag{9.2.14}$$

where w_{deep} is the actual amount of water moving into the deep aquifer on day i (mm H_2O), $w_{deep,mx}$ is the maximum amount of water moving into the deep aquifer on day i (mm H_2O), aq_{sh} is the amount of water stored in the shallow aquifer at the beginning of day i (mm H_2O) and $aq_{shthr,rvp}$ is the threshold water level in the shallow aquifer for revap or percolation to deep aquifer to occur (mm H_2O).

9.2.5 PUMPING

If the shallow aquifer is specified as the source of irrigation water or water removed for use outside the watershed, the model will allow an amount of water up to the total volume of the shallow aquifer to be removed on any given day. Detailed information on water management may be found in Chapter 21.

9.2.6 GROUNDWATER HEIGHT

Although SWAT does not currently print groundwater height in the output files, the water table height is updated daily by the model. Groundwater height is related to groundwater flow by equation 9.2.4.

$$Q_{gw} = \frac{8000 \cdot K_{sat}}{L_{gw}^{2}} \cdot h_{wtbl} = \frac{8000 \cdot \mu}{10} \cdot \frac{10 \cdot K_{sat}}{\mu \cdot L_{gw}^{2}} \cdot h_{wtbl} = 800 \cdot \mu \cdot \alpha_{gw} \cdot h_{wtbl} \tag{9.2.15}$$

where Q_{gw} is the groundwater flow into the main channel on day i (mm H_2O), K_{sat} is the hydraulic conductivity of the aquifer (mm/day), L_{gw} is the distance from the ridge or subbasin divide for the groundwater system to the main channel (m), h_{wtbl} is the water table height (m), μ is the specific yield of the shallow aquifer (m/m), and α_{gw} is the baseflow recession constant. Substituting this definition for Q_{gw} into equation 9.2.7 gives

$$h_{wtbl,i} = h_{wtbl,i-1} \cdot \exp\left[-\alpha_{gw} \cdot \Delta t\right] + \frac{w_{rchrg} \cdot \left(1 - \exp\left[-\alpha_{gw} \cdot \Delta t\right]\right)}{800 \cdot \mu \cdot \alpha_{gw}} \tag{9.2.16}$$

where $h_{wtbl,i}$ is the water table height on day i (m), $h_{wtbl,i-1}$ is the water table height on day i-1 (m), α_{gw} is the baseflow recession constant, Δt is the time step (1 day),

w_{rchrg} is the amount of recharge entering the aquifer on day i (mm H_2O), and μ is the specific yield of the shallow aquifer (m/m).

Table 9-1: SWAT input variables used in shallow aquifer calculations.

Variable name	Definition	File Name
GW_DELAY	δ_{gw}: Delay time for aquifer recharge (days)	.gw
GWQMN	$aq_{shthr,q}$: Threshold water level in shallow aquifer for base flow (mm H_2O)	.gw
ALPHA_BF	α_{gw}: Baseflow recession constant	.gw
REVAPMN	$aq_{shthr,rvp}$: Threshold water level in shallow aquifer for revap or percolation to deep aquifer (mm H_2O)	.gw
GW_REVAP	β_{rev}: Revap coefficient	.gw
RCHRG_DP	β_{deep}: Aquifer percolation coefficient	.gw
GW_SPYLD	μ: Specific yield of the shallow aquifer (m/m)	.gw

9.3 DEEP AQUIFER

The water balance for the deep aquifer is:

$$aq_{dp,i} = aq_{dp,i-1} + w_{deep} - w_{pump,dp} \qquad 9.3.1$$

where $aq_{dp,i}$ is the amount of water stored in the deep aquifer on day i (mm H_2O), $aq_{dp,i\text{-}1}$ is the amount of water stored in the deep aquifer on day i-1 (mm H_2O), w_{deep} is the amount of water percolating from the shallow aquifer into the deep aquifer on day i (mm H_2O), and $w_{pump,dp}$ is the amount of water removed from the deep aquifer by pumping on day i (mm H_2O). The amount of water percolating into the deep aquifer is calculated with the equations reviewed in section 9.2.4. If the deep aquifer is specified as the source of irrigation water or water removed for use outside the watershed, the model will allow an amount of water up to the total volume of the deep aquifer to be removed on any given day.

Water entering the deep aquifer is not considered in future water budget calculations and can be considered to be lost from the system.

9.4 NOMENCLATURE

BFD	Number of baseflow days for the watershed
E_o	Potential evapotranspiration (mm d^{-1})
K_{sat}	Hydraulic conductivity of the aquifer (mm/day)
L_{gw}	Distance from the ridge or subbasin divide for the groundwater system to the main channel (m)
N	Time lapsed since the start of the recession (days)
Q_{gw}	Groundwater flow, or base flow, into the main channel (mm H_2O)
$Q_{gw,0}$	Groundwater flow at the start of the recession (mm H_2O)
$Q_{gw,N}$	Groundwater flow on day N (mm H_2O)
aq_{dp}	Amount of water stored in the deep aquifer (mm H_2O)
aq_{sh}	Amount of water stored in the shallow aquifer (mm H_2O)
$aq_{shthr,q}$	Threshold water level in shallow aquifer for base flow (mm H_2O)
$aq_{shthr,rvp}$	Threshold water level in shallow aquifer for revap or percolation to deep aquifer (mm H_2O)
h_{wtbl}	Water table height (m)
$w_{crk,btm}$	Amount of water flow past the lower boundary of the soil profile due to bypass flow (mm H_2O)
w_{deep}	Amount of water percolating from the shallow aquifer into the deep aquifer (mm H_2O)
$w_{deep,mx}$	Maximum amount of water moving into the deep aquifer (mm H_2O)
$w_{pump,dp}$	Amount of water removed from the deep aquifer by pumping (mm H_2O)
$w_{pump,sh}$	Amount of water removed from the shallow aquifer by pumping (mm H_2O)
w_{rchrg}	Amount of water entering the aquifer via recharge (mm H_2O)
w_{revap}	Amount of water moving into the soil zone in response to water deficiencies (mm H_2O)
$w_{revap,mx}$	Maximum amount of water moving into the soil zone in response to water deficiencies on day i (mm H_2O)
w_{seep}	Total amount of water exiting the bottom of the soil profile (mm H_2O)
α_{gw}	Baseflow recession constant
β_{deep}	Aquifer percolation coefficient
β_{rev}	Revap coefficient
δ_{gw}	Delay time or drainage time for aquifer recharge (days)
μ	Specific yield of the shallow aquifer (m/m)

9.5 REFERENCES

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NUTRIENTS/PESTICIDES

The fate and transport of nutrients and pesticides in a watershed depend on the transformations the compounds undergo in the soil environment. SWAT models the complete nutrient cycle for nitrogen and phosphorus as well as the degradation of any pesticides applied in an HRU.

The following three chapters review the methodology used by SWAT to simulate nutrient and pesticide processes in the soil.

CHAPTER 10

EQUATIONS: NITROGEN

The complexity of the nitrogen cycle and nitrogen's importance in plant growth have made this element the subject of much research. The nitrogen cycle is a dynamic system that includes the water, atmosphere and soil. Plants require nitrogen more than any other essential element, excluding carbon, oxygen and hydrogen.

10.1 NITROGEN CYCLE

The three major 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 or residue application, fixation by symbiotic or nonsymbiotic bacteria, and rain. Nitrogen is removed from the soil by plant uptake, leaching, volatilization, denitrification and erosion. Figure 10-1 shows the major components of the nitrogen cycle.

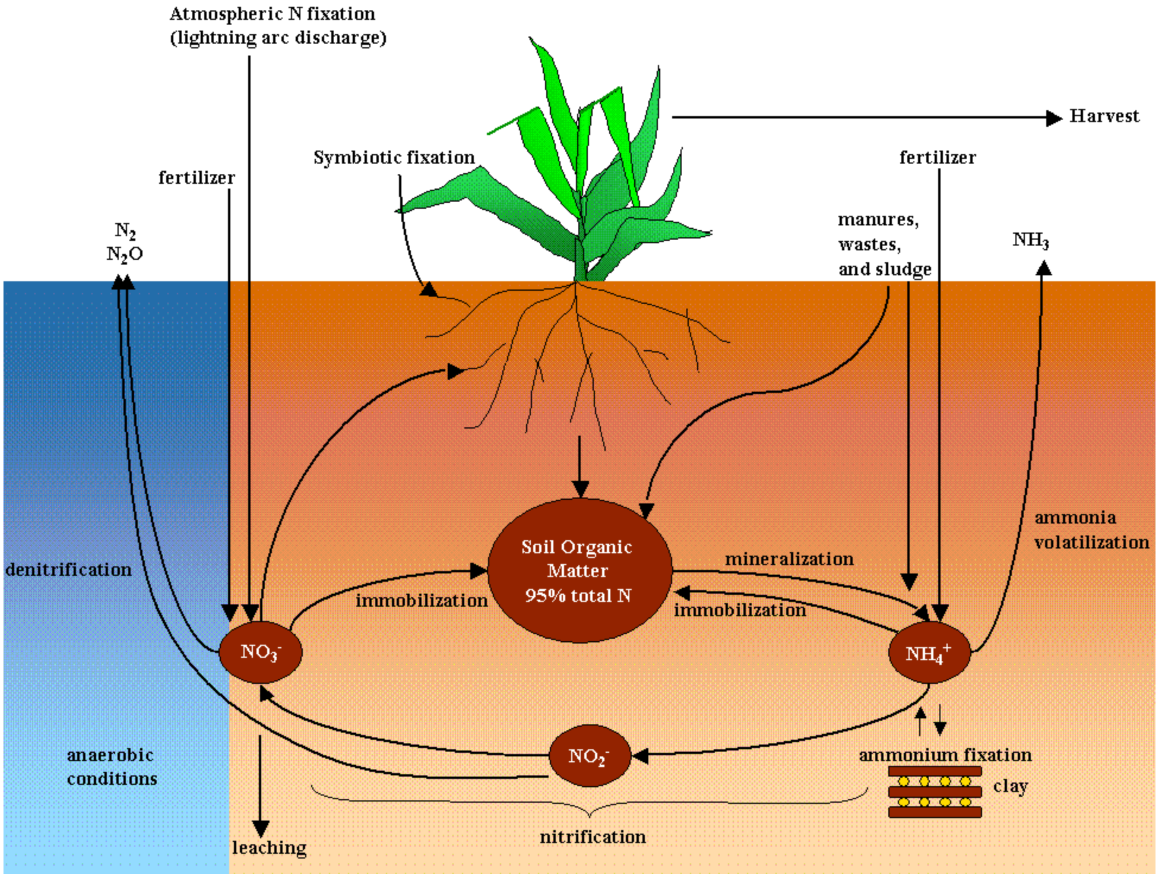

Figure 10-1: The nitrogen cycle

Nitrogen is considered to be an extremely reactive element. The highly reactive nature of nitrogen results from its ability to exist in a number of valance states. The valence state or oxidation state describes the number of electrons orbiting the nucleus of the nitrogen atom relative to the number present in an electronically neutral atom. The valence state will be positive as the atom looses electrons and will be negative as the atom gains electrons. Examples of nitrogen in different valence states are:

most oxidized	+5	NO_3^-	nitrate
	+4	NO_2	nitrogen dioxide
	+3	NO_2^-	nitrite
	+2	NO	nitrogen monoxide (gas)
	+1	N_2O	nitrous oxide (laughing gas)
	0	N_2	N_2 gas or elemental N
	-1	NH_4OH	hydroxylamine
	-2	N_2H_4	hydrozine
most reduced	-3	NH_3 or NH_4^+	ammonia gas or ammonium

The ability of nitrogen to vary its valence state makes it a highly mobile element. Predicting the movement of nitrogen between the different pools in the soil is critical to the successful management of this element in the environment.

SWAT monitors five different pools of nitrogen in the soil (Figure 10-2). Two pools are inorganic forms of nitrogen, NH_4^+ and NO_3^-, while the other three pools are organic forms of nitrogen. Fresh organic N is associated with crop residue and microbial biomass while the active and stable organic N pools are associated with the soil humus. The organic nitrogen associated with humus is partitioned into two pools to account for the variation in availability of humic substances to mineralization.

NITROGEN

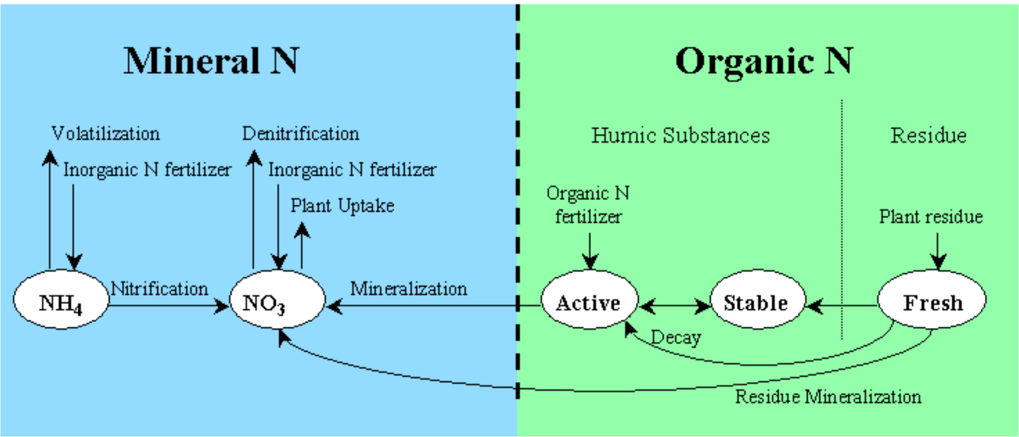

Figure 10-2: SWAT soil nitrogen pools and processes that move nitrogen in and out of pools.

10.1.1 INITIALIZATION OF SOIL NITROGEN LEVELS

Users may define the amount of nitrate and organic nitrogen contained in humic substances for all soil layers at the beginning of the simulation. If the user does not specify initial nitrogen concentrations, SWAT will initialize levels of nitrogen in the different pools.

Initial nitrate levels in the soil are varied by depth using the relationship:

$$NO3_{conc,z} = 7 \cdot \exp\left(\frac{-z}{1000}\right) \qquad 10.1.1$$

where $NO3_{conc,z}$ is the concentration of nitrate in the soil at depth z (mg/kg or ppm), and z is the depth from the soil surface (mm). The nitrate concentration with depth calculated from equation 10.1.1 is displayed in Figure 10-3. The nitrate concentration for a layer is calculated by solving equation 10.1.1 for the horizon’s lower boundary depth.

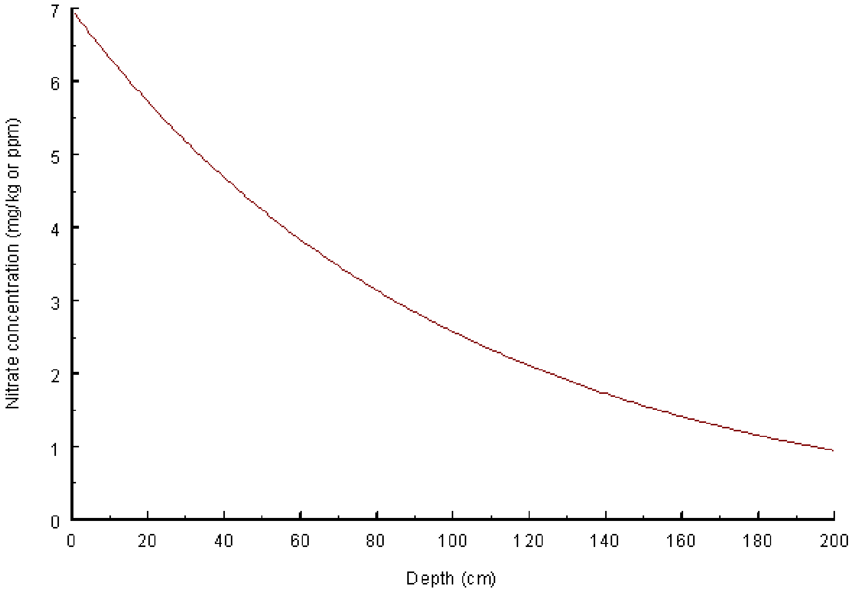

Figure 10-3: Nitrate concentration with depth.

Organic nitrogen levels are assigned assuming that the C:N ratio for humic materials is 14:1. The concentration of humic organic nitrogen in a soil layer is calculated:

$$orgN_{hum,ly} = 10^4 \cdot \left(\frac{orgC_{ly}}{14}\right) \qquad 10.1.2$$

where $orgN_{hum,ly}$ is the concentration of humic organic nitrogen in the layer (mg/kg or ppm), and $orgC_{ly}$ is the amount of organic carbon in the layer (%). The humic organic N is partitioned between the active and stable pools using the following equations:

$$orgN_{act,ly} = orgN_{hum,ly} \cdot fr_{actN} \qquad 10.1.3$$

$$orgN_{sta,ly} = orgN_{hum,ly} \cdot (1 - fr_{actN}) \qquad 10.1.4$$

where $orgN_{act,ly}$ is the concentration of nitrogen in the active organic pool (mg/kg), $orgN_{hum,ly}$ is the concentration of humic organic nitrogen in the layer (mg/kg), fr_{actN} is the fraction of humic nitrogen in the active pool, and $orgN_{sta,ly}$ is the concentration of nitrogen in the stable organic pool (mg/kg). The fraction of humic nitrogen in the active pool, fr_{actN}, is set to 0.02.

Nitrogen in the fresh organic pool is set to zero in all layers except the top 10 mm of soil. In the top 10 mm, the fresh organic nitrogen pool is set to 0.15% of the initial amount of residue on the soil surface.

$$orgN_{frsh,surf} = 0.0015 \cdot rsd_{surf} \qquad 10.1.5$$

where $orgN_{frsh,surf}$ is the nitrogen in the fresh organic pool in the top 10 mm (kg N/ha), and rsd_{surf} is material in the residue pool for the top 10 mm of soil (kg/ha).

The ammonium pool for soil nitrogen, $NH4_{ly}$, is initialized to 0 ppm.

While SWAT allows nutrient levels to be input as concentrations, it performs all calculations on a mass basis. To convert a concentration to a mass, the concentration is multiplied by the bulk density and depth of the layer and divided by 100:

$$\frac{conc_N \cdot \rho_b \cdot depth_{ly}}{100} = \frac{\text{kg N}}{\text{ha}} \qquad 10.1.6$$

where $conc_N$ is the concentration of nitrogen in a layer (mg/kg or ppm), ρ_b is the bulk density of the layer (Mg/m^3), and $depth_{ly}$ is the depth of the layer (mm).

Table 10-1: SWAT input variables that pertain to nitrogen pools.

Variable Name	Definition	Input File
SOL_NO3	$NO3_{conc,ly}$: Initial NO_3 concentration in soil layer (mg/kg or ppm)	.chm
SOL_ORGN	$orgN_{hum,ly}$: Initial humic organic nitrogen in soil layer (mg/kg or ppm)	.chm
RSDIN	rsd_{surf}: Material in the residue pool for the top 10mm of soil (kg ha^{-1})	.hru
SOL_BD	ρ_b: Bulk density of the layer (Mg/m^3)	.sol
SOL_CBN	$orgC_{ly}$: Amount of organic carbon in the layer (%)	.sol

10.2 MINERALIZATION & DECOMPOSITION / IMMOBILIZATION

Decomposition is the breakdown of fresh organic residue into simpler organic components. Mineralization is the microbial conversion of organic, plant-unavailable nitrogen to inorganic, plant-available nitrogen. Immobilization is the microbial conversion of plant-available inorganic soil nitrogen to plant-unavailable organic nitrogen.

Bacteria decompose organic material to obtain energy for growth processes. Plant residue is broken down into glucose which is then converted to energy:

$$C_6H_{12}O_6 + O_2 \xrightarrow{\text{energy released}} 6CO_2 + 6H_2O$$

The energy released by the conversion of glucose to carbon dioxide and water is used for various cell processes, including protein synthesis. Protein synthesis requires nitrogen. If the residue from which the glucose is obtained contains enough nitrogen, the bacteria will use nitrogen from the organic material to meet the demand for protein synthesis. If the nitrogen content of the residue is too low to meet the bacterial demand for nitrogen, the bacteria will use NH_4^+ and NO_3^- from the soil solution to meet its needs. If the nitrogen content of the residue exceeds the bacterial demand for nitrogen, the bacterial will release the excess nitrogen into soil solution as NH_4^+. A general relationship between C:N ratio and mineralization/immobilization is:

C:N > 30:1	immobilization occurs, a net decrease in soil NH_4^+ and NO_3^-
20:1 ≤ C:N ≤ 30:1	expect no net change; immobilization and mineralization processes are at equilibrium

C:N < 20:1 mineralization occurs, a net gain in soil NH_4^+ and NO_3^-

The nitrogen mineralization algorithms in SWAT are **net** mineralization algorithms which incorporate immobilization into the equations. The algorithms were adapted from the PAPRAN mineralization model (Seligman and van Keulen, 1981). Two sources are considered for mineralization: the fresh organic N pool associated with crop residue and microbial biomass and the active organic N pool associated with soil humus. Mineralization and decomposition are allowed to occur only if the temperature of the soil layer is above 0°C.

Mineralization and decomposition are dependent on water availability and temperature. Two factors are used in the mineralization and decomposition equations to account for the impact of temperature and water on these processes.

The nutrient cycling temperature factor is calculated:

$$\gamma_{tmp,ly} = 0.9 \cdot \frac{T_{soil,ly}}{T_{soil,ly} + \exp\left[9.93 - 0.312 \cdot T_{soil,ly}\right]} + 0.1 \qquad 10.2.1$$

where $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly*, and $T_{soil,ly}$ is the temperature of layer *ly* (°C). The nutrient cycling temperature factor is never allowed to fall below 0.1.

The nutrient cycling water factor is calculated:

$$\gamma_{sw,ly} = \frac{SW_{ly}}{FC_{ly}} \qquad 10.2.2$$

where $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly*, SW_{ly} is the water content of layer *ly* on a given day (mm H_2O), and FC_{ly} is the water content of layer *ly* at field capacity (mm H_2O). The nutrient cycling water factor is never allowed to fall below 0.05.

10.2.1 HUMUS MINERALIZATION

Nitrogen is allowed to move between the active and stable organic pools in the humus fraction. The amount of nitrogen transferred from one pool to the other is calculated:

$$N_{trns,ly} = \beta_{trns} \cdot orgN_{act,ly} \cdot \left(\frac{1}{fr_{actN}} - 1\right) - orgN_{sta,ly} \qquad 10.2.3$$

$N_{trns,ly}$ is the amount of nitrogen transferred between the active and stable organic pools (kg N/ha), β_{trns} is the rate constant (1×10^{-5}), $orgN_{act,ly}$ is the amount of nitrogen in the active organic pool (kg N/ha), fr_{actN} is the fraction of humic nitrogen in the active pool (0.02), and $orgN_{sta,ly}$ is the amount of nitrogen in the stable organic pool (kg N/ha). When $N_{trns,ly}$ is positive, nitrogen is moving from the active organic pool to the stable organic pool. When $N_{trns,ly}$ is negative, nitrogen is moving from the stable organic pool to the active organic pool.

Mineralization from the humus active organic N pool is calculated:

$$N_{mina,ly} = \beta_{min} \cdot \left(\gamma_{tmp,ly} \cdot \gamma_{sw,ly}\right)^{1/2} \cdot orgN_{act,ly} \qquad 10.2.4$$

where $N_{mina,ly}$ is the nitrogen mineralized from the humus active organic N pool (kg N/ha), β_{min} is the rate coefficient for mineralization of the humus active organic nutrients, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly*, $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly*, $orgN_{act,ly}$ is the amount of nitrogen in the active organic pool (kg N/ha).

Nitrogen mineralized from the humus active organic pool is added to the nitrate pool in the layer.

10.2.2 RESIDUE DECOMPOSITION & MINERALIZATION

Decomposition and mineralization of the fresh organic nitrogen pool is allowed only in the first soil layer. Decomposition and mineralization are controlled by a decay rate constant that is updated daily. The decay rate constant is calculated as a function of the C:N ratio and C:P ratio of the residue, temperature and soil water content.

The C:N ratio of the residue is calculated:

$$\varepsilon_{C:N} = \frac{0.58 \cdot rsd_{ly}}{orgN_{frsh,ly} + NO3_{ly}} \qquad 10.2.5$$

where $\varepsilon_{C:N}$ is the C:N ratio of the residue in the soil layer, rsd_{ly} is the residue in layer *ly* (kg/ha), 0.58 is the fraction of residue that is carbon, $orgN_{frsh,ly}$ is the nitrogen in the fresh organic pool in layer *ly* (kg N/ha), and $NO3_{ly}$ is the amount of nitrate in layer *ly* (kg N/ha).

The C:P ratio of the residue is calculated:

$$\varepsilon_{C:P} = \frac{0.58 \cdot rsd_{ly}}{orgP_{frsh,ly} + P_{solution,ly}} \qquad 10.2.6$$

where $\varepsilon_{C:P}$ is the C:P ratio of the residue in the soil layer, rsd_{ly} is the residue in layer ly (kg/ha), 0.58 is the fraction of residue that is carbon, $orgP_{frsh,ly}$ is the phosphorus in the fresh organic pool in layer ly (kg P/ha), and $P_{solution,ly}$ is the amount of phosphorus in solution in layer ly (kg P/ha).

The decay rate constant defines the fraction of residue that is decomposed. The decay rate constant is calculated:

$$\delta_{ntr,ly} = \beta_{rsd} \cdot \gamma_{ntr,ly} \cdot \left(\gamma_{tmp,ly} \cdot \gamma_{sw,ly}\right)^{1/2} \qquad 10.2.7$$

where $\delta_{ntr,ly}$ is the residue decay rate constant, β_{rsd} is the rate coefficient for mineralization of the residue fresh organic nutrients, $\gamma_{ntr,ly}$ is the nutrient cycling residue composition factor for layer ly, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer ly, and $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer ly.

The nutrient cycling residue composition factor is calculated:

$$\gamma_{ntr,ly} = \min\begin{cases} \exp\left[-0.693 \cdot \dfrac{(\varepsilon_{C:N} - 25)}{25}\right] \\ \exp\left[-0.693 \cdot \dfrac{(\varepsilon_{C:P} - 200)}{200}\right] \\ 1.0 \end{cases} \qquad 10.2.8$$

where $\gamma_{ntr,ly}$ is the nutrient cycling residue composition factor for layer ly, $\varepsilon_{C:N}$ is the C:N ratio on the residue in the soil layer, and $\varepsilon_{C:P}$ is the C:P ratio on the residue in the soil layer.

Mineralization from the residue fresh organic N pool is then calculated:

$$N_{minf,ly} = 0.8 \cdot \delta_{ntr,ly} \cdot orgN_{frsh,ly} \qquad 10.2.9$$

where $N_{minf,ly}$ is the nitrogen mineralized from the fresh organic N pool (kg N/ha), $\delta_{ntr,ly}$ is the residue decay rate constant, and $orgN_{frsh,ly}$ is the nitrogen in the fresh organic pool in layer ly (kg N/ha). Nitrogen mineralized from the fresh organic pool is added to the nitrate pool in the layer.

Decomposition from the residue fresh organic N pool is calculated:

$$N_{dec,ly} = 0.2 \cdot \delta_{ntr,ly} \cdot orgN_{frsh,ly} \qquad 10.2.9$$

where $N_{dec,ly}$ is the nitrogen decomposed from the fresh organic N pool (kg N/ha), $\delta_{ntr,ly}$ is the residue decay rate constant, and $orgN_{frsh,ly}$ is the nitrogen in the fresh organic pool in layer ly (kg N/ha). Nitrogen decomposed from the fresh organic pool is added to the humus active organic pool in the layer.

Table 10-2: SWAT input variables that pertain to mineralization.

Variable Name	Definition	Input File
CMN	β_{min}: Rate coefficient for mineralization of the humus active organic nutrients	.bsn
RSDCO	β_{rsd}: Rate coefficient for mineralization of the residue fresh organic nutrients	.bsn
RSDCO_PL	β_{rsd}: Rate coefficient for mineralization of the residue fresh organic nutrients	crop.dat

10.3 NITRIFICATION & AMMONIA VOLATILIZATION

Nitrification is the two-step bacterial oxidation of NH_4^+ to NO_3^-.

step 1: $2NH_4^+ + 3O_2 \xrightarrow{-12e^-} 2NO_2^- + 2H_2O + 4H^+$ (*Nitrosomonas*)

step 2: $2NO_2^- + O_2 \xrightarrow{-4e^-} 2NO_3^-$ (*Nitrobacter*)

Ammonia volatilization is the gaseous loss of NH_3 that occurs when ammonium, NH_4^+, is surface applied to a calcareous soil or when urea, $(NH_2)_2CO$, is surface applied to any soil.

NH_4^+ surface applied to a calcareous soil:

step 1: $CaCO_3 + 2NH_4^+X \longleftrightarrow (NH_4)_2CO_3 + CaX_2$

step 2: $(NH_4)CO_3 \longleftrightarrow 2NH_3 + CO_2 + H_2O$

Urea surface applied to any soil:

step 1: $(NH_2)_2CO + 2H_2O \xleftrightarrow{\text{urease enzyme}} (NH_4)_2CO_3$

step 2: $(NH_4)_2CO_3 \longleftrightarrow 2NH_3 + CO_2 + H_2O$

SWAT simulates nitrification and ammonia volatilization using a combination of the methods developed by Reddy et al. (1979) and Godwin et al. (1984). The total amount of nitrification and ammonia volatilization is calculated, and then partitioned between the two processes. Nitrification is a function of soil temperature and soil water content while ammonia volatilization is a function of soil temperature and depth. Three coefficients are used in the nitrification/volatilization algorithms to account for the impact of these parameters. Nitrification/volatilization occurs only when the temperature of the soil layer exceeds 5°C.

The nitrification/volatilization temperature factor is calculated:

$$\eta_{tmp,ly} = 0.41 \cdot \frac{\left(T_{soil,ly} - 5\right)}{10} \qquad \text{if } T_{soil,ly} > 5 \qquad 10.3.1$$

where $\eta_{tmp,ly}$ is the nitrification/volatilization temperature factor, and $T_{soil,ly}$ is the temperature of layer *ly* (°C).

The nitrification soil water factor is calculated:

$$\eta_{sw,ly} = \frac{SW_{ly} - WP_{ly}}{0.25 \cdot \left(FC_{ly} - WP_{ly}\right)} \qquad \text{if } SW_{ly} - WP_{ly} < 0.25 \cdot \left(FC_{ly} - WP_{ly}\right) \qquad 10.3.2$$

$$\eta_{sw,ly} = 1.0 \qquad \text{if } SW_{ly} - WP_{ly} \geq 0.25 \cdot \left(FC_{ly} - WP_{ly}\right) \qquad 10.3.3$$

where $\eta_{sw,ly}$ is the nitrification soil water factor, SW_{ly} is the soil water content of layer *ly* on a given day (mm H_2O), WP_{ly} is the amount of water held in the soil layer at wilting point water content (mm H_2O), and FC_{ly} is the amount of water held in the soil layer at field capacity water content (mm H_2O).

The volatilization depth factor is calculated:

$$\eta_{midz,ly} = 1 - \frac{z_{mid,ly}}{z_{mid,ly} + \exp\left[4.706 - 0.305 \cdot z_{mid,ly}\right]} \qquad 10.3.4$$

where $\eta_{midz,ly}$ is the volatilization depth factor, and $z_{mid,ly}$ is the depth from the soil surface to the middle of the layer (mm).

The impact of environmental factors on nitrification and ammonia volatilization in a given layer is defined by the nitrification regulator and volatilization regulator. The nitrification regulator is calculated:

$$\eta_{nit,ly} = \eta_{tmp,ly} \cdot \eta_{sw,ly} \qquad 10.3.5$$

and the volatilization regulator is calculated:

$$\eta_{vol,ly} = \eta_{tmp,ly} \cdot \eta_{midz,ly} \qquad 10.3.6$$

where $\eta_{nit,ly}$ is the nitrification regulator, $\eta_{vol,ly}$ is the volatilization regulator, $\eta_{tmp,ly}$ is the nitrification/volatilization temperature factor, $\eta_{sw,ly}$ is the nitrification soil water factor, and $\eta_{midz,ly}$ is the volatilization depth factor.

The total amount of ammonium lost to nitrification and volatilization is calculated using a first-order kinetic rate equation (Reddy et al., 1979):

$$N_{nit|vol,ly} = NH4_{ly} \cdot \left(1 - \exp\left[-\eta_{nit,ly} - \eta_{vol,ly}\right]\right) \qquad 10.3.7$$

where $N_{nit|vol,ly}$ is the amount of ammonium converted via nitrification and volatilization in layer *ly* (kg N/ha), $NH4_{ly}$ is the amount of ammonium in layer *ly* (kg N/ha), $\eta_{nit,ly}$ is the nitrification regulator, and $\eta_{vol,ly}$ is the volatilization regulator.

To partition $N_{nit|vol,ly}$ between nitrification and volatilization, the expression by which $NH4_{ly}$ is multiplied in equation 10.3.7, is solved using each regulator individually to obtain a fraction of ammonium removed by each process:

$$fr_{nit,ly} = 1 - \exp\left[-\eta_{nit,ly}\right] \qquad 10.3.8$$

$$fr_{vol,ly} = 1 - \exp\left[-\eta_{vol,ly}\right] \qquad 10.3.9$$

where $fr_{nit,ly}$ is the estimated fraction of nitrogen lost by nitrification, $fr_{vol,ly}$ is the estimated fraction of nitrogen lost by volatilization, $\eta_{nit,ly}$ is the nitrification regulator, and $\eta_{vol,ly}$ is the volatilization regulator.

The amount of nitrogen removed from the ammonium pool by nitrification is then calculated:

$$N_{nit,ly} = \frac{fr_{nit,ly}}{\left(fr_{nit,ly} + fr_{vol,ly}\right)} \cdot N_{nit|vol,ly} \qquad 10.3.10$$

and the amount of nitrogen removed from the ammonium pool by volatilization is:

$$N_{vol,ly} = \frac{fr_{vol,ly}}{\left(fr_{nit,ly} + fr_{vol,ly}\right)} \cdot N_{nit|vol,ly} \qquad 10.3.11$$

where $N_{nit,ly}$ is the amount of nitrogen converted from NH_4^+ to NO_3^- in layer *ly* (kg N/ha), $N_{vol,ly}$ is the amount of nitrogen converted from NH_4^+ to NH_3 in layer *ly* (kg

N/ha), $fr_{nit,ly}$ is the estimated fraction of nitrogen lost by nitrification, $fr_{vol,ly}$ is the estimated fraction of nitrogen lost by volatilization, and $N_{nit|vol,ly}$ is the amount of ammonium converted via nitrification and volatilization in layer *ly* (kg N/ha)

10.4 DENITRIFICATION

Denitrification is the bacterial reduction of nitrate, NO_3^-, to N_2 or N_2O gases under anaerobic (reduced) conditions. Denitrification is a function of water content, temperature, presence of a carbon source and nitrate.

In general, when the water-filled porosity is greater than 60% denitrification will be observed in a soil. As soil water content increases, anaerobic conditions develop due to the fact that oxygen diffuses through water 10,000 times slower than through air. Because the rate of oxygen diffusion through water slows as the water temperature increases, temperature will also influence denitrification.

Cropping systems where water is ponded, such as rice, can lose a large fraction of fertilizer by denitrification. For a regular cropping system, an estimated 10-20% of nitrogen fertilizer may be lost to denitrification. Under a rice cropping system, 50% of nitrogen fertilizer may be lost to denitrification. In a flooded cropping system, the depth of water plays an important role because it controls the amount of water oxygen has to diffuse through to reach the soil.

SWAT determines the amount of nitrate lost to denitrification with the equation:

$$N_{denit,ly} = NO3_{ly} \cdot \left(1 - \exp\left[-1.4 \cdot \gamma_{tmp,ly} \cdot orgC_{ly}\right]\right) \quad \text{if} \quad \gamma_{sw,ly} \geq 0.95 \qquad 10.4.1$$

$$N_{denit,ly} = 0.0 \quad \text{if} \quad \gamma_{sw,ly} < 0.95 \qquad 10.4.2$$

where $N_{denit,ly}$ is the amount of nitrogen lost to denitrification (kg N/ha), $NO3_{ly}$ is the amount of nitrate in layer *ly* (kg N/ha), $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly* calculated with equation 10.2.1, $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly* calculated with equation 10.2.2, $orgC_{ly}$ is the amount of organic carbon in the layer (%).

Table 10-3: SWAT input variables that pertain to denitrification.

Variable Name	Definition	Input File
SOL_CBN	$orgC_{ly}$: Amount of organic carbon in the layer (%)	.sol

10.5 NITROGEN IN RAINFALL

Lightning discharge converts atmospheric N_2 to nitric acid which can then be transferred to the soil with precipitation. The chemical steps involved are:

step 1: $N_2 + O_2 \xrightarrow{\text{arc of electricity}} 2NO$ (monoxide)

step 2: $2NO + O_2 \longrightarrow NO_2$ (dioxide)

step 3: $3NO_2 + H_2O \longrightarrow 2HNO_2 + NO$ (nitric acid and monoxide)

More nitrogen will be added to the soil with rainfall in areas with a high amount of lightning activity than in areas with little lightning.

The amount of nitrate added to the soil in rainfall is calculated:

$$N_{rain} = 0.01 \cdot R_{NO3} \cdot R_{day} \qquad 10.5.1$$

where N_{rain} is nitrate added by rainfall (kg N/ha), R_{NO3} is the concentration of nitrogen in the rain (mg N/L), and R_{day} is the amount of precipitation on a given day (mm H_2O). The nitrogen in rainfall is added to the nitrate pool in the top 10 mm of soil.

Table 10-4: SWAT input variables that pertain to nitrogen in rainfall.

Variable Name	Definition	Input File
RCN	R_{NO3}: Concentration of nitrogen in the rain (mg N/L)	.bsn

10.6 FIXATION

Legumes are able to obtain a portion of their nitrogen demand through fixation of atmospheric N_2 performed by rhizobia living in association with the plant. In exchange for nitrogen, the plant supplies the bacteria with carbohydrates.

SWAT simulates nitrogen fixation by legumes when the soil does not supply the plant with the amount of nitrogen needed for growth. The nitrogen obtained by fixation is incorporated directly into the plant biomass and never enters the soil (unless plant biomass is added to the soil as residue after the plant is killed). The equations for nitrogen fixation by legumes are reviewed in Chapter 18.

10.7 UPWARD MOVEMENT OF NITRATE IN WATER

As water evaporates from the soil surface, the water content at the surface drops, creating a gradient in the profile. Water from lower in the profile will move upward in response to the gradient, carrying dissolved nutrients with it. SWAT allows nitrate to be transported from the first soil layer defined in the .sol file to the surface top 10 mm of soil with the equation:

$$N_{evap} = 0.1 \cdot NO3_{ly} \cdot \frac{E''_{soil,ly}}{SW_{ly}}$$

where N_{evap} is the amount of nitrate moving from the first soil layer to the soil surface zone (kg N/ha), $NO3_{ly}$ is the nitrate content of the first soil layer (kg N/ha), $E''_{soil,ly}$ is the amount of water removed from the first soil layer as a result of evaporation (mm H_2O), and SW_{ly} is the soil water content of the first soil layer (mm H_2O).

10.8 LEACHING

The majority of plant-essential nutrients are cations which are attracted and sorbed to negatively-charged soil particles. As plants extract these cations from soil solution, the soil particles release bound cations into soil solution to bring the ratio of nutrients in solution and on soil particles back into equilibrium. In effect, the soil buffers the concentration of cations in solution.

In contrast, nitrate is an anion and is not attracted to or sorbed by soil particles. Because retention of nitrate by soils is minimal, nitrate is very susceptible to leaching. The algorithms used by SWAT to calculated nitrate leaching simultaneously solve for loss of nitrate in surface runoff and lateral flow also. These algorithms are reviewed in Chapter 14.

10.9 NOMENCLATURE

$E''_{soil,ly}$	Amount of water removed from layer *ly* by evaporation (mm H_2O)
FC_{ly}	Water content of layer *ly* at field capacity (mm H_2O)
$N_{dec,ly}$	Nitrogen decomposed from the fresh organic N pool (kg N/ha)
$N_{denit,ly}$	Amount of nitrogen lost to denitrification (kg N/ha)
N_{evap}	Amount of nitrate moving from the first soil layer to the soil surface zone (kg N/ha)
$N_{mina,ly}$	Nitrogen mineralized from the humus active organic N pool (kg N/ha)
$N_{minf,ly}$	Nitrogen mineralized from the fresh organic N pool (kg N/ha)
$N_{nit,ly}$	Amount of nitrogen converted from NH_4^+ to NO_3^- in layer *ly* (kg N/ha)
$N_{nit\vert vol,ly}$	Amount of ammonium converted via nitrification and volatilization in layer *ly* (kg N/ha)
N_{rain}	Nitrate added by rainfall (kg N/ha)
$N_{trns,ly}$	Amount of nitrogen transferred between the active and stable organic pools (kg N/ha)
$N_{vol,ly}$	Amount of nitrogen converted from NH_4^+ to NH_3 in layer *ly* (kg N/ha)
$NH4_{ly}$	Ammonium content of layer *ly* (kg NH_4-N/ha)
$NO3_{conc,z}$	Concentration of nitrate in the soil at depth *z* (mg/kg or ppm)
$NO3_{ly}$	Nitrate content of soil layer *ly* (kg NO_3-N/ha)
$P_{solution,ly}$	Solution phosphorus content of soil layer *ly* (kg P/ha)
R_{day}	Amount of rainfall on a given day (mm H_2O)
R_{NO3}	Concentration of nitrogen in the rain (mg N/L)
SW_{ly}	Soil water content of layer *ly* (mm H_2O)
$T_{soil,ly}$	Temperature of layer *ly* (°C)
WP_{ly}	Water content of layer *ly* at wilting point (mm H_2O)

$conc_N$	Concentration of nitrogen in a layer (mg/kg or ppm)
$depth_{ly}$	Depth of the layer (mm)
fr_{actN}	Fraction of humic nitrogen in the active pool
$fr_{nit,ly}$	Estimated fraction of nitrogen lost by nitrification
$fr_{vol,ly}$	Estimated fraction of nitrogen lost by volatilization
$orgC_{ly}$	Amount of organic carbon in the layer (%)
$orgN_{act,ly}$	Nitrogen in the active organic pool in layer *ly* (mg/kg or kg N/ha)
$orgN_{frsh,ly}$	Nitrogen in the fresh organic pool in layer *ly* (kg N/ha)
$orgN_{hum,ly}$	Concentration of humic organic nitrogen in the layer (mg/kg or ppm)
$orgN_{sta,ly}$	Nitrogen in the stable organic pool in layer *ly* (mg/kg or kg N/ha)
$orgP_{frsh,ly}$	Phosphorus in the fresh organic pool in layer *ly* (kg P/ha)
rsd_{ly}	Residue in layer *ly* (kg/ha)
z	Depth below soil surface (mm)
$z_{mid,ly}$	Depth from the soil surface to the middle of the layer (mm)

β_{min}	Rate coefficient for mineralization of the humus active organic nutrients
β_{rsd}	Rate coefficient for mineralization of the residue fresh organic nutrients

β_{trns}	Rate constant for nitrogen transfer between active and stable organic pools (1×10^{-5})
$\delta_{ntr,ly}$	Residue decay rate constant
$\varepsilon_{C:N}$	Residue C:N ratio in the soil layer
$\varepsilon_{C:P}$	Residue C:P ratio in the soil layer
$\gamma_{ntr,ly}$	Nutrient cycling residue composition factor for layer *ly*
$\gamma_{sw,ly}$	Nutrient cycling water factor for layer *ly*
$\gamma_{tmp,ly}$	Nutrient cycling temperature factor for layer *ly*
$\eta_{midz,ly}$	Volatilization depth factor
$\eta_{nit,ly}$	Nitrification regulator
$\eta_{sw,ly}$	Nitrification soil water factor
$\eta_{tmp,ly}$	Nitrification/volatilization temperature factor
$\eta_{vol,ly}$	Volatilization regulator
ρ_b	Bulk density of the layer (Mg/m^3)

10.10 REFERENCES

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CHAPTER 11

EQUATIONS: PHOSPHORUS

Although plant phosphorus demand is considerably less than nitrogen demand, phosphorus is required for many essential functions. The most important of these is its role in energy storage and transfer. Energy obtained from photosynthesis and metabolism of carbohydrates is stored in phosphorus compounds for later use in growth and reproductive processes.

11.1 PHOSPHORUS CYCLE

The three major forms of phosphorus in mineral soils are organic phosphorus associated with humus, insoluble forms of mineral phosphorus, and plant-available phosphorus in soil solution. Phosphorus may be added to the soil by fertilizer, manure or residue application. Phosphorus is removed from the soil by plant uptake and erosion. Figure 11-1 shows the major components of the phosphorus cycle.

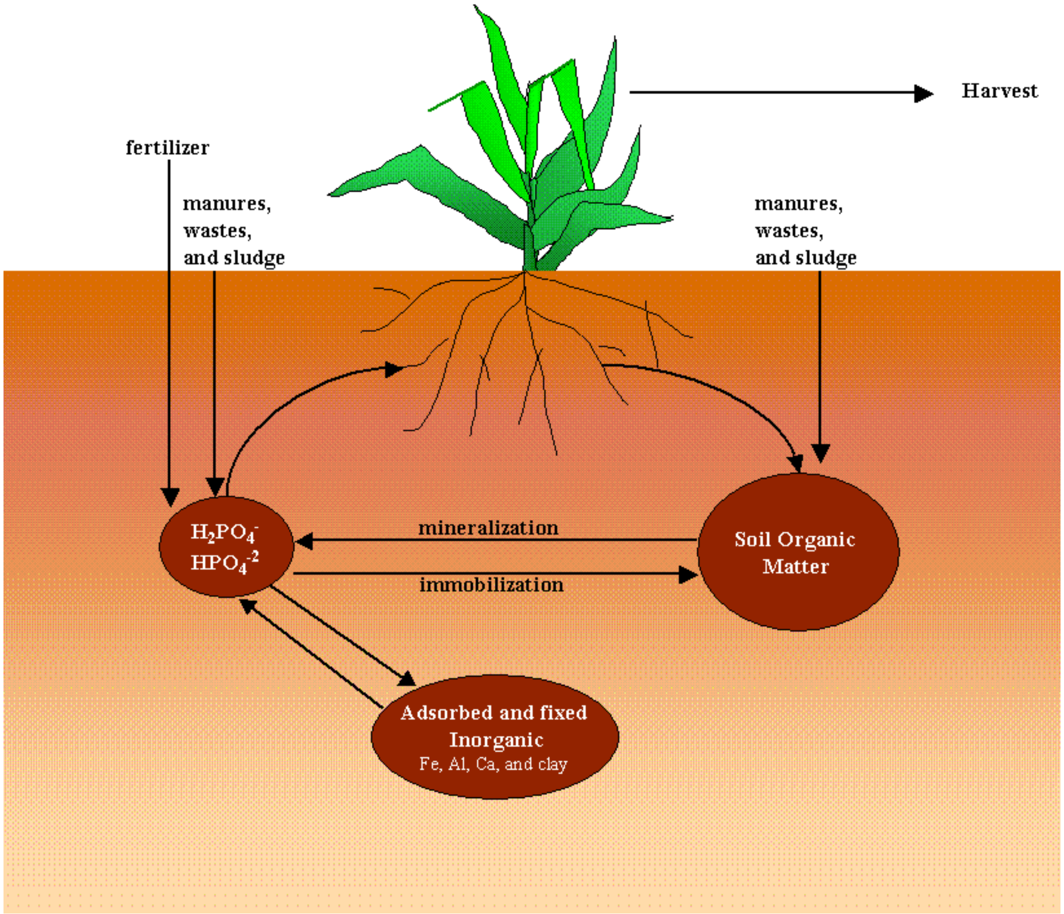

Figure 11-1: The phosphorus cycle

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. Sharpley and Syers (1979) observed that surface runoff is the primary mechanism by which phosphorus is exported from most catchments.

SWAT monitors six different pools of phosphorus in the soil (Figure 11-2). Three pools are inorganic forms of phosphorus while the other three pools are organic forms of phosphorus. Fresh organic P is associated with crop residue and microbial biomass while the active and stable organic P pools are associated with the soil humus. The organic phosphorus associated with humus is partitioned into two pools to account for the variation in availability of humic substances to mineralization. Soil inorganic P is divided into solution, active, and stable pools. The solution pool is in rapid equilibrium (several days or weeks) with the active pool. The active pool is in slow equilibrium with the stable pool.

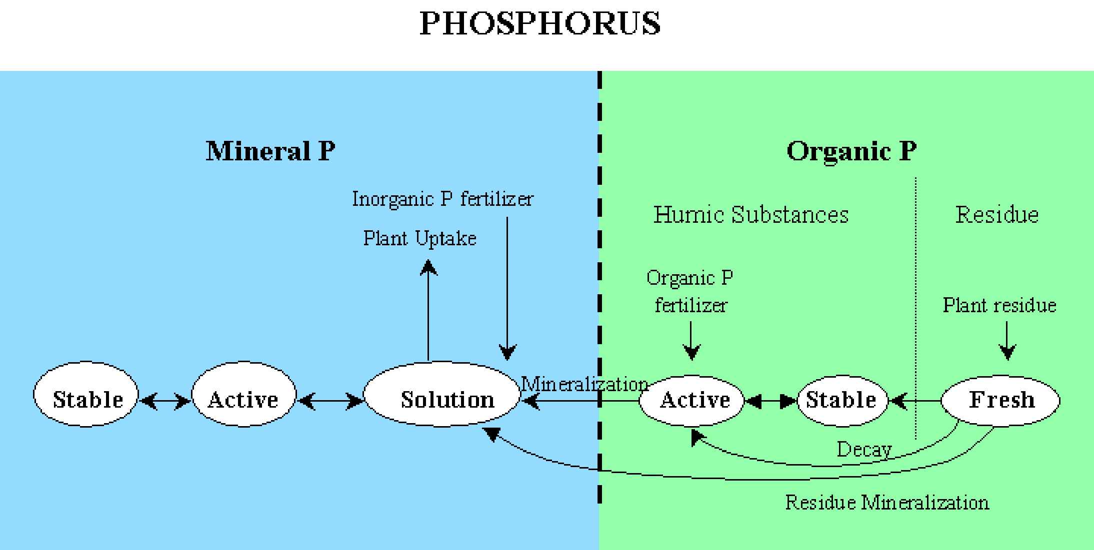

Figure 11-2: SWAT soil phosphorus pools and processes that move P in and out of pools.

11.1.1 INITIALIZATION OF SOIL PHOSPHORUS LEVELS

Users may define the amount of soluble P and organic phosphorus contained in humic substances for all soil layers at the beginning of the simulation. If the user does not specify initial phosphorus concentrations, SWAT will initialize levels of phosphorus in the different pools.

The concentration of solution phosphorus in all layers is initially set to 5 mg/kg soil. This concentration is representative of unmanaged land under native vegetation. A concentration of 25 mg/kg soil in the plow layer is considered representative of cropland (Cope et al., 1981).

The concentration of phosphorus in the active mineral pool is initialized to (Jones et al., 1984):

$$minP_{act,ly} = P_{solution,ly} \cdot \frac{1 - pai}{pai} \qquad 11.1.1$$

where $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (mg/kg), $P_{solution,ly}$ is the amount of phosphorus in solution (mg/kg), and pai is the phosphorus availability index.

The concentration of phosphorus in the stable mineral pool is initialized to (Jones et al., 1984):

$$minP_{sta,ly} = 4 \cdot minP_{act,ly} \qquad 11.1.2$$

where $minP_{sta,ly}$ is the amount of phosphorus in the stable mineral pool (mg/kg), and $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (mg/kg).

Organic phosphorus levels are assigned assuming that the N:P ratio for humic materials is 8:1. The concentration of humic organic phosphorus in a soil layer is calculated:

$$orgP_{hum,ly} = 0.125 \cdot orgN_{hum,ly} \qquad 11.1.3$$

where $orgP_{hum,ly}$ is the concentration of humic organic phosphorus in the layer (mg/kg) and $orgN_{hum,ly}$ is the concentration of humic organic nitrogen in the layer (mg/kg).

Phosphorus in the fresh organic pool is set to zero in all layers except the top 10mm of soil. In the top 10 mm, the fresh organic phosphorus pool is set to 0.03% of the initial amount of residue on the soil surface.

$$orgP_{frsh,surf} = 0.0003 \cdot rsd_{surf} \qquad 11.1.4$$

where $orgP_{frsh,surf}$ is the phosphorus in the fresh organic pool in the top 10mm (kg P/ha), and rsd_{surf} is material in the residue pool for the top 10mm of soil (kg/ha).

While SWAT allows nutrient levels to be input as concentrations, it performs all calculations on a mass basis. To convert a concentration to a mass, the concentration is multiplied by the bulk density and depth of the layer and divided by 100:

$$\frac{conc_P \cdot \rho_b \cdot depth_{ly}}{100} = \frac{\text{kg P}}{\text{ha}} \qquad 11.1.5$$

where $conc_P$ is the concentration of phosphorus in a layer (mg/kg or ppm), ρ_b is the bulk density of the layer (Mg/m^3), and $depth_{ly}$ is the depth of the layer (mm).

Table 11-1: SWAT input variables that pertain to nitrogen pools.

Variable Name	Definition	Input File
SOL_SOLP	$P_{solution,ly}$: Initial soluble P concentration in soil layer (mg/kg or ppm)	.chm
SOL_ORGP	$orgP_{hum,ly}$: Initial humic organic phosphorus in soil layer (mg/kg or ppm)	.chm
PSP	pai: Phosphorus availability index	.bsn
RSDIN	rsd_{surf}: Material in the residue pool for the top 10mm of soil (kg ha^{-1})	.hru
SOL_BD	ρ_b: Bulk density of the layer (Mg/m^3)	.sol

11.2 MINERALIZATION & DECOMPOSITION / IMMOBILIZATION

Decomposition is the breakdown of fresh organic residue into simpler organic components. Mineralization is the microbial conversion of organic, plant-unavailable phosphorus to inorganic, plant-available phosphorus. Immobilization is the microbial conversion of plant-available inorganic soil phosphorus to plant-unavailable organic phosphorus.

The phosphorus mineralization algorithms in SWAT are **net** mineralization algorithms which incorporate immobilization into the equations. The phosphorus mineralization algorithms developed by Jones et al. (1984) are similar in structure to the nitrogen mineralization algorithms. Two sources are considered for mineralization: the fresh organic P pool associated with crop residue and microbial biomass and the active organic P pool associated with soil humus. Mineralization and decomposition are allowed to occur only if the temperature of the soil layer is above 0°C.

Mineralization and decomposition are dependent on water availability and temperature. Two factors are used in the mineralization and decomposition equations to account for the impact of temperature and water on these processes.

The nutrient cycling temperature factor is calculated:

$$\gamma_{tmp,ly} = 0.9 \cdot \frac{T_{soil,ly}}{T_{soil,ly} + \exp\left[9.93 - 0.312 \cdot T_{soil,ly}\right]} + 0.1 \qquad 11.2.1$$

where $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly*, and $T_{soil,ly}$ is the temperature of layer *ly* (°C). The nutrient cycling temperature factor is never allowed to fall below 0.1.

The nutrient cycling water factor is calculated:

$$\gamma_{sw,ly} = \frac{SW_{ly}}{FC_{ly}} \qquad 11.2.2$$

where $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly*, SW_{ly} is the water content of layer *ly* on a given day (mm H_2O), and FC_{ly} is the water content of layer *ly* at field capacity (mm H_2O).). The nutrient cycling water factor is never allowed to fall below 0.05.

11.2.1 HUMUS MINERALIZATION

Phosphorus in the humus fraction is partitioned between the active and stable organic pools using the ratio of humus active organic N to stable organic N. The amount of phosphorus in the active and stable organic pools is calculated:

$$orgP_{act,ly} = orgP_{hum,ly} \cdot \frac{orgN_{act,ly}}{orgN_{act,ly} + orgN_{sta,ly}} \qquad 11.2.3$$

$$orgP_{sta,ly} = orgP_{hum,ly} \cdot \frac{orgN_{sta,ly}}{orgN_{act,ly} + orgN_{sta,ly}} \qquad 11.2.4$$

where $orgP_{act,ly}$ is the amount of phosphorus in the active organic pool (kg P/ha), $orgP_{sta,ly}$ is the amount of phosphorus in the stable organic pool (kg P/ha), $orgP_{hum,ly}$ is the concentration of humic organic phosphorus in the layer (kg P/ha), $orgN_{act,ly}$ is the amount of nitrogen in the active organic pool (kg N/ha), and $orgN_{sta,ly}$ is the amount of nitrogen in the stable organic pool (kg N/ha).

Mineralization from the humus active organic P pool is calculated:

$$P_{mina,ly} = 1.4 \cdot \beta_{min} \cdot \left(\gamma_{tmp,ly} \cdot \gamma_{sw,ly}\right)^{1/2} \cdot orgP_{act,ly} \qquad 11.2.5$$

where $P_{mina,ly}$ is the phosphorus mineralized from the humus active organic P pool (kg P/ha), β_{min} is the rate coefficient for mineralization of the humus active organic nutrients, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly*, $\gamma_{sw,ly}$

is the nutrient cycling water factor for layer *ly*, and $orgP_{act,ly}$ is the amount of phosphorus in the active organic pool (kg P/ha).

Phosphorus mineralized from the humus active organic pool is added to the solution P pool in the layer.

11.2.2 RESIDUE DECOMPOSITION & MINERALIZATION

Decomposition and mineralization of the fresh organic phosphorus pool is allowed only in the first soil layer. Decomposition and mineralization are controlled by a decay rate constant that is updated daily. The decay rate constant is calculated as a function of the C:N ratio and C:P ratio of the residue, temperature and soil water content.

The C:N ratio of the residue is calculated:

$$\varepsilon_{C:N} = \frac{0.58 \cdot rsd_{ly}}{orgN_{frsh,ly} + NO3_{ly}} \qquad 11.2.6$$

where $\varepsilon_{C:N}$ is the C:N ratio of the residue in the soil layer, rsd_{ly} is the residue in layer *ly* (kg/ha), 0.58 is the fraction of residue that is carbon, $orgN_{frsh,ly}$ is the nitrogen in the fresh organic pool in layer *ly* (kg N/ha), and $NO3_{ly}$ is the amount of nitrate in layer *ly* (kg N/ha).

The C:P ratio of the residue is calculated:

$$\varepsilon_{C:P} = \frac{0.58 \cdot rsd_{ly}}{orgP_{frsh,ly} + P_{solution,ly}} \qquad 11.2.7$$

where $\varepsilon_{C:P}$ is the C:P ratio of the residue in the soil layer, rsd_{ly} is the residue in layer *ly* (kg/ha), 0.58 is the fraction of residue that is carbon, $orgP_{frsh,ly}$ is the phosphorus in the fresh organic pool in layer *ly* (kg P/ha), and $P_{solution,ly}$ is the amount of phosphorus in solution in layer *ly* (kg P/ha).

The decay rate constant defines the fraction of residue that is decomposed. The decay rate constant is calculated:

$$\delta_{ntr,ly} = \beta_{rsd} \cdot \gamma_{ntr,ly} \cdot \left(\gamma_{tmp,ly} \cdot \gamma_{sw,ly}\right)^{1/2} \qquad 11.2.8$$

where $\delta_{ntr,ly}$ is the residue decay rate constant, β_{rsd} is the rate coefficient for mineralization of the residue fresh organic nutrients, $\gamma_{ntr,ly}$ is the nutrient cycling residue composition factor for layer *ly*, $\gamma_{tmp,ly}$ is the nutrient cycling temperature factor for layer *ly*, and $\gamma_{sw,ly}$ is the nutrient cycling water factor for layer *ly*.

The nutrient cycling residue composition factor is calculated:

$$\gamma_{ntr,ly} = \min \begin{cases} \exp\left[-0.693 \cdot \dfrac{(\varepsilon_{C:N} - 25)}{25}\right] \\ \exp\left[-0.693 \cdot \dfrac{(\varepsilon_{C:P} - 200)}{200}\right] \\ 1.0 \end{cases} \qquad 11.2.9$$

where $\gamma_{ntr,ly}$ is the nutrient cycling residue composition factor for layer *ly*, $\varepsilon_{C:N}$ is the C:N ratio on the residue in the soil layer, and $\varepsilon_{C:P}$ is the C:P ratio on the residue in the soil layer.

Mineralization from the residue fresh organic P pool is then calculated:

$$P_{minf,ly} = 0.8 \cdot \delta_{ntr,ly} \cdot orgP_{frsh,ly} \qquad 11.2.10$$

where $P_{minf,ly}$ is the phosphorus mineralized from the fresh organic P pool (kg P/ha), $\delta_{ntr,ly}$ is the residue decay rate constant, and $orgP_{frsh,ly}$ is the phosphorus in the fresh organic pool in layer *ly* (kg P/ha). Phosphorus mineralized from the fresh organic pool is added to the solution P pool in the layer.

Decomposition from the residue fresh organic P pool is calculated:

$$P_{dec,ly} = 0.2 \cdot \delta_{ntr,ly} \cdot orgP_{frsh,ly} \qquad 11.2.11$$

where $P_{dec,ly}$ is the phosphorus decomposed from the fresh organic P pool (kg P/ha), $\delta_{ntr,ly}$ is the residue decay rate constant, and $orgP_{frsh,ly}$ is the phosphorus in the fresh organic pool in layer *ly* (kg P/ha). Phosphorus decomposed from the fresh organic pool is added to the humus organic pool in the layer.

Table 11-2: SWAT input variables that pertain to mineralization.

Variable Name	Definition	Input File
CMN	β_{min}: Rate coefficient for mineralization of the humus active organic nutrients	.bsn
RSDCO	β_{rsd}: Rate coefficient for mineralization of the residue fresh organic nutrients	.bsn
RSDCO_PL	β_{rsd}: Rate coefficient for mineralization of the residue fresh organic nutrients	crop.dat

11.3 SORPTION OF INORGANIC P

Many studies have shown that after an application of soluble P fertilizer, solution P concentration decreases rapidly with time due to reaction with the soil. This initial “fast” reaction is followed by a much slower decrease in solution P that may continue for several years (Barrow and Shaw, 1975; Munns and Fox, 1976; Rajan and Fox, 1972; Sharpley, 1982). In order to account for the initial rapid decrease in solution P, SWAT assumes a rapid equilibrium exists between solution P and an “active” mineral pool. The subsequent slow reaction is simulated by the slow equilibrium assumed to exist between the “active” and “stable” mineral pools. The algorithms governing movement of inorganic phosphorus between these three pools are taken from Jones et al. (1984).

Equilibration between the solution and active mineral pool is governed by the phosphorus availability index. This index specifies the fraction of fertilizer P which is in solution after an incubation period, i.e. after the rapid reaction period.

A number of methods have been developed to measure the phosphorus availability index. Jones et al. (1984) recommends a method outlined by Sharpley et al. (1984) in which various amounts of phosphorus are added in solution to the soil as K_2HPO_4. The soil is wetted to field capacity and then dried slowly at 25°C. When dry, the soil is rewetted with deionized water. The soil is exposed to several wetting and drying cycles over a 6-month incubation period. At the end of the incubation period, solution phosphorus is determined by extraction with anion exchange resin.

The P availability index is then calculated:

$$pai = \frac{P_{solution,f} - P_{solution,i}}{fert_{minP}} \qquad 11.3.1$$

where pai is the phosphorus availability index, $P_{solution,f}$ is the amount of phosphorus in solution after fertilization and incubation, $P_{solution,i}$ is the amount of phosphorus in solution before fertilization, and $fert_{minP}$ is the amount of soluble P fertilizer added to the sample.

The movement of phosphorus between the solution and active mineral pools is governed by the equilibration equations:

$$P_{sol|act,ly} = P_{solution,ly} - minP_{act,ly} \cdot \left(\frac{pai}{1-pai} \right) \quad \text{if} \quad P_{solution,ly} > minP_{act,ly} \cdot \left(\frac{pai}{1-pai} \right) \qquad 11.3.2$$

$$P_{sol|act,ly} = 0.1 \cdot \left(P_{solution,ly} - minP_{act,ly} \cdot \left(\frac{pai}{1-pai} \right) \right) \quad \text{if} \quad P_{solution,ly} < minP_{act,ly} \cdot \left(\frac{pai}{1-pai} \right) \qquad 11.3.3$$

where $P_{sol|act,ly}$ is the amount of phosphorus transferred between the soluble and active mineral pool (kg P/ha), $P_{solution,ly}$ is the amount of phosphorus in solution (kg P/ha), $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (kg P/ha), and pai is the phosphorus availability index. When $P_{sol|act,ly}$ is positive, phosphorus is being transferred from solution to the active mineral pool. When $P_{sol|act,ly}$ is negative, phosphorus is being transferred from the active mineral pool to solution. Note that the rate of flow from the active mineral pool to solution is 1/10th the rate of flow from solution to the active mineral pool.

SWAT simulates slow phosphorus sorption by assuming the active mineral phosphorus pool is in slow equilibrium with the stable mineral phosphorus pool. At equilibrium, the stable mineral pool is 4 times the size of the active mineral pool.

When not in equilibrium, the movement of phosphorus between the active and stable mineral pools is governed by the equations:

$$P_{act|sta,ly} = \beta_{eqP} \cdot \left(4 \cdot minP_{act,ly} - minP_{sta,ly} \right) \quad \text{if} \quad minP_{sta,ly} < 4 \cdot minP_{act,ly} \qquad 11.3.4$$

$$P_{act|sta,ly} = 0.1 \cdot \beta_{eqP} \cdot \left(4 \cdot minP_{act,ly} - minP_{sta,ly} \right) \quad \text{if} \quad minP_{sta,ly} > 4 \cdot minP_{act,ly} \qquad 11.3.5$$

where $P_{act|sta,ly}$ is the amount of phosphorus transferred between the active and stable mineral pools (kg P/ha), β_{eqP} is the slow equilibration rate constant (0.0006 d^{-1}), $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (kg P/ha), and $minP_{sta,ly}$ is the amount of phosphorus in the stable mineral pool (kg P/ha). When $P_{act|sta,ly}$ is positive, phosphorus is being transferred from the active mineral pool to the stable mineral pool. When $P_{act|sta,ly}$ is negative, phosphorus is being transferred from the stable mineral pool to the active mineral pool. Note that the rate of flow from the stable mineral pool to the active mineral pool is 1/10th the rate of flow from the active mineral pool to the stable mineral pool.

Table 11-3: SWAT input variables that pertain to inorganic P sorption processes.

Variable Name	Definition	Input File
PSP	*pai*: Phosphorus availability index	.bsn

11.4 LEACHING

The primary mechanism of phosphorus movement in the soil is by diffusion. Diffusion is the migration of ions over small distances (1-2 mm) in the soil solution in response to a concentration gradient. The concentration gradient is created when plant roots remove soluble phosphorus from soil solution, depleting solution P in the root zone.

Due to the low mobility of phosphorus, SWAT allows soluble P to leach only from the top 10 mm of soil into the first soil layer. The amount of solution P moving from the top 10 mm into the first soil layer is:

$$P_{perc} = \frac{P_{solution,surf} \cdot w_{perc,surf}}{10 \cdot \rho_b \cdot depth_{surf} \cdot k_{d,perc}} \qquad 11.4.1$$

where P_{perc} is the amount of phosphorus moving from the top 10 mm into the first soil layer (kg P/ha), $P_{solution,surf}$ is the amount of phosphorus in solution in the top 10 mm (kg P/ha), $w_{perc,surf}$ is the amount of water percolating to the first soil layer from the top 10 mm on a given day (mm H_2O), ρ_b is the bulk density of the top 10 mm (Mg/m^3) (assumed to be equivalent to bulk density of first soil layer),

$depth_{surf}$ is the depth of the "surface" layer (10 mm), and $k_{d,perc}$ is the phosphorus percolation coefficient (10 m^3/Mg). The phosphorus percolation coefficient is the ratio of the phosphorus concentration in the surface 10 mm of soil to the concentration of phosphorus in percolate.

Table 11-4: SWAT input variables that pertain to phosphorus leaching.

Variable Name	Definition	Input File
SOL_BD	ρ_b: Bulk density of the layer (Mg/m^3)	.sol
PPERCO	$k_{d,perc}$: Phosphorus percolation coefficient (10 m^3/Mg)	.bsn

11.5 NOMENCLATURE

FC_{ly}	Water content of layer *ly* at field capacity (mm H_2O)
$NO3_{ly}$	Nitrate content of soil layer *ly* (kg NO_3-N/ha)
$P_{act\|sta,ly}$	Amount of phosphorus transferred between the active and stable mineral pools (kg P/ha)
$P_{dec,ly}$	Phosphorus decomposed from the fresh organic P pool (kg P/ha)
$P_{mina,ly}$	Phosphorus mineralized from the humus active organic P pool (kg P/ha)
$P_{minf,ly}$	Phosphorus mineralized from the fresh organic P pool (kg P/ha),
P_{perc}	Amount of phosphorus moving from the top 10 mm into the first soil layer (kg P/ha)
$P_{solution,ly}$	Amount of phosphorus in solution (mg/kg)
$P_{sol\|act,ly}$	Amount of phosphorus transferred between the soluble and active mineral pool (kg P/ha)
SW_{ly}	Soil water content of layer *ly* (mm H_2O)
$T_{soil,ly}$	Temperature of layer *ly* (°C)
$conc_P$	Concentration of phosphorus in a layer (mg/kg or ppm)
$depth_{ly}$	Depth of the layer (mm)
$k_{d,perc}$	Phosphorus percolation coefficient (10 m^3/Mg)
$minP_{act,ly}$	Amount of phosphorus in the active mineral pool (mg/kg or kg P/ha)
$minP_{sta,ly}$	Amount of phosphorus in the stable mineral pool (mg/kg or kg P/ha)
$orgN_{act,ly}$	Nitrogen in the active organic pool in layer *ly* (mg/kg or kg N/ha)
$orgN_{frsh,ly}$	Nitrogen in the fresh organic pool in layer *ly* (kg N/ha)
$orgN_{hum,ly}$	Amount of nitrogen in humic organic pool in the layer (mg/kg or kg N/ha)
$orgN_{sta,ly}$	Nitrogen in the stable organic pool in layer *ly* (mg/kg or kg N/ha)
$orgP_{act,ly}$	Amount of phosphorus in the active organic pool (kg P/ha)
$orgP_{frsh,ly}$	Phosphorus in the fresh organic pool in layer *ly* (kg P/ha)
$orgP_{hum,ly}$	Amount of phosphorus in humic organic pool in the layer (mg/kg or kg P/ha)
$orgP_{sta,ly}$	Amount of phosphorus in the stable organic pool (kg P/ha)
pai	Phosphorus availability index
rsd_{ly}	Residue in layer *ly* (kg/ha)

$w_{perc,ly}$	Amount of water percolating to the underlying soil layer on a given day (mm H_2O)
β_{eqP}	Slow equilibration rate constant (0.0006 d^{-1})
β_{min}	Rate coefficient for mineralization of the humus active organic nutrients
β_{rsd}	Rate coefficient for mineralization of the residue fresh organic nutrients
$\delta_{ntr,ly}$	Residue decay rate constant
$\varepsilon_{C:N}$	Residue C:N ratio in the soil layer
$\varepsilon_{C:P}$	Residue C:P ratio in the soil layer
$\gamma_{ntr,ly}$	Nutrient cycling residue composition factor for layer *ly*
$\gamma_{sw,ly}$	Nutrient cycling water factor for layer *ly*
$\gamma_{tmp,ly}$	Nutrient cycling temperature factor for layer *ly*
ρ_b	Bulk density of the layer (Mg/m^3)

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CHAPTER 12

EQUATIONS: PESTICIDES

One of the primary purposes of tillage and harvesting practices in early farming systems was to remove as much plant residue from the field as possible so that pests had no food source to sustain them until the next growing season. As research linked erosion to lack of soil cover, farmers began to perform fewer tillage operations and altered harvesting methods to leave more residue. As mechanical methods of pest control were minimized or eliminated, chemical methods of pest control began to assume a key role in the management of unwanted organisms.

Pesticides are toxic by design, and there is a natural concern about the impact of their presence in the environment on human health and environmental quality. The fate and transport of a pesticide are governed by properties such as solubility in water, volatility and ease of degradation. The algorithms in SWAT used to model pesticide movement and fate are adapted from GLEAMS (Leonard et al., 1987).

Pesticide may be aerially applied to an HRU with some fraction intercepted by plant foliage and some fraction reaching the soil. Pesticide may also be incorporated into the soil through tillage. SWAT monitors pesticide amounts on foliage and in all soil layers. Figure 12-1 shows the potential pathways and processes simulated in SWAT.

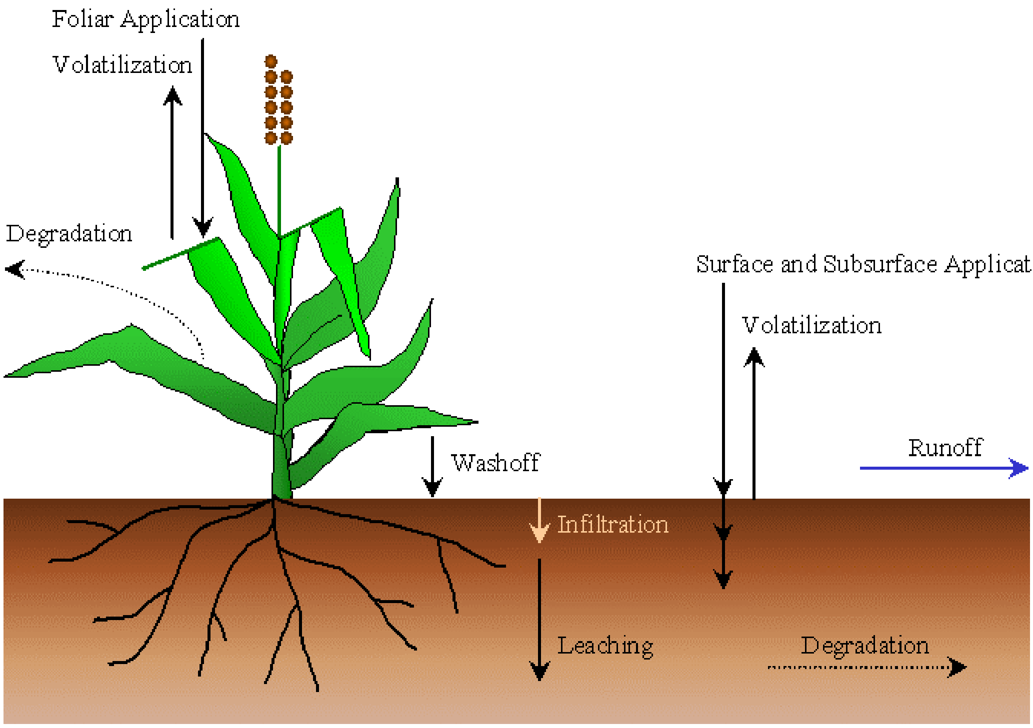

Figure 12-1: Pesticide fate and transport in SWAT.

12.1 WASH-OFF

A portion of the pesticide on plant foliage may be washed off during rain events. The fraction washed off is a function of plant morphology, pesticide solubility, and the timing and intensity of the rainfall event. Wash-off will occur when the amount of precipitation on a given day exceeds 2.54 mm.

The amount of pesticide washing off plant foliage during a precipitation event on a given day is calculated:

$$pst_{f,wsh} = fr_{wsh} \cdot pst_f \qquad 12.1.1$$

where $pst_{f,wsh}$ is the amount of pesticide on foliage that is washed off the plant and onto the soil surface on a given day (kg pst/ha), fr_{wsh} is the wash-off fraction for the pesticide, and pst_f is the amount of pesticide on the foliage (kg pst/ha). The wash-off fraction represents the portion of the pesticide on the foliage that is dislodgable.

Table 12-1: SWAT input variables that pertain to pesticide wash-off.

Variable Name	Definition	Input File
WOF	fr_{wsh}: Wash-off fraction for the pesticide	pest.dat

12.2 DEGRADATION

Degradation is the conversion of a compound into less complex forms. A compound in the soil may degrade upon exposure to light (photo degradation), reaction with chemicals present in the soil (chemical degradation) or through use as a substrate for organisms (biodegradation).

The majority of pesticides in use today are organic compounds. Because organic compounds contain carbon, which is used by microbes in biological reactions to produce energy, organic pesticides may be susceptible to microbial degradation. In contrast, pesticides that are inorganic are not susceptible to microbial degradation. Examples of pesticides that will not degrade are lead arsenate, a metallic salt commonly applied in orchards before DDT was invented, and arsenic acid, a compound formerly used to defoliate cotton.

Pesticides vary in their susceptibility to degradation. Compounds with chain structures are easier to break apart than compounds containing aromatic rings or other complex structures. The susceptibility of a pesticide to degradation is quantified by the pesticide's half-life.

The half-life for a pesticide defines the number of days required for a given pesticide concentration to be reduced by one-half. The soil half-life entered for a pesticide is a lumped parameter that includes the net effect of volatilization, photolysis, hydrolysis, biological degradation and chemical reactions in the soil. Because pesticide on foliage degrades more rapidly than pesticide in the soil, SWAT allows a different half-life to be defined for foliar degradation.

Pesticide degradation or removal in all soil layers is governed by first-order kinetics:

$$pst_{s,ly,t} = pst_{s,ly,o} \cdot \exp\left[-k_{p,soil} \cdot t\right] \qquad 12.2.1$$

where $pst_{s,ly,t}$ is the amount of pesticide in the soil layer at time t (kg pst/ha), $pst_{s,ly,o}$ is the initial amount of pesticide in the soil layer (kg pst/ha), $k_{p,soil}$ is the rate constant for degradation or removal of the pesticide in soil (1/day), and t is the time elapsed since the initial pesticide amount was determined (days). The rate constant is related to the soil half-life as follows:

$$t_{1/2,s} = \frac{0.693}{k_{p,soil}} \qquad 12.2.2$$

where $t_{1/2,s}$ is the half-life of the pesticide in the soil (days).

The equation governing pesticide degradation on foliage is:

$$pst_{f,t} = pst_{f,o} \cdot \exp\left[-k_{p,foliar} \cdot t\right] \qquad 12.2.3$$

where $pst_{f,t}$ is the amount of pesticide on the foliage at time t (kg pst/ha), $pst_{f,o}$ is the initial amount of pesticide on the foliage (kg pst/ha), $k_{p,foliar}$ is the rate constant for degradation or removal of the pesticide on foliage (1/day), and t is the time elapsed since the initial pesticide amount was determined (days). The rate constant is related to the foliar half-life as follows:

$$t_{1/2,f} = \frac{0.693}{k_{p,foliar}} \qquad 12.2.4$$

where $t_{1/2,f}$ is the half-life of the pesticide on foliage (days).

Table 12-2: SWAT input variables that pertain to pesticide degradation.

Variable Name	Definition	Input File
HLIFE_S	$t_{1/2,s}$: Half-life of the pesticide in the soil (days)	pest.dat
HLIFE_F	$t_{1/2,f}$: Half-life of the pesticide on foliage (days)	pest.dat

12.3 LEACHING

Highly water-soluble pesticides can be transported with percolation deep into the soil profile and potentially pollute shallow groundwater systems. The algorithms used by SWAT to calculated pesticide leaching simultaneously solve for loss of pesticide in surface runoff and lateral flow also. These algorithms are reviewed in Chapter 15.

12.4 NOMENCLATURE

fr_{wsh}	Wash-off fraction for the pesticide
$k_{p,foliar}$	Rate constant for degradation or removal of the pesticide on foliage (1/day)
$k_{p,soil}$	Rate constant for degradation or removal of the pesticide in soil (1/day)
pst_f	Amount of pesticide on the foliage (kg pst/ha)
$pst_{f,wsh}$	Amount of pesticide on foliage that is washed off the plant and onto the soil surface on a given day (kg pst/ha)
$pst_{s,ly}$	Amount of pesticide in the soil (kg pst/ha)
t	Time elapsed since the initial pesticide amount was determined (days)
$t_{1/2,f}$	Half-life of the pesticide on foliage (days)
$t_{1/2,s}$	Half-life of the pesticide in the soil (days)

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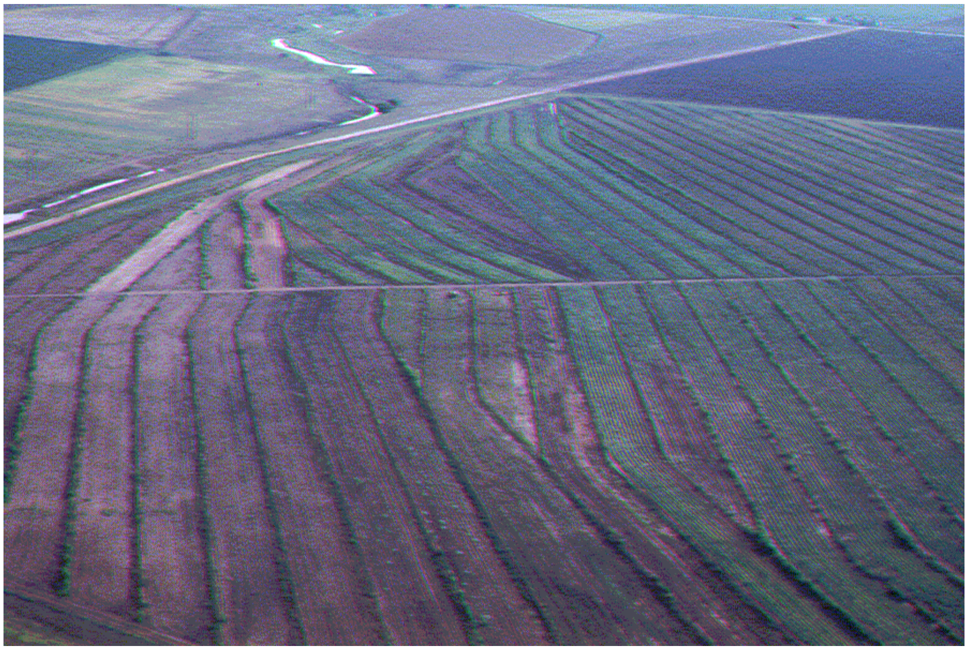
EROSION

Transport of sediment, nutrients and pesticides from land areas to water bodies is a consequence of weathering that acts on landforms. Soil and water conservation planning requires knowledge of the relations between factors that cause loss of soil and water and those that help to reduce such losses.

The following three chapters review the methodology used by SWAT to simulate erosion processes.



CHAPTER 13

EQUATIONS: SEDIMENT

Erosion caused by rainfall and runoff is computed with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). MUSLE is a modified version of the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965, 1978).

USLE predicts average annual gross erosion as a function of rainfall energy. In MUSLE, the rainfall energy factor is replaced with a runoff factor. This improves the sediment yield prediction, eliminates the need for delivery ratios, and allows the equation to be applied to individual storm events. Sediment yield prediction is improved because runoff is a function of antecedent moisture condition as well as rainfall energy. Delivery ratios (the sediment yield at any point along the channel divided by the source erosion above that point) are required by the USLE because the rainfall factor represents energy used in detachment only. Delivery ratios are not needed with MUSLE because the runoff factor represents energy used in detaching and transporting sediment.

13.1 MUSLE

The modified universal soil loss equation (Williams, 1995) is:

$$sed = 11.8 \cdot \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \qquad 13.1.1$$

where sed is the sediment yield on a given day (metric tons), Q_{surf} is the surface runoff volume (mm H_2O/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm)), 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. Surface runoff and peak rate calculations are reviewed in Chapter 6. The USLE factors are discussed in the following sections.

13.1.1 SOIL ERODIBILITY FACTOR

Some soils erode more easily than others even when all other factors are the same. This difference is termed soil erodibility and is caused by the properties of the soil itself. Wischmeier and Smith (1978) define the soil erodibility factor as the soil loss rate per erosion index unit for a specified soil as measured on a unit plot. A unit plot is 22.1-m (72.6-ft) long, with a uniform length-wise slope of 9-percent, in continuous fallow, tilled up and down the slope. Continuous fallow is defined as land that has been tilled and kept free of vegetation for more than 2 years. The units for the USLE soil erodibility factor in MUSLE are numerically equivalent to the traditional English units of 0.01 (ton acre hr)/(acre ft-ton inch).

Wischmeier and Smith (1978) noted that a soil type usually becomes less erodible with decrease in silt fraction, regardless of whether the corresponding increase is in the sand fraction or clay fraction.

Direct measurement of the erodibility factor is time consuming and costly. Wischmeier et al. (1971) developed a general equation to calculate the soil erodibility factor when the silt and very fine sand content makes up less than 70% of the soil particle size distribution.

$$K_{USLE} = \frac{0.00021 \cdot M^{1.14} \cdot (12 - OM) + 3.25 \cdot (c_{soilstr} - 2) + 2.5 \cdot (c_{perm} - 3)}{100} \qquad 13.1.2$$

where K_{USLE} is the soil erodibility factor, M is the particle-size parameter, OM is the percent organic matter (%), $c_{soilstr}$ is the soil structure code used in soil classification, and c_{perm} is the profile permeability class.

The particle-size parameter, M, is calculated

$$M = (m_{silt} + m_{vfs}) \cdot (100 - m_c) \qquad 13.1.3$$

where m_{silt} is the percent silt content (0.002-0.05 mm diameter particles), m_{vfs} is the percent very fine sand content (0.05-0.10 mm diameter particles), and m_c is the percent clay content (< 0.002 mm diameter particles).

The percent organic matter content, OM, of a layer can be calculated:

$$OM = 1.72 \cdot orgC \qquad 13.1.4$$

where $orgC$ is the percent organic carbon content of the layer (%).

Soil structure refers to the aggregation of primary soil particles into compound particles which are separated from adjoining aggregates by surfaces of weakness. An individual natural soil aggregate is called a ped. Field description of soil structure notes the shape and arrangement of peds, the size of peds, and the distinctness and durability of visible peds. USDA Soil Survey terminology for structure consists of separate sets of terms defining each of these three qualities. Shape and arrangement of peds are designated as type of soil structure; size of peds as class; and degree of distinctness as grade.

The soil-structure codes for equation 13.1.2 are defined by the type and class of soil structure present in the layer. There are four primary types of structure:

-Platy, with particles arranged around a plane, generally horizontal

-Prismlike, with particles arranged around a verticle line and bounded by relatively flat vertical surfaces

-Blocklike or polyhedral, with particles arranged around a point and bounded by flat or rounded surfaces which are casts of the molds formed by the faces of surrounding peds

-Spheroidal or polyhedral, with particles arranged around a point and bounded by curved or very irregular surfaces that are not accomodated to the adjoining aggregates

Each of the last three types has two subtypes:

-Prismlike
  Prismatic: without rounded upper ends
  Columnar: with rounded caps

-Blocklike
  Angular Blocky: bounded by planes intersecting at relatively sharp angles
  Subangular Blocky: having mixed rounded and plane faces with vertices mostly rounded

-Spheroidal
  Granular: relatively non-porous
  Crumb: very porous

The size criteria for the class will vary by type of structure and are summarized in Table 13-1. The codes assigned to $c_{soilstr}$ are:

1	very fine granular
2	fine granular
3	medium or coarse granular
4	blocky, platy, prismlike or massive

Table 13-1: Size classes of soil structure

	Shape of structure			
Size Classes	**Platy**	**Prismatic and Columnar**	**Blocky**	**Granular**
Very fine	< 1 mm	< 10 mm	< 5 mm	< 1 mm
Fine	1-2 mm	10-20 mm	5-10 mm	1-2 mm
Medium	2-5 mm	20-50 mm	10-20 mm	2-5 mm
Coarse	5-10 mm	50-100 mm	20-50 mm	5-10 mm
Very coarse	> 10 mm	> 100 mm	> 50 mm	> 10 mm

Permeability is defined as the capacity of the soil to transmit water and air through the most restricted horizon (layer) when moist. The profile permeability classes are based on the lowest saturated hydraulic conductivity in the profile. The codes assigned to c_{perm} are:

1	rapid (> 150 mm/hr)
2	moderate to rapid (50-150 mm/hr)
3	moderate (15-50 mm/hr)
4	slow to moderate (5-15 mm/hr)
5	slow (1-5 mm/hr)
6	very slow (< 1 mm/hr)

Williams (1995) proposed an alternative equation:

$$K_{USLE} = f_{csand} \cdot f_{cl-si} \cdot f_{orgc} \cdot f_{hisand} \qquad 13.1.5$$

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, $f_{cl\text{-}si}$ 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. The factors are calculated:

$$f_{csand} = \left(0.2 + 0.3 \cdot \exp\left[-0.256 \cdot m_s \cdot \left(1 - \frac{m_{silt}}{100}\right)\right]\right) \qquad 13.1.6$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3} \qquad 13.1.7$$

$$f_{orgc} = \left(1 - \frac{0.25 \cdot orgC}{orgC + \exp\left[3.72 - 2.95 \cdot orgC\right]}\right) \qquad 13.1.8$$

$$f_{hisand} = \left(1 - \frac{0.7 \cdot \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp\left[-5.51 + 22.9 \cdot \left(1 - \frac{m_s}{100}\right)\right]}\right) \qquad 13.1.9$$

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

13.1.2 COVER AND MANAGEMENT FACTOR

The USLE cover and management factor, C_{USLE}, is defined as the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow (Wischmeier and Smith, 1978). The plant canopy affects erosion by reducing the effective rainfall energy of intercepted raindrops. Water drops falling from the canopy may regain appreciable velocity but it will be less than the terminal velocity of free-falling raindrops. The average fall height of drops from the canopy and the density of the canopy will determine the reduction in rainfall energy expended at the soil surface. A given percentage of residue on the soil surface is more effective that the same percentage of canopy cover. Residue intercepts falling raindrops so near the surface that drops regain no fall velocity. Residue also obstructs runoff flow, reducing its velocity and transport capacity.

Because plant cover varies during the growth cycle of the plant, SWAT updates C_{USLE} daily using the equation:

$$C_{USLE} = \exp\left(\left[\ln(0.8) - \ln\left(C_{USLE,mn}\right)\right] \cdot \exp\left[-0.00115 \cdot rsd_{surf}\right] + \ln\left[C_{USLE,mn}\right]\right) \qquad 13.1.10$$

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

The minimum C factor can be estimated from a known average annual C factor using the following equation (Arnold and Williams, 1995):

$$C_{USLE,mn} = 1.463 \ln\left[C_{USLE,aa}\right] + 0.1034 \qquad 13.1.11$$

where $C_{USLE,mn}$ is the minimum C factor for the land cover and $C_{USLE,aa}$ is the average annual C factor for the land cover.

13.1.3 SUPPORT PRACTICE FACTOR

The support practice factor, P_{USLE}, is defined as the ratio of soil loss with a specific support practice to the corresponding loss with up-and-down slope culture. Support practices include contour tillage, stripcropping on the contour, and terrace systems. Stabilized waterways for the disposal of excess rainfall are a necessary part of each of these practices.

Contour tillage and planting provides almost complete protection against erosion from storms of low to moderate intensity, but little or no protection against occasional severe storms that cause extensive breakovers of contoured rows. Contouring is most effective on slopes of 3 to 8 percent. Values for P_{USLE} and slope-length limits for contour support practices are given in Table 13-2.

Table 13-2: P factor values and slope-length limits for contouring (Wischmeier and Smith, 1978).

Land slope (%)	P_{USLE}	**Maximum length (m)**
1 to 2	0.60	122
3 to 5	0.50	91
6 to 8	0.50	61
9 to 12	0.60	37
13 to 16	0.70	24
17 to 20	0.80	18
21 to 25	0.90	15

Stripcropping is a practice in which contoured strips of sod are alternated with equal-width strips of row crop or small grain. Recommended values for contour stripcropping are given in Table 13-3.

Table 13-3: P factor values, maximum strip width and slope-length limits for contour stripcropping (Wischmeier and Smith, 1978).

Land slope (%)	P_{USLE} **values**[1]			**Strip width (m)**	**Maximum length (m)**
	A	**B**	**C**		
1 to 2	0.30	0.45	0.60	40	244
3 to 5	0.25	0.38	0.50	30	183
6 to 8	0.25	0.38	0.50	30	122
9 to 12	0.30	0.45	0.60	24	73
13 to 16	0.35	0.52	0.70	24	49
17 to 20	0.40	0.60	0.80	18	37
21 to 25	0.45	0.68	0.90	15	30

[1] P values:

A: For 4-year rotation of row crop, small grain with meadow seeding, and 2 years of meadow. A second row crop can replace the small grain if meadow is established in it.

B: For 4-year rotation of 2 years row crop, winter grain with meadow seeding, and 1-year meadow.

C: For alternate strips of row crop and winter grain

Terraces are a series of horizontal ridges made in a hillside. There are several types of terraces. Broadbase terraces are constructed on gently sloping land and the channel and ridge are cropped the same as the interterrace area. The steep backslope terrace, where the backslope is in sod, is most common on steeper land. Impoundment terraces are terraces with underground outlets.

Terraces divide the slope of the hill into segments equal to the horizontal terrace interval. With terracing, the slope length is the terrace interval. For broadbase terraces, the horizontal terrace interval is the distance from the center of the ridge to the center of the channel for the terrace below. The horizontal terrace interval for steep backslope terraces is the distance from the point where cultivation begins at the base of the ridge to the base of the frontslope of the terrace below.

Values for P_{USLE} for contour farming terraced fields are listed in Table 13-4. These values apply to broadbase, steep backslope and level terraces. Keep in mind that the values given in Table 13-4 do not account for all erosion control benefits of terraces. The shorter slope-length used in the calculation of the length-slope factor will produce additional reduction.

Table 13-4: P factor values for contour-farmed terraced fields (from Wischmeier and Smith, 1978)[1]

Land slope (%)	**Farm planning**		**Computing sediment yield**[3]	
	Contour P factor[2]	**Stripcrop P factor**	**Graded channels sod outlets**	**Steep backslope underground outlets**
1 to 2	0.60	0.30	0.12	0.05
3 to 8	0.50	0.25	0.10	0.05
9 to 12	0.60	0.30	0.12	0.05
13 to 16	0.70	0.35	0.14	0.05
17 to 20	0.80	0.40	0.16	0.06
21 to 25	0.90	0.45	0.18	0.06

[1] Slope length is the horizontal terrace interval. The listed values are for contour farming. No additional contouring factor is used in the computation.

[2] Use these values for control of interterrace erosion within specified soil loss tolerances.

[3] These values include entrapment efficiency and are used for control of offsite sediment within limits and for estimating the field’s contribution to watershed sediment yield.

13.1.4 TOPOGRAPHIC FACTOR

The topographic factor, LS_{USLE}, is the expected ratio of soil loss per unit area from a field slope to that from a 22.1-m length of uniform 9 percent slope under otherwise identical conditions. The topographic factor is calculated:

$$LS_{USLE} = \left(\frac{L_{hill}}{22.1}\right)^{m} \cdot \left(65.41 \cdot \sin^2(\alpha_{hill}) + 4.56 \cdot \sin\alpha_{hill} + 0.065\right) \qquad 13.1.12$$

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

$$m = 0.6 \cdot \left(1 - \exp\left[-35.835 \cdot slp\right]\right) \qquad 13.1.13$$

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

$$slp = \tan\alpha_{hill} \qquad 13.1.14$$

13.1.5 COARSE FRAGMENT FACTOR

The coarse fragment factor is calculated:

$$CFRG = \exp(-0.053 \cdot rock) \qquad 13.1.15$$

where *rock* is the percent rock in the first soil layer (%).

Table 13-5: SWAT input variables that pertain to sediment yield.

Variable Name	Definition	Input File
USLE_K	K_{USLE}: USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm))	.sol
USLE_C	$C_{USLE,mn}$: Minimum value for the cover and management factor for the land cover	crop.dat
USLE_P	P_{USLE}: USLE support practice factor	.mgt
SLSUBBSN	L_{hill}: Slope length (m)	.hru
SLOPE	*slp*: Average slope of the subbasin (% or m/m)	.hru
ROCK	*rock*: Percent rock in the first soil layer (%)	.sol

13.2 USLE

For comparative purposes, SWAT prints out sediment loadings calculated with USLE. ***These values are not used by the model, they are for comparison only***. The universal soil loss equation (Williams, 1995) is:

$$sed = 1.292 \cdot EI_{USLE} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \qquad 13.2.1$$

where *sed* is the sediment yield on a given day (metric tons/ha), EI_{USLE} is the rainfall erosion index (0.017 m-metric ton cm/(m^2 hr)), K_{USLE} is the USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm)), 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. The factors other than EI_{USLE} are discussed in the preceeding sections.

13.2.1 RAINFALL ERODIBILITY INDEX

The value of EI_{USLE} for a given rainstorm is the product, total storm energy times the maximum 30 minute intensity. The storm energy indicates the volume of rainfall and runoff while the 30 minute intensity indicates the prolonged peak rates of detachment and runoff.

$$EI_{USLE} = E_{storm} \cdot I_{30} \qquad 13.2.2$$

where EI_{USLE} is the rainfall erosion index (0.017 m-metric ton cm/(m^2 hr)), E_{storm} is the total storm energy (0.0017 m-metric ton/m^2), and I_{30} is the maximum 30-minute intensity (mm/hr).

The energy of a rainstorm is a function of the amount of rain and of all the storm's component intensities. Because rainfall is provided to the model in daily totals, an assumption must be made about variation in rainfall intensity. The rainfall intensity variation with time is assumed to be exponentially distributed:

$$i_t = i_{mx} \cdot \exp\left(-\frac{t}{k_i} \right) \qquad 13.2.3$$

where i_t is the rainfall intensity at time t (mm/hr), i_{mx} is the maximum rainfall intensity (mm/hr), t is the time (hr), and k_i is the decay constant for rainfall intensity (hr).

The USLE energy equation is

$$E_{storm} = \Delta R_{day} \cdot \left(12.1 + 8.9 \cdot \log_{10}\left[\frac{\Delta R_{day}}{\Delta t} \right] \right) \qquad 13.2.4$$

where ΔR_{day} is the amount of rainfall during the time interval (mm H_2O), and Δt is the time interval (hr). This equation may be expressed analytically as:

$$E_{storm} = 12.1 \int_0^\infty i_t dt + 8.9 \int_0^\infty i_t \log_{10} i_t dt \qquad 13.2.5$$

Combining equation 13.2.5 and 13.2.3 and integrating gives the equation for estimating daily rainfall energy:

$$E_{storm} = \frac{R_{day}}{1000} \cdot \left(12.1 + 8.9 \cdot \left(\log_{10}\left[i_{mx} \right] - 0.434 \right) \right) \qquad 13.2.6$$

where R_{day} is the amount of precipitation falling on a given day (mm H_2O), and i_{mx} is the maximum rainfall intensity (mm/hr). To compute the maximum rainfall intensity, i_{mx}, equation 13.2.3 is integrated to give

$$R_{day} = i_{mx} \cdot k_i \qquad 13.2.7$$

and

$$R_t = R_{day} \cdot \left(1 - \exp\left[-\frac{t}{k_i} \right] \right) \qquad 13.2.8$$

where R_{day} is the amount of precipitation falling on a given day (mm H_2O), i_{mx} is the maximum rainfall intensity (mm/hr), k_i is the decay constant for rainfall intensity (hr), R_t is the amount of rain falling during a time interval (mm H_2O), and t is the time interval (hr). The maximum half-hour rainfall for the precipitation event is known:

$$R_{0.5} = \alpha_{0.5} \cdot R_{day} \qquad 13.2.9$$

where $R_{0.5}$ is the maximum half-hour rainfall (mm H_2O), $\alpha_{0.5}$ is the maximum half-hour rainfall expressed as a fraction of daily rainfall, and R_{day} is the amount of precipitation falling on a given day (mm H_2O). Calculation of $\alpha_{0.5}$ is reviewed in Chapter 4. Substituting equation 13.2.9 and 13.2.7 into 13.2.8 and solving for the maximum intensity gives:

$$i_{mx} = -2 \cdot R_{day} \cdot \ln\left(1 - \alpha_{0.5}\right) \qquad 13.2.10$$

where i_{mx} is the maximum rainfall intensity (mm/hr), R_{day} is the amount of precipitation falling on a given day (mm H_2O), and $\alpha_{0.5}$ is the maximum half-hour rainfall expressed as a fraction of daily rainfall.

The maximum 30 minute intensity is calculated:

$$I_{30} = 2 \cdot \alpha_{0.5} \cdot R_{day} \qquad 13.2.3$$

where I_{30} is the maximum 30-minute intensity (mm/hr), $\alpha_{0.5}$ is the maximum half-hour rainfall expressed as a fraction of daily rainfall, and R_{day} is the amount of precipitation falling on a given day (mm H_2O).

Table 13-6: SWAT input variables that pertain to USLE sediment yield.

Variable Name	Definition	Input File
USLE_K	K_{USLE}: USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm))	.sol
USLE_C	$C_{USLE,mn}$: Minimum value for the cover and management factor for the land cover	crop.dat
USLE_P	P_{USLE}: USLE support practice factor	.mgt
SLSUBBSN	L_{hill}: Slope length (m)	.hru
SLOPE	*slp*: Average slope of the subbasin (% or m/m)	.hru
ROCK	*rock*: Percent rock in the first soil layer (%)	.sol

13.3 SNOW COVER EFFECTS

The erosive power of rain and runoff will be less when snow cover is present than when there is no snow cover. During periods when snow is present in an HRU, SWAT modifies the sediment yield using the following relationship:

$$sed = \frac{sed'}{\exp\left[\dfrac{3 \cdot SNO}{25.4}\right]} \qquad 13.3.1$$

where *sed* is the sediment yield on a given day (metric tons), sed' is the sediment yield calculated with MUSLE (metric tons), and *SNO* is the water content of the snow cover (mm H_2O).

13.4 SEDIMENT LAG IN SURFACE RUNOFF

In large subbasins with a time of concentration greater than 1 day, only a portion of the surface runoff will reach the main channel on the day it is generated. SWAT incorporates a surface runoff storage feature to lag a portion of the surface runoff release to the main channel. Sediment in the surface runoff is lagged as well.

Once the sediment load in surface runoff is calculated, the amount of sediment released to the main channel is calculated:

$$sed = \left(sed' + sed_{stor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 13.4.1$$

where *sed* is the amount of sediment discharged to the main channel on a given day (metric tons), sed' is the amount of sediment load generated in the HRU on a given day (metric tons), $sed_{stor,i-1}$ is the sediment stored or lagged from the previous day (metric tons), *surlag* is the surface runoff lag coefficient, and t_{conc} is the time of concentration for the HRU (hrs).

The expression $\left(1-\exp\left[\frac{-surlag}{t_{conc}}\right]\right)$ in equation 13.4.1 represents the fraction of the total available sediment that will be allowed to enter the reach on any one day. Figure 13-1 plots values for this expression at different values for *surlag* and t_{conc}.

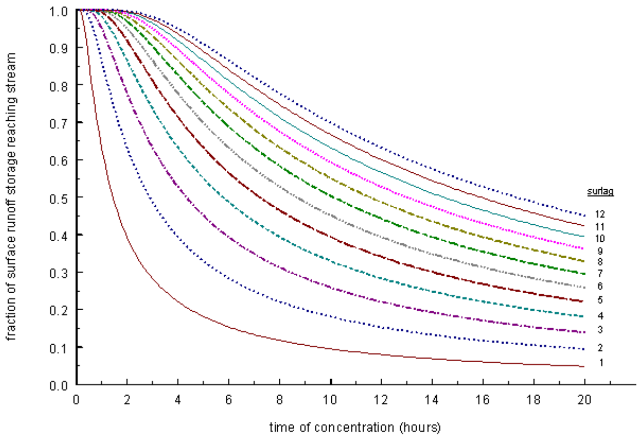


Figure 13-1: Influence of *surlag* and t_{conc} on fraction of surface runoff and sediment released.

Note that for a given time of concentration, as *surlag* decreases in value more sediment is held in storage.

Table 13-7: SWAT input variables that pertain to sediment lag calculations.

Variable Name	Definition	Input File
SURLAG	*surlag*: surface runoff lag coefficient	.bsn

13.5 SEDIMENT IN LATERAL & GROUNDWATER FLOW

SWAT allows the lateral and groundwater flow to contribute sediment to the main channel. The amount of sediment contributed by lateral and groundwater flow is calculated:

$$sed_{lat} = \frac{(Q_{lat} + Q_{gw}) \cdot area_{hru} \cdot conc_{sed}}{1000} \qquad 13.5.1$$

where sed_{lat} is the sediment loading in lateral and groundwater flow (metric tons), Q_{lat} is the lateral flow for a given day (mm H_2O), Q_{gw} is the groundwater flow for a given day (mm H_2O), $area_{hru}$ is the area of the HRU (km^2), and $conc_{sed}$ is the concentration of sediment in lateral and groundwater flow (mg/L).

Table 13-8: SWAT input variables that pertain to sediment lag calculations.

Variable Name	Definition	Input File
LAT_SED	$conc_{sed}$: Concentration of sediment in lateral and groundwater flow (mg/L)	.hru

13.6 NOMENCLATURE

C_{USLE}	USLE cover and management factor
$C_{USLE,aa}$	Average annual C factor for the land cover
$C_{USLE,mn}$	Minimum value for the cover and management factor for the land cover
$CFRG$	Coarse fragment factor
E_{storm}	Total storm energy (0.0017 m-metric ton/m^2),
EI_{USLE}	Rainfall erosion index (0.017 m-metric ton cm/(m^2 hr))
I_{30}	Maximum 30 minute intensity (mm/hr)
K_{USLE}	USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm))
L_{hill}	Slope length (m)
LS_{USLE}	USLE topographic factor
M	Particle-size parameter for estimation of USLE K factor
OM	Percent organic matter (%)
P_{USLE}	USLE support practice factor
Q_{gw}	Groundwater flow for a given day (mm H_2O)
Q_{lat}	Lateral flow (mm H_2O)
Q_{surf}	Surface runoff volume (mm H_2O/ha)
R_{day}	Amount of rainfall on a given day (mm H_2O)
SNO	Water content of the snow cover (mm H_2O)

$area_{hru}$	HRU area (ha or km^2)
c_{perm}	Profile-permeability class
$c_{soilstr}$	Soil-structure code used in soil classification
$conc_{sed}$	Concentration of sediment in lateral and groundwater flow (mg/L)
f_{cl-si}	Factor that gives low soil erodibility factors for soils with high clay to silt ratios
f_{csand}	Factor that gives low soil erodibility factors for soils with high coarse-sand contents and high values for soils with little sand
f_{hisand}	Factor that reduces soil erodibility for soils with extremely high sand contents
f_{orgc}	Factor that reduces soil erodibility for soils with high organic carbon content
i_{mx}	Maximum rainfall intensity (mm/hr)
i_t	Rainfall intensity at time t (mm/hr)
k_i	Decay constant for rainfall intensity (hr)
m	Exponential term in USLE LS factor calculation
m_c	Percent clay content (< 0.002 mm diameter particles)
m_s	Percent sand content

m_{silt}	Percent silt content (0.002-0.05 mm diameter particles)
m_{vfs}	Percent very fine sand content (0.05-0.10 mm diameter particles)
$orgC_{ly}$	Amount of organic carbon in the layer (%)
q_{peak}	Peak runoff rate (m^3/s)
$rock$	Percent rock in soil layer (%)
rsd_{surf}	Amount of residue on the soil surface (kg/ha)
sed	Sediment yield on a given day (metric tons)
sed_{lat}	Sediment loading in lateral and groundwater flow (metric tons)
$sed_{stor,i-1}$	Sediment stored or lagged from the previous day (metric tons)
slp	Average slope of the subbasin (m/m)
$surlag$	Surface runoff lag coefficient
t	Time (hr)
t_{conc}	Time of concentration for a subbasin (hr)
$\alpha_{0.5}$	Maximum half-hour rainfall expressed as a fraction of daily rainfall
α_{hill}	Angle of the slope

13.7 REFERENCES

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CHAPTER 14

EQUATIONS: NUTRIENT TRANSPORT

The transport of nutrients from land areas into streams and water bodies is a normal result of soil weathering and erosion processes. However, excessive loading of nutrients into streams and water bodies will accelerate eutrophication and render the water unfit for human consumption. This chapter reviews the algorithms governing movement of mineral and organic forms of nitrogen and phosphorus from land areas to the stream network.

14.1 NITRATE MOVEMENT

Most soil minerals are negatively charged at normal pH and the net interaction with anions such as nitrate is a repulsion from particle surfaces. This repulsion is termed negative adsorption or anion exclusion.

Anions are excluded from the area immediately adjacent to mineral surfaces due to preferential attraction of cations to these sites. This process has a direct impact on the transport of anions through the soil for it effectively excludes anions from the slowest moving portion of the soil water volume found closest to the charged particle surfaces (Jury et al, 1991). In effect, the net pathway of the anion through the soil is shorter than it would be if all the soil water had to be used (Thomas and McMahon, 1972).

Nitrate may be transported with surface runoff, lateral flow or percolation. To calculate the amount of nitrate moved with the water, the concentration of nitrate in the mobile water is calculated. This concentration is then multiplied by the volume of water moving in each pathway to obtain the mass of nitrate lost from the soil layer.

The concentration of nitrate in the mobile water fraction is calculated:

$$conc_{NO3,mobile} = \frac{NO3_{ly} \cdot \exp\left[\frac{-w_{mobile}}{(1-\theta_e)\cdot SAT_{ly}}\right]}{w_{mobile}} \qquad 14.1.2$$

where $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for a given layer (kg N/mm H_2O), $NO3_{ly}$ is the amount of nitrate in the layer (kg N/ha), w_{mobile} is the amount of mobile water in the layer (mm H_2O), θ_e is the fraction of porosity from which anions are excluded, and SAT_{ly} is the saturated water content of the soil layer (mm H_2O). The amount of mobile water in the layer is the amount of water lost by surface runoff, lateral flow or percolation:

$$w_{mobile} = Q_{surf} + Q_{lat,ly} + w_{perc,ly} \qquad \text{for top 10 mm} \qquad 14.1.3$$

$$w_{mobile} = Q_{lat,ly} + w_{perc,ly} \qquad \text{for lower soil layers} \qquad 14.1.4$$

where w_{mobile} is the amount of mobile water in the layer (mm H_2O), Q_{surf} is the surface runoff generated on a given day (mm H_2O), $Q_{lat,ly}$ is the water discharged from the layer by lateral flow (mm H_2O), and $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O). Surface runoff is allowed to interact with and transport nutrients from the top 10 mm of soil.

Nitrate removed in surface runoff is calculated:

$$NO3_{surf} = \beta_{NO3} \cdot conc_{NO3,mobile} \cdot Q_{surf} \qquad 14.1.5$$

where $NO3_{surf}$ is the nitrate removed in surface runoff (kg N/ha), β_{NO3} is the nitrate percolation coefficient, $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for the top 10 mm of soil (kg N/mm H_2O), and Q_{surf} is the surface runoff generated on a given day (mm H_2O). The nitrate percolation coefficient allows the user to set the concentration of nitrate in surface runoff to a fraction of the concentration in percolate.

Nitrate removed in lateral flow is calculated:

$$NO3_{lat,ly} = \beta_{NO3} \cdot conc_{NO3,mobile} \cdot Q_{lat,ly} \qquad \text{for top 10 mm} \qquad 14.1.6$$

$$NO3_{lat,ly} = conc_{NO3,mobile} \cdot Q_{lat,ly} \qquad \text{for lower layers} \qquad 14.1.7$$

where $NO3_{lat,ly}$ is the nitrate removed in lateral flow from a layer (kg N/ha), β_{NO3} is the nitrate percolation coefficient, $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for the layer (kg N/mm H_2O), and $Q_{lat,ly}$ is the water discharged from the layer by lateral flow (mm H_2O).

Nitrate moved to the underlying layer by percolation is calculated:

$$NO3_{perc,ly} = conc_{NO3,mobile} \cdot w_{perc,ly} \qquad 14.1.8$$

where $NO3_{perc,ly}$ is the nitrate moved to the underlying layer by percolation (kg N/ha), $conc_{NO3,mobile}$ is the concentration of nitrate in the mobile water for the layer (kg N/mm H_2O), and $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O).

Table 14-1: SWAT input variables that pertain to nitrate transport.

Variable Name	**Definition**	**Input File**
ANION_EXCL	θ_e: Fraction of porosity from which anions are excluded	.sol
NPERCO	β_{NO3}: Nitrate percolation coefficient	.bsn

14.2 ORGANIC N IN SURFACE RUNOFF

Organic N attached to soil particles may be transported by surface runoff to the main channel. This form of nitrogen is associated with the sediment loading from the HRU and changes in sediment loading will be reflected in the organic nitrogen loading. The amount of organic nitrogen transported with sediment to the stream is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978).

$$orgN_{surf} = 0.001 \cdot conc_{orgN} \cdot \frac{sed}{area_{hru}} \cdot \varepsilon_{N:sed} \qquad 14.2.1$$

where $orgN_{surf}$ is the amount of organic nitrogen transported to the main channel in surface runoff (kg N/ha), $conc_{orgN}$ is the concentration of organic nitrogen in the top 10 mm (g N/ metric ton soil), sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and $\varepsilon_{N:sed}$ is the nitrogen enrichment ratio.

The concentration of organic nitrogen in the soil surface layer, $conc_{orgN}$, is calculated:

$$conc_{orgN} = 100 \cdot \frac{\left(orgN_{frsh,surf} + orgN_{sta,surf} + orgN_{act,surf}\right)}{\rho_b \cdot depth_{surf}} \qquad 14.2.2$$

where $orgN_{frsh,surf}$ is nitrogen in the fresh organic pool in the top 10mm (kg N/ha), $orgN_{sta,surf}$ is nitrogen in the stable organic pool (kg N/ha), $orgN_{act,surf}$ is nitrogen in the active organic pool in the top 10 mm (kg N/ha), ρ_b is the bulk density of the first soil layer (Mg/m^3), and $depth_{surf}$ is the depth of the soil surface layer (10 mm).

14.2.1 ENRICHMENT RATIO

As surface runoff flows over the soil surface, part of the water's energy is used to pick up and transport soil particles. The smaller particles weigh less and are more easily transported than coarser particles. When the particle size distribution of the transported sediment is compared to that of the soil surface layer, the sediment load to the main channel has a greater proportion of clay sized particles. In other words, the sediment load is enriched in clay particles. Organic nitrogen in the soil is attached primarily to colloidal (clay) particles, so the sediment load will also contain a greater proportion or concentration of organic N than that found in the soil surface layer.

The enrichment ratio is defined as the ratio of the concentration of organic nitrogen transported with the sediment to the concentration in the soil surface layer. SWAT will calculate an enrichment ratio for each storm event, or allow the user to define a particular enrichment ratio for organic nitrogen that is used for all storms during the simulation. To calculate the enrichment ratio, SWAT uses a relationship described by Menzel (1980) in which the enrichment ratio is logarithmically related to sediment concentration. The equation used to calculate the nitrogen enrichment ratio, $\varepsilon_{N:sed}$, for each storm event is:

$$\varepsilon_{N:sed} = 0.78 \cdot \left(conc_{sed,surq}\right)^{-0.2468} \qquad 14.2.3$$

where $conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H_2O). The concentration of sediment in surface runoff is calculated:

$$conc_{sed,surq} = \frac{sed}{10 \cdot area_{hru} \cdot Q_{surf}} \qquad 14.2.4$$

where sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and $Q_{,surf}$ is the amount of surface runoff on a given day (mm H_2O).

Table 14-2: SWAT input variables that pertain to organic N loading.

Variable Name	Definition	Input File
SOL_BD	ρ_b: Bulk density (Mg/m^3)	.sol
ERORGN	$\varepsilon_{N:sed}$: Organic nitrogen enrichment ratio	.hru

14.3 SOLUBLE PHOSPHORUS MOVEMENT

The primary mechanism of phosphorus movement in the soil is by diffusion. Diffusion is the migration of ions over small distances (1-2 mm) in the soil solution in response to a concentration gradient. Due to the low mobility of solution phosphorus, surface runoff will only partially interact with the solution P stored in the top 10 mm of soil. The amount of solution P transported in surface runoff is:

$$P_{surf} = \frac{P_{solution,surf} \cdot Q_{surf}}{\rho_b \cdot depth_{surf} \cdot k_{d,surf}} \qquad 14.3.1$$

where P_{surf} is the amount of soluble phosphorus lost in surface runoff (kg P/ha), $P_{solution,surf}$ is the amount of phosphorus in solution in the top 10 mm (kg P/ha), $Q_{,surf}$ is the amount of surface runoff on a given day (mm H_2O), ρ_b is the bulk density of the top 10 mm (Mg/m^3) (assumed to be equivalent to bulk density of first soil layer), $depth_{surf}$ is the depth of the "surface" layer (10 mm), and $k_{d,surf}$ is the phosphorus soil partitioning coefficient (m^3/Mg). The phosphorus soil partitioning coefficient is the ratio of the soluble phosphorus concentration in the surface 10 mm of soil to the concentration of soluble phosphorus in surface runoff.

Table 14-3: SWAT input variables that pertain to soluble P runoff.

Variable Name	**Definition**	**Input File**
SOL_BD	ρ_b: Bulk density (Mg/m^3)	.sol
PHOSKD	$k_{d,surf}$: Phosphorus soil partitioning coefficient (m^3/Mg)	.bsn

14.4 ORGANIC & MINERAL P ATTACHED TO SEDIMENT IN SURFACE RUNOFF

Organic and mineral P attached to soil particles may be transported by surface runoff to the main channel. This form of phosphorus is associated with the sediment loading from the HRU and changes in sediment loading will be reflected in the loading of these forms of phophorus. The amount of phosphorus transported with sediment to the stream is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978).

$$sedP_{surf} = 0.001 \cdot conc_{sedP} \cdot \frac{sed}{area_{hru}} \cdot \varepsilon_{P:sed} \qquad 14.4.1$$

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

The concentration of phosphorus attached to sediment in the soil surface layer, $conc_{sedP}$, is calculated:

$$conc_{sedP} = 100 \cdot \frac{\left(minP_{act,surf} + minP_{sta,surf} + orgP_{hum,surf} + orgP_{frsh,surf}\right)}{\rho_b \cdot depth_{surf}} \qquad 14.4.2$$

where $minP_{act,surf}$ is the amount of phosphorus in the active mineral pool in the top 10 mm (kg P/ha), $minP_{sta,surf}$ is the amount of phosphorus in the stable mineral pool in the top 10 mm (kg P/ha), $orgP_{hum,surf}$ is the amount of phosphorus in humic organic pool in the top 10 mm (kg P/ha), $orgP_{frsh,surf}$ is the amount of phosphorus in the fresh organic pool in the top 10 mm (kg P/ha), ρ_b is the bulk density of the first soil layer (Mg/m^3), and $depth_{surf}$ is the depth of the soil surface layer (10 mm).

14.4.1 ENRICHMENT RATIO

The enrichment ratio is defined as the ratio of the concentration of phosphorus transported with the sediment to the concentration of phosphorus in the soil surface layer. SWAT will calculate an enrichment ratio for each storm event, or allow the user to define a particular enrichment ratio for phosphorus attached to sediment that is used for all storms during the simulation. To calculate the enrichment ratio, SWAT uses a relationship described by Menzel (1980) in which the enrichment ratio is logarithmically related to sediment concentration. The equation used to calculate the phosphorus enrichment ratio, $\varepsilon_{P:sed}$, for each storm event is:

$$\varepsilon_{P:sed} = 0.78 \cdot \left(conc_{sed,surq}\right)^{-0.2468} \qquad 14.4.3$$

where $conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H_2O). The concentration of sediment in surface runoff is calculated:

$$conc_{sed,surq} = \frac{sed}{10 \cdot area_{hru} \cdot Q_{surf}} \qquad 14.4.4$$

where sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and Q_{surf} is the amount of surface runoff on a given day (mm H_2O).

Table 14-4: SWAT input variables that pertain to loading of P attached to sediment.

Variable Name	Definition	Input File
SOL_BD	ρ_b: Bulk density (Mg/m^3)	.sol
ERORGP	$\varepsilon_{P:sed}$: Phosphorus enrichment ratio	.hru

14.5 NUTRIENT LAG IN SURFACE RUNOFF AND LATERAL FLOW

In large subbasins with a time of concentration greater than 1 day, only a portion of the surface runoff and lateral flow will reach the main channel on the day it is generated. SWAT incorporates a storage feature to lag a portion of the surface runoff and lateral flow release to the main channel. Nutrients in the surface runoff and lateral flow are lagged as well.

Once the nutrient load in surface runoff and lateral flow is determined, the amount of nutrients released to the main channel is calculated:

$$NO3_{surf} = \left(NO3'_{surf} + NO3_{surstor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 14.5.1$$

$$NO3_{lat} = \left(NO3'_{lat} + NO3_{latstor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-1}{TT_{lat}}\right]\right) \qquad 14.5.2$$

$$orgN_{surf} = \left(orgN'_{surf} + orgN_{stor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 14.5.3$$

$$P_{surf} = \left(P'_{surf} + P_{stor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 14.5.4$$

$$sedP_{surf} = \left(sedP'_{surf} + sedP_{stor,i-1}\right) \cdot \left(1 - \exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 14.5.5$$

where $NO3_{surf}$ is the amount of nitrate discharged to the main channel in surface runoff on a given day (kg N/ha), $NO3'_{surf}$ is the amount of surface runoff nitrate generated in the HRU on a given day (kg N/ha), $NO3_{surstor,i-1}$ is the surface runoff nitrate stored or lagged from the previous day (kg N/ha), $NO3_{lat}$ is the amount of nitrate discharged to the main channel in lateral flow on a given day (kg N/ha),

$NO3'_{lat}$ is the amount of lateral flow nitrate generated in the HRU on a given day (kg N/ha), $NO3_{latstor,i-1}$ is the lateral flow nitrate stored or lagged from the previous day (kg N/ha), $orgN_{surf}$ is the amount of organic N discharged to the main channel in surface runoff on a given day (kg N/ha), $orgN'_{surf}$ is the organic N loading generated in the HRU on a given day (kg N/ha), $orgN_{stor,i-1}$ is the organic N stored or lagged from the previous day (kg N/ha), P_{surf} is the amount of solution P discharged to the main channel in surface runoff on a given day (kg P/ha), P'_{surf} is the amount of solution P loading generated in the HRU on a given day (kg P/ha), $P_{stor,i-1}$ is the solution P loading stored or lagged from the previous day (kg P/ha), $sedP_{surf}$ is the amount of sediment-attached P discharged to the main channel in surface runoff on a given day (kg P/ha), $sedP'_{surf}$ is the amount of sediment-attached P loading generated in the HRU on a given day (kg P/ha), $sedP_{stor,i-1}$ is the sediment-attached P stored or lagged from the previous day (kg P/ha), $surlag$ is the surface runoff lag coefficient, t_{conc} is the time of concentration for the HRU (hrs) and TT_{lag} is the lateral flow travel time (days).

Table 14-5: SWAT input variables that pertain to nutrient lag calculations.

Variable Name	Definition	Input File
SURLAG	*surlag*: surface runoff lag coefficient	.bsn
LAT_TTIME	TT_{lag}: Lateral flow travel time (days)	.hru

14.6 NOMENCLATURE

$NO3_{lat,ly}$ Nitrate removed in lateral flow from a layer (kg N/ha)
$NO3'_{lat}$ Amount of lateral flow nitrate generated in HRU on a given day (kg N/ha)
$NO3_{latstor,i-1}$ Lateral flow nitrate stored or lagged from the previous day (kg N/ha)
$NO3_{ly}$ Amount of nitrate in the layer (kg N/ha)
$NO3_{perc,ly}$ Nitrate moved to the underlying layer by percolation (kg N/ha)
$NO3_{surf}$ Nitrate removed in surface runoff (kg N/ha)
$NO3'_{surf}$ Amount of surface runoff nitrate generated in HRU on a given day (kg N/ha)
$NO3_{surstor,i-1}$ Surface runoff nitrate stored or lagged from the previous day (kg N/ha)
$P_{solution,surf}$ Amount of phosphorus in solution in the top 10 mm (kg P/ha)
$P_{stor,i-1}$ Solution P loading stored or lagged from the previous day (kg P/ha)
P_{surf} Amount of soluble phosphorus lost in surface runoff (kg P/ha)
P'_{surf} Amount of solution P loading generated in HRU on a given day (kg P/ha)

Q_{lat}	Lateral flow from soil layer (mm H_2O)
Q_{surf}	Accumulated runoff or rainfall excess (mm H_2O)
SAT_{ly}	Saturated water content of the soil layer (mm H_2O)
TT_{lag}	Lateral flow travel time (days)

$area_{hru}$	HRU area (ha)
$conc_{NO3,mobile}$	Concentration of nitrate in the mobile water for a given layer (kg N/mm H_2O)
$conc_{orgN}$	Concentration of organic nitrogen in the soil surface top 10 mm (g N/ metric ton soil)
$conc_{sed,surq}$	Concentration of sediment in surface runoff (Mg sed/m^3 H_2O)
$conc_{sedP}$	Concentration of phosphorus attached to sediment in the top 10 mm (g P/ metric ton soil)
$depth_{surf}$	Depth of the "surface" layer (10 mm)
$k_{d,surf}$	Phosphorus soil partitioning coefficient (m^3/Mg)
$minP_{act,ly}$	Amount of phosphorus in the active mineral pool (kg P/ha)
$minP_{sta,ly}$	Amount of phosphorus in the stable mineral pool (kg P/ha)
$orgN_{act,ly}$	Nitrogen in the active organic pool (mg/kg or kg N/ha)
$orgN_{frsh,surf}$	Nitrogen in the fresh organic pool in the top 10mm (kg N/ha)
$orgN_{sta,ly}$	Nitrogen in the stable organic pool (mg/kg or kg N/ha)
$orgN_{stor,i-1}$	Surface runoff organic N stored or lagged from the previous day (kg N/ha)
$orgN_{surf}$	Amount of organic nitrogen transport to the main channel in surface runoff (kg N/ha)
$orgN'_{surf}$	Amount of surface runoff organic N generated in HRU on a given day (kg N/ha)
$orgP_{frsh,ly}$	Phosphorus in the fresh organic pool in layer *ly* (kg P/ha)
$orgP_{hum,ly}$	Amount of phosphorus in humic organic pool in the layer (kg P/ha)
sed	Sediment yield on a given day (metric tons)
$sedP_{stor,i-1}$	Sediment-attached P stored or lagged from the previous day (kg P/ha)
$sedP_{surf}$	Amount of phosphorus transported with sediment to the main channel in surface runoff (kg P/ha)
$sedP'_{surf}$	Amount of sediment-attached P loading generated in HRU on a given day (kg P/ha)
$surlag$	Surface runoff lag coefficient
t_{conc}	Time of concentration for a subbasin (hr)
w_{mobile}	Amount of mobile water in the layer (mm H_2O)
$w_{perc,ly}$	Amount of water percolating to the underlying soil layer on a given day (mm H_2O)

β_{NO3}	Nitrate percolation coefficient
θ_e	Fraction of porosity from which anions are excluded
$\varepsilon_{N:sed}$	Nitrogen enrichment ratio
$\varepsilon_{P:sed}$	Phosphorus enrichment ratio
ρ_b	Bulk density (Mg/m^3)

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CHAPTER 15

EQUATIONS: PESTICIDE TRANSPORT

The transport of pesticide from land areas into streams and water bodies is a result of soil weathering and erosion processes. Excessive loading of pesticides in streams and water bodies can produce toxic conditions that harm aquatic life and render the water unfit for human consumption. This chapter reviews the algorithms governing movement of soluble and sorbed forms of pesticide from land areas to the stream network. Pesticide transport algorithms in SWAT were taken from EPIC (Williams, 1995).

15.1 PHASE DISTRIBUTION OF PESTICIDE

Pesticide in the soil environment can be transported in solution or attached to sediment. The partitioning of a pesticide between the solution and soil phases is defined by the soil adsorption coefficient for the pesticide. The soil adsorption coefficient is the ratio of the pesticide concentration in the soil or solid phase to the pesticide concentration in the solution or liquid phase:

$$K_p = \frac{C_{solidphase}}{C_{solution}} \qquad 15.1.1$$

where K_p is the soil adsorption coefficient ((mg/kg)/(mg/L) or m^3/ton), $C_{solidphase}$ is the concentration of the pesticide sorbed to the solid phase (mg chemical/kg solid material or g/ton), and $C_{solution}$ is the concentration of the pesticide in solution (mg chemical/L solution or g/ton). The definition of the soil adsorption coefficient in equation 15.1.1 assumes that the pesticide sorption process is linear with concentration and instantaneously reversible.

Because the partitioning of pesticide is dependent upon the amount of organic material in the soil, the soil adsorption coefficient input to the model is normalized for soil organic carbon content. The relationship between the soil adsorption coefficient and the soil adsorption coefficient normalized for soil organic carbon content is:

$$K_p = K_{oc} \cdot \frac{orgC}{100} \qquad 15.1.2$$

where K_p is the soil adsorption coefficient ((mg/kg)/(mg/L)), K_{oc} is the soil adsorption coefficient normalized for soil organic carbon content ((mg/kg)/(mg/L) or m^3/ton), and $orgC$ is the percent organic carbon present in the soil.

Table 15-1: SWAT input variables that pertain to pesticide phase partitioning.

Variable Name	Definition	Input File
SOL_CBN	$orgC_{ly}$: Amount of organic carbon in the layer (%)	.sol
SKOC	K_{oc}: Soil adsorption coefficient normalized for soil organic carbon content (ml/g or (mg/kg)/(mg/L) or L/kg)	pest.dat

15.2 MOVEMENT OF SOLUBLE PESTICIDE

Pesticide in the soluble phase may be transported with surface runoff, lateral flow or percolation. The change in the amount of pesticide contained in a soil layer due to transport in solution with flow is a function of time, concentration and amount of flow:

$$\frac{dpst_{s,ly}}{dt} = 0.01 \cdot C_{solution} \cdot w_{mobile} \qquad 15.2.1$$

where $pst_{s,ly}$ is the amount of pesticide in the soil layer (kg pst/ha), $C_{solution}$ is the pesticide concentration in solution (mg/L or g/ton), and w_{mobile} is the amount of mobile water on a given day (mm H_2O). The amount of mobile water in the layer is the amount of water lost by surface runoff, lateral flow or percolation:

$$w_{mobile} = Q_{surf} + Q_{lat,surf} + w_{perc,surf} \quad \text{for top 10 mm} \qquad 15.2.2$$

$$w_{mobile} = Q_{lat,ly} + w_{perc,ly} \quad \text{for lower soil layers} \qquad 15.2.3$$

where w_{mobile} is the amount of mobile water in the layer (mm H_2O), Q_{surf} is the surface runoff generated on a given day (mm H_2O), $Q_{lat,ly}$ is the water discharged from the layer by lateral flow (mm H_2O), and $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O).

The total amount of pesticide in the soil layer is the sum of the adsorbed and dissolved phases:

$$pst_{s,ly} = 0.01 \cdot \left(C_{solution} \cdot SAT_{ly} + C_{solidphase} \cdot \rho_b \cdot depth_{ly}\right) \qquad 15.2.4$$

where $pst_{s,ly}$ is the amount of pesticide in the soil layer (kg pst/ha), $C_{solution}$ is the pesticide concentration in solution (mg/L or g/ton), SAT_{ly} is the amount of water in the soil layer at saturation (mm H_2O), $C_{solidphase}$ is the concentration of the pesticide sorbed to the solid phase (mg/kg or g/ton), ρ_b is the bulk density of the soil layer (Mg/m^3), and $depth_{ly}$ is the depth of the soil layer (mm). Rearranging equation 15.1.1 to solve for $C_{solidphase}$ and substituting into equation 15.2.4 yields:

$$pst_{s,ly} = 0.01 \cdot \left(C_{solution} \cdot SAT_{ly} + C_{solution} \cdot K_p \cdot \rho_b \cdot depth_{ly}\right) \qquad 15.2.5$$

which rearranges to

$$C_{solution} = \frac{pst_{s,ly}}{0.01 \cdot \left(SAT_{ly} + K_p \cdot \rho_b \cdot depth_{ly}\right)} \qquad 15.2.6$$

Combining equation 15.2.6 with equation 15.2.1 yields

$$\frac{dpst_{s,ly}}{dt} = \frac{pst_{s,ly} \cdot w_{mobile}}{\left(SAT_{ly} + K_p \cdot \rho_b \cdot depth_{ly}\right)} \qquad 15.2.7$$

Integration of equation 15.2.7 gives

$$pst_{s,ly,t} = pst_{s,ly,o} \cdot \exp\left[\frac{-w_{mobile}}{\left(SAT_{ly} + K_p \cdot \rho_b \cdot depth_{ly}\right)}\right] \qquad 15.2.8$$

where $pst_{s,ly,t}$ is the amount of pesticide in the soil layer at time t (kg pst/ha), $pst_{s,ly,o}$ is the initial amount of pesticide in the soil layer (kg pst/ha), w_{mobile} is the amount of mobile water in the layer (mm H_2O), SAT_{ly} is the amount of water in the soil layer at saturation (mm H_2O), K_p is the soil adsorption coefficient ((mg/kg)/(mg/L)), ρ_b is the bulk density of the soil layer (Mg/m^3), and $depth_{ly}$ is the depth of the soil layer (mm).

To obtain the amount of pesticide removed in solution with the flow, the final amount of pesticide is subtracted from the initial amount of pesticide:

$$pst_{flow} = pst_{s,ly,o} \cdot \left(1 - \exp\left[\frac{-w_{mobile}}{\left(SAT_{ly} + K_p \cdot \rho_b \cdot depth_{ly}\right)}\right]\right) \qquad 15.2.9$$

where pst_{flow} is the amount of pesticide removed in the flow (kg pst/ha) and all other terms were previously defined.

The pesticide concentration in the mobile water is calculated:

$$conc_{pst,flow} = \min\begin{cases} pst_{flow} / w_{mobile} \\ \\ pst_{sol} / 100. \end{cases} \qquad 15.2.10$$

where $conc_{pst,flow}$ is the concentration of pesticide in the mobile water (kg pst/ha-mm H_2O), pst_{flow} is the amount of pesticide removed in the flow (kg pst/ha), w_{mobile} is the amount of mobile water in the layer (mm H_2O), and pst_{sol} is the solubility of the pesticide in water (mg/L).

Pesticide moved to the underlying layer by percolation is calculated:

$$pst_{perc,ly} = conc_{pst,flow} \cdot w_{perc,ly} \qquad 15.2.11$$

where $pst_{perc,ly}$ is the pesticide moved to the underlying layer by percolation (kg pst/ha), $conc_{pst,flow}$ is the concentration of pesticide in the mobile water for the layer (kg pst/mm H_2O), and $w_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm H_2O).

Pesticide removed in lateral flow is calculated:

$$pst_{lat,surf} = \beta_{pst} \cdot conc_{pst,flow} \cdot Q_{lat,surf} \quad \text{for top 10 mm} \qquad 15.2.12$$

$$pst_{lat,ly} = conc_{pst,flow} \cdot Q_{lat,ly} \quad \text{for lower layers} \qquad 15.2.13$$

where $pst_{lat,ly}$ is the pesticide removed in lateral flow from a layer (kg pst/ha), β_{pst} is the pesticide percolation coefficient, $conc_{pst,flow}$ is the concentration of pesticide in the mobile water for the layer (kg pst/mm H_2O), and $Q_{lat,ly}$ is the water discharged from the layer by lateral flow (mm H_2O). The pesticide percolation coefficient allows the user to set the concentration of pesticide in runoff and lateral flow from the top 10 mm to a fraction of the concentration in percolate.

Pesticide removed in surface runoff is calculated:

$$pst_{surf} = \beta_{pst} \cdot conc_{pst,flow} \cdot Q_{surf} \qquad 15.2.14$$

where pst_{surf} is the pesticide removed in surface runoff (kg pst/ha), β_{pst} is the pesticide percolation coefficient, $conc_{pst,flow}$ is the concentration of pesticide in the mobile water for the top 10 mm of soil (kg pst/mm H_2O), and Q_{surf} is the surface runoff generated on a given day (mm H_2O).

Table 15-2: SWAT input variables that pertain to pesticide transport in solution.

Variable Name	Definition	Input File
SOL_BD	ρ_b: Soil bulk density (Mg m^{-3})	.sol
WSOL	pst_{sol}: Solubility of the pesticide in water (mg/L)	pest.dat
PERCOP	β_{pst}: Pesticide percolation coefficient	.bsn

15.3 TRANSPORT OF SORBED PESTICIDE

Pesticide attached to soil particles may be transported by surface runoff to the main channel. This phase of pesticide is associated with the sediment loading from the HRU and changes in sediment loading will be reflected in the loading of sorbed pesticide. The amount of pesticide transported with sediment to the stream is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978).

$$pst_{sed} = 0.001 \cdot C_{solidphase} \cdot \frac{sed}{area_{hru}} \cdot \varepsilon_{pst:sed} \qquad 15.3.1$$

where pst_{sed} is the amount of sorbed pesticide transported to the main channel in surface runoff (kg pst/ha), $C_{solidphase}$ is the concentration of pesticide on sediment in the top 10 mm (g pst/ metric ton soil), sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and $\varepsilon_{pst:sed}$ is the pesticide enrichment ratio.

The total amount of pesticide in the soil layer is the sum of the adsorbed and dissolved phases:

$$pst_{s,ly} = 0.01 \cdot \left(C_{solution} \cdot SAT_{ly} + C_{solidphase} \cdot \rho_b \cdot depth_{ly}\right) \qquad 15.3.2$$

where $pst_{s,ly}$ is the amount of pesticide in the soil layer (kg pst/ha), $C_{solution}$ is the pesticide concentration in solution (mg/L or g/ton), SAT_{ly} is the amount of water in the soil layer at saturation (mm H_2O), $C_{solidphase}$ is the concentration of the pesticide sorbed to the solid phase (mg/kg or g/ton), ρ_b is the bulk density of the soil layer (Mg/m^3), and $depth_{ly}$ is the depth of the soil layer (mm). Rearranging equation 15.1.1 to solve for $C_{solution}$ and substituting into equation 15.3.2 yields:

$$pst_{s,ly} = 0.01 \cdot \left(\frac{C_{solidphase}}{K_p} \cdot SAT_{ly} + C_{solidphase} \cdot \rho_b \cdot depth_{ly}\right) \qquad 15.3.3$$

which rearranges to

$$C_{solidphase} = \frac{100 \cdot K_p \cdot pst_{s,ly}}{\left(SAT_{ly} + K_p \cdot \rho_b \cdot depth_{ly}\right)} \qquad 15.3.4$$

where $C_{solidphase}$ is the concentration of the pesticide sorbed to the solid phase (mg/kg or g/ton), K_p is the soil adsorption coefficient ((mg/kg)/(mg/L) or m^3/ton)

$pst_{s,ly}$ is the amount of pesticide in the soil layer (kg pst/ha), SAT_{ly} is the amount of water in the soil layer at saturation (mm H_2O), , ρ_b is the bulk density of the soil layer (Mg/m^3), and $depth_{ly}$ is the depth of the soil layer (mm).

15.3.1 ENRICHMENT RATIO

As surface runoff flows over the soil surface, part of the water's energy is used to pick up and transport soil particles. The smaller particles weigh less and are more easily transported than coarser particles. When the particle size distribution of the transported sediment is compared to that of the soil surface layer, the sediment load to the main channel has a greater proportion of clay sized particles. In other words, the sediment load is enriched in clay particles. The sorbed phase of pesticide in the soil is attached primarily to colloidal (clay) particles, so the sediment load will also contain a greater proportion or concentration of pesticide than that found in the soil surface layer.

The enrichment ratio is defined as the ratio of the concentration of sorbed pesticide transported with the sediment to the concentration in the soil surface layer. SWAT will calculate an enrichment ratio for each storm event, or allow the user to define a particular enrichment ratio for sorbed pesticide that is used for all storms during the simulation. To calculate the enrichment ratio, SWAT uses a relationship described by Menzel (1980) in which the enrichment ratio is logarithmically related to sediment concentration. The equation used to calculate the pesticide enrichment ratio, $\varepsilon_{pst:sed}$, for each storm event is:

$$\varepsilon_{pst:sed} = 0.78 \cdot \left(conc_{sed,surq}\right)^{-0.2468} \qquad 15.3.5$$

where $conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H_2O). The concentration of sediment in surface runoff is calculated:

$$conc_{sed,surq} = \frac{sed}{10 \cdot area_{hru} \cdot Q_{surf}} \qquad 15.3.6$$

where sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and Q_{surf} is the amount of surface runoff on a given day (mm H_2O).

Table 15-3: SWAT input variables that pertain to sorbed pesticide loading.

Variable Name	Definition	Input File
SOL_BD	ρ_b: Bulk density (Mg/m^3)	.sol
PSTENR	$\varepsilon_{pst:sed}$: Pesticide enrichment ratio	.chm

15.4 PESTICIDE LAG IN SURFACE RUNOFF AND LATERAL FLOW

In large subbasins with a time of concentration greater than 1 day, only a portion of the surface runoff and lateral flow will reach the main channel on the day it is generated. SWAT incorporates a storage feature to lag a portion of the surface runoff and lateral flow release to the main channel. Pesticides in the surface runoff and lateral flow are lagged as well.

Once the pesticide load in surface runoff and lateral flow is determined, the amount of pesticide released to the main channel is calculated:

$$pst_{surf} = \left(pst'_{surf} + pst_{surstor,i-1}\right)\cdot\left(1-\exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 15.4.1$$

$$pst_{lat} = \left(pst'_{lat} + pst_{latstor,i-1}\right)\cdot\left(1-\exp\left[\frac{-1}{TT_{lat}}\right]\right) \qquad 15.4.2$$

$$pst_{sed} = \left(pst'_{sed} + pst_{sedstor,i-1}\right)\cdot\left(1-\exp\left[\frac{-surlag}{t_{conc}}\right]\right) \qquad 15.4.3$$

where pst_{surf} is the amount of soluble pesticide discharged to the main channel in surface runoff on a given day (kg pst/ha), pst'_{surf} is the amount of surface runoff soluble pesticide generated in HRU on a given day (kg pst/ha), $pst_{surstor,i-1}$ is the surface runoff soluble pesticide stored or lagged from the previous day (kg pst/ha), pst_{lat} is the amount of soluble pesticide discharged to the main channel in lateral flow on a given day (kg pst/ha), pst'_{lat} is the amount of lateral flow soluble pesticide generated in HRU on a given day (kg pst/ha), $pst_{latstor,i-1}$ is the lateral flow pesticide stored or lagged from the previous day (kg pst/ha), pst_{sed} is the amount of sorbed pesticide discharged to the main channel in surface runoff on a given day (kg pst/ha), pst'_{sed} is the sorbed pesticide loading generated in HRU on a given day (kg pst/ha), $pst_{sedstor,i-1}$ is the sorbed pesticide stored or lagged from the previous day (kg pst/ha), $surlag$ is the surface runoff lag coefficient, t_{conc} is the time of concentration for the HRU (hrs) and TT_{lag} is the lateral flow travel time (days).

Table 15-4: SWAT input variables that pertain to pesticide lag calculations.

Variable Name	Definition	Input File
SURLAG	*surlag*: surface runoff lag coefficient	.bsn
LAT_TTIME	TT_{lag}: Lateral flow travel time (days)	.hru

15.5 NOMENCLATURE

$C_{solidphase}$	Concentration of the pesticide sorbed to the solid phase (mg/kg or g/ton)
$C_{solution}$	Concentration of the pesticide in solution (mg/L or g/ton)
K_{oc}	Soil adsorption coefficient normalized for soil organic carbon content (ml/g or (mg/kg)/(mg/L) or L/kg)
K_p	Soil adsorption coefficient ((mg/kg)/(mg/L))
Q_{lat}	Lateral flow from soil layer (mm H_2O)
Q_{surf}	Accumulated runoff or rainfall excess (mm H_2O)
SAT_{ly}	Soil water content of layer *ly* at saturation (mm H_2O)
TT_{lag}	Lateral flow travel time (days)

$area_{hru}$	HRU area (ha)
$conc_{pst,flow}$	Concentration of pesticide in the mobile water (kg pst/ha-mm H_2O)
$conc_{sed,surq}$	Concentration of sediment in surface runoff (Mg sed/m^3 H_2O)
$depth_{ly}$	Depth of the soil layer (mm)
$orgC_{ly}$	Amount of organic carbon in the layer (%)
pst_{flow}	Amount of pesticide removed in the flow (kg pst/ha)
$pst_{lat,ly}$	Pesticide removed in lateral flow from a layer (kg pst/ha)
pst'_{lat}	Amount of lateral flow soluble pesticide generated in HRU on a given day (kg pst/ha)
$pst_{latstor,i-1}$	Lateral flow pesticide stored or lagged from the previous day (kg pst/ha)
$pst_{perc,ly}$	Pesticide moved to the underlying layer by percolation (kg pst/ha)
$pst_{s,ly}$	Amount of pesticide in the soil (kg pst/ha)
pst_{sed}	Amount of sorbed pesticide transported to the main channel in surface runoff (kg pst/ha)
pst'_{sed}	Sorbed pesticide loading generated in HRU on a given day (kg pst/ha)
$pst_{sedstor,i-1}$	Sorbed pesticide stored or lagged from the previous day (kg pst/ha)
pst_{sol}	Solubility of the pesticide in water (mg/L)
pst_{surf}	Pesticide removed in surface runoff (kg pst/ha)

pst'_{surf}	Amount of surface runoff soluble pesticide generated in HRU on a given day (kg pst/ha)
$pst_{surstor,i-1}$	Surface runoff soluble pesticide stored or lagged from the previous day (kg pst/ha)
sed	Sediment yield on a given day (metric tons)
$surlag$	Surface runoff lag coefficient
t_{conc}	Time of concentration for a subbasin (hr)
w_{mobile}	Amount of mobile water in the layer (mm H_2O)
$w_{perc,ly}$	Amount of water percolating to the underlying soil layer on a given day (mm H_2O)
β_{pst}	Pesticide percolation coefficient
$\varepsilon_{pst:sed}$	Pesticide enrichment ratio
ρ_b	Soil bulk density (Mg m^{-3})
ρ_w	Density of water (1 Mg m^{-3})

15.6 REFERENCES

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CHAPTER 16

EQUATIONS: WATER QUALITY PARAMETERS

In addition to sediment, nutrients and pesticides, SWAT calculates the amount of algae, dissolved oxygen and carbonaceous biological oxygen demand (CBOD) entering the main channel with surface runoff. Loadings of these three parameters are required to monitor the quality of stream water. This chapter reviews the algorithms governing movement of algae, dissolved oxygen and CBOD from land areas to the stream network.

16.1 ALGAE

Suspended algal biomass is assumed to be directly proportional to chlorophyll *a*. Therefore, the algal biomass loading to the stream can be estimated as the chlorophyll *a* loading from the land area. Cluis et al. (1988) developed a relationships between the nutrient enrichment index (total N: total P), chlorophyll *a*, and algal growth potential in the North Yamaska River, Canada.

$$\left(AGP + chla\right) \cdot v_{surf} = f \cdot \left(\frac{TN}{TP}\right)^g \qquad 16.1.1$$

where AGP is the algal growth potential (mg/L), $chla$ is the chlorophyll *a* concentration in the surface runoff (μg/L), v_{surf} is the surface runoff flow rate (m^3/s), TN is the total Kjeldahl nitrogen load (kmoles), TP is the total phosphorus load (kmoles), f is a coefficient and g is an exponent.

The chlorophyll *a* concentration in surface runoff is calculated in SWAT using a simplified version of Cluis et al.'s exponential function (1988):

$$chla = 0 \qquad \text{if } (v_{surf} < 10^{-5} \text{ m}^3\text{/s}) \text{ or } (TP \text{ and } TN < 10^{-6}) \qquad 16.1.2$$

$$chla = \frac{0.5 \cdot 10^{2.7}}{v_{surf}} \qquad \text{if } v_{surf} > 10^{-5} \text{ m}^3\text{/s}, \text{ and } (TP \text{ and } TN > 10^{-6}) \qquad 16.1.3$$

$$chla = \frac{0.5 \cdot 10^{0.5}}{v_{surf}} \qquad \text{if } v_{surf} > 10^{-5} \text{ m}^3\text{/s}, \; TP < 10^{-6} \text{ and } TN > 10^{-6} \qquad 16.1.4$$

16.2 CARBONACEOUS BIOLOGICAL OXYGEN DEMAND

Carbonaceous biological oxygen demand (CBOD) defines the amount of oxygen required to decompose the organic matter transported in surface runoff. The SWAT loading function for the ultimate CBOD is based on a relationship given by Thomann and Mueller (1987):

$$cbod_{surq} = \frac{2.7 \cdot orgC_{surq}}{Q_{surf} \cdot area_{hru}} \qquad 16.2.1$$

where $cbod_{surq}$ is the CBOD concentration in surface runoff (mg CBOD/L), $orgC_{surq}$ is the organic carbon in surface runoff (kg orgC), Q_{surf} is the surface runoff on a given day (mm H_2O), and $area_{hru}$ is the area of the HRU (km^2).

The amount of organic carbon in surface runoff is calculated:

$$orgC_{surq} = 1000 \cdot \frac{orgC_{surf}}{100} \cdot sed \cdot \varepsilon_{C:sed} \tag{16.2.2}$$

where $orgC_{surq}$ is the organic carbon in surface runoff (kg orgC), $orgC_{surf}$ is the percent organic carbon in the top 10 mm of soil (%), sed is the sediment loading from the HRU (metric tons), and $\varepsilon_{C:sed}$ is the carbon enrichment ratio.

16.2.1 ENRICHMENT RATIO

As surface runoff flows over the soil surface, part of the water's energy is used to pick up and transport soil particles. The smaller particles weigh less and are more easily transported than coarser particles. When the particle size distribution of the transported sediment is compared to that of the soil surface layer, the sediment load to the main channel has a greater proportion of clay sized particles. In other words, the sediment load is enriched in clay particles. Organic carbon in the soil is attached primarily to colloidal (clay) particles, so the sediment load will also contain a greater proportion or concentration of organic carbon than that found in the soil surface layer.

The enrichment ratio is defined as the ratio of the concentration of organic carbon transported with the sediment to the concentration in the soil surface layer. SWAT will calculate an enrichment ratio for each storm event. To calculate the enrichment ratio, SWAT uses a relationship described by Menzel (1980) in which the enrichment ratio is logarithmically related to sediment concentration. The equation used to calculate the carbon enrichment ratio, $\varepsilon_{C:sed}$, for each storm event is:

$$\varepsilon_{C:sed} = 0.78 \cdot \left(conc_{sed,surq}\right)^{-0.2468} \tag{16.2.3}$$

where $conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H_2O). The concentration of sediment in surface runoff is calculated:

$$conc_{sed,surq} = \frac{sed}{10 \cdot area_{hru} \cdot Q_{surf}} \qquad 16.2.4$$

where sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and Q_{surf} is the amount of surface runoff on a given day (mm H_2O).

Table 16-1: SWAT input variables that pertain to CBOD in surface runoff.

Variable Name	Definition	Input File
SOL_CBN	$orgC_{ly}$: Percent organic carbon in the top 10 mm of soil (%)	.sol

16.3 DISSOLVED OXYGEN

Rainfall is assumed to be saturated with oxygen. To determine the dissolved oxygen concentration of surface runoff, the oxygen uptake by the oxygen demanding substance in runoff is subtracted from the saturation oxygen concentration.

$$Ox_{surf} = Ox_{sat} - \kappa_1 \cdot cbod_{surq} \cdot \frac{t_{ov}}{24} \qquad 16.3.1$$

where Ox_{surf} is the dissolved oxygen concentration in surface runoff (mg O_2/L), Ox_{sat} is the saturation oxygen concentration (mg O_2/L), κ_1 is the CBOD deoxygenation rate (day^{-1}), $cbod_{surq}$ is the CBOD concentration in surface runoff (mg CBOD/L), and t_{ov} is the time of concentration for overland flow (hr). For loadings from HRUs, SWAT assumes $\kappa_1 = 1.047$ day^{-1}.

16.3.1 OXYGEN SATURATION CONCENTRATION

The amount of oxygen that can be dissolved in water is a function of temperature, concentration of dissolved solids, and atmospheric pressure. An equation developed by APHA (1985) is used to calculate the saturation concentration of dissolved oxygen:

$$Ox_{sat} = \exp\left[-139.34410 + \frac{1.575701\times10^{5}}{T_{wat,K}} - \frac{6.642308\times10^{7}}{\left(T_{wat,K}\right)^{2}} + \frac{1.243800\times10^{10}}{\left(T_{wat,K}\right)^{3}} - \frac{8.621949\times10^{11}}{\left(T_{wat,K}\right)^{4}}\right] \qquad 16.3.2$$

where Ox_{sat} is the equilibrium saturation oxygen concentration at 1.00 atm (mg O_2/L), and $T_{wat,K}$ is the water temperature in Kelvin (273.15+°C).

16.4 NOMENCLATURE

AGP	Algal growth potential (mg/L)
Ox_{sat}	Saturation oxygen concentration (mg O_2/L)
Ox_{surf}	Dissolved oxygen concentration in surface runoff (mg O_2/L)
Q_{surf}	Surface runoff on a given day (mm H_2O)
$T_{wat,K}$	Water temperature in Kelvin (273.15+°C)
TN	Total Kjeldahl nitrogen load (moles)
TP	Total phosphorus load (moles)
$area_{hru}$	Area of the HRU (km^2)
$cbod_{surq}$	CBOD concentration in surface runoff (mg CBOD/L)
$chla$	Chlorophyll *a* concentration in the surface runoff (μg/L)
$conc_{sed,surq}$	Concentration of sediment in surface runoff (Mg sed/m^3 H_2O)
f	Coefficient
g	Exponent
$orgC_{surf}$	Percent organic carbon in the top 10 mm of soil (%)
$orgC_{surq}$	Organic carbon in surface runoff (kg orgC),
sed	Sediment loading from the HRU (metric tons)
t_{ov}	Time of concentration for overland flow (hr)
v_{surf}	Surface runoff flow rate (m^3/s)
$\varepsilon_{C:sed}$	Carbon enrichment ratio
κ_1	CBOD deoxygenation rate (day^{-1})

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LAND COVER/PLANT

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. Portions of the EPIC plant growth model that were not incorporated into SWAT include detailed root growth, micronutrient cycling and toxicity responses, and the simultaneous growth of multiple plant species in the same HRU.

CHAPTER 17

EQUATIONS: GROWTH CYCLE

The growth cycle of a plant is controlled by plant attributes summarized in the plant growth database and by the timing of operations listed in the management file. This chapter reviews the heat unit theory used to regulate the growth cycle of plants. Chapter 20 focuses on the impact of user inputs in management operations on the growth and development of plants.

17.1 HEAT UNITS

Temperature is one of the most important factors governing plant growth. Each plant has its own temperature range, i.e. its minimum, optimum, and maximum for growth. For any plant, a minimum or base temperature must be reached before any growth will take place. Above the base temperature, the higher the temperature the more rapid the growth rate of the plant. Once the optimum temperature is exceeded the growth rate will begin to slow until a maximum temperature is reached at which growth ceases.

In the 1920s and 1930s, canning factories were searching for ways to time the planting of sweet peas so that there would be a steady flow of peas at the peak of perfection to the factory. Crops planted at weekly intervals in the early spring would sometimes come to maturity with only a 1- or 2-day differential while at other times there was a 6- to 8-day differential (Boswell, 1926; 1929). A heat unit theory was suggested (Boswell, 1926; Magoon and Culpepper, 1932) that was revised and successfully applied (Barnard, 1948; Phillips, 1950) by canning companies to determine when plantings should be made to ensure a steady harvest of peas with no “bunching” or “breaks”.

The heat unit theory postulates that plants have heat requirements that can be quantified and linked to time to maturity. Because a plant will not grow when the mean temperature falls below its base temperature, the only portion of the mean daily temperature that contributes towards the plant’s development is the amount that exceeds the base temperature. To measure the total heat requirements of a plant, the accumulation of daily mean air temperatures above the plant’s base temperature is recorded over the period of the plant’s growth and expressed in terms of heat units. For example, assume sweet peas are growing with a base temperature of 5°C. If the mean temperature on a given day is 20°C, the heat units accumulated on that day are 20 – 5 = 15 heat units. Knowing the planting date, maturity date, base temperature and mean daily temperatures, the total number of heat units required to bring a crop to maturity can be calculated.

The heat index used by SWAT is a direct summation index. Each degree of the daily mean temperature above the base temperature is one heat unit. This method assumes that the rate of growth is directly proportional to the increase in temperature. It is important to keep in mind that the heat unit theory without a high temperature cutoff does not account for the impact of harmful high temperatures. SWAT assumes that all heat above the base temperature accelerates crop growth and development.

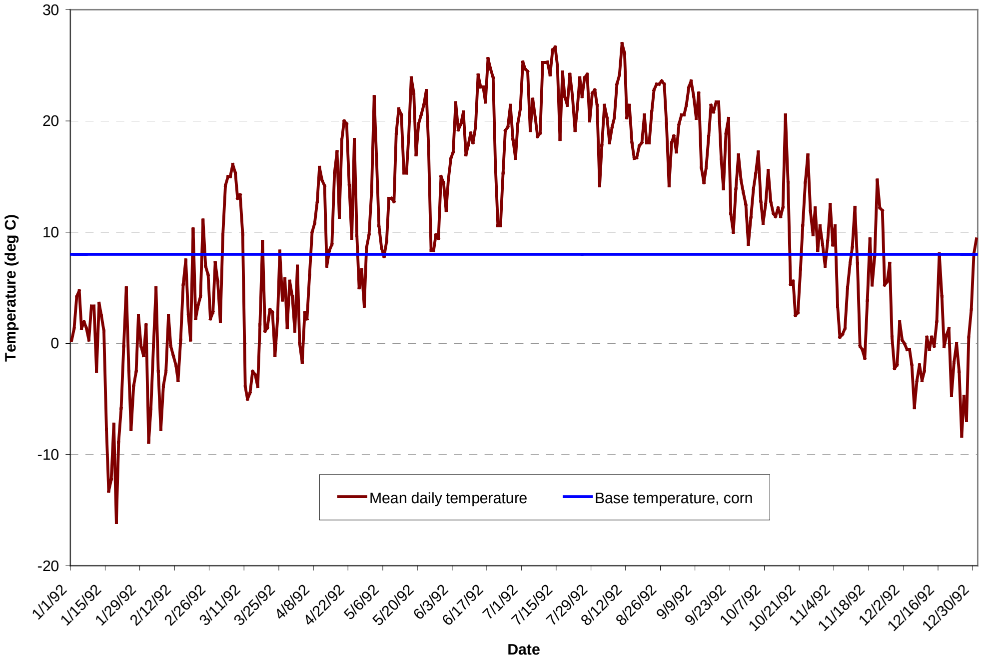

Figure 17-1: Mean daily temperature recorded for Greenfield, Indiana

The mean daily temperature during 1992 for Greenfield, Indiana is plotted in Figure 17-1 along with the base temperature for corn (8°C). Crop growth will only occur on those days where the mean daily temperature exceeds the base temperature. The heat unit accumulation for a given day is calculated with the equation:

$$HU = \overline{T}_{av} - T_{base} \qquad \text{when} \quad \overline{T}_{av} > T_{base} \qquad 17.1.1$$

where HU is the number of heat units accumulated on a given day (heat units), $\overline{T}_{av}$ is the mean daily temperature (°C), and T_{base} is the plant's base or minimum temperature for growth (°C). The total number of heat units required for a plant to reach maturity is calculated:

$$PHU = \sum_{d=1}^{m} HU \qquad 17.1.2$$

where *PHU* is the total heat units required for plant maturity (heat units), *HU* is the number of heat units accumulated on day *d* where *d* = 1 on the day of planting and *m* is the number of days required for a plant to reach maturity. *PHU* is also referred to as potential heat units.

When calculating the potential heat units for a plant, the number of days to reach maturity must be known. For most crops, these numbers have been quantified and are easily accessible. For other plants, such as forest or range, the time that the plants begin to develop buds should be used as the beginning of the growing season and the time that the plant seeds reach maturation is the end of the growing season. For the Greenfield Indiana example, a 120 day corn hybrid was planted on May 15. Summing daily heat unit values, the total heat units required to bring the corn to maturity was 1456.

17.1.1 HEAT UNIT SCHEDULING

As the heat unit theory was proven to be a reliable predictor of harvest dates for all types of crops, it was adapted by researchers for prediction of the timing of other plant development stages such as flowering (Cross and Zuber, 1972). The successful adaptation of heat units to predict the timing of plant stages has subsequently led to the use of heat units to schedule management operations.

SWAT allows management operations to be scheduled by day or by fraction of potential heat units. For each operation the model checks to see if a month and day has been specified for timing of the operation. If this information is provided, SWAT will perform the operation on that month and day. If the month and day are not specified, the model requires a fraction of potential heat units to be specified. As a general rule, if exact dates are available for scheduling operations, these dates should be used.

Scheduling by heat units allows the model to time operations as a function of temperature. This method of timing is useful for several situations. When very large watersheds are being simulated where the climate in one portion of the watershed is different enough from the climate in another section of the watershed to affect timing of operations, heat unit scheduling may be beneficial. By using heat unit scheduling, only one generic management file has to be made for a given land use. This generic set of operations can then be used wherever the land use is found in the watershed. Also, in areas where the climate can vary greatly from year to year, heat unit scheduling will allow the model to adjust the timing of operations to the weather conditions for each year.

To schedule by heat units, the timing of the operations are expressed as fractions of the potential heat units for the plant or fraction of maturity. Let us use the following example for corn in Indiana.

Date	**Operation**	**Heat Units Accumulated**	**Fraction of *PHU***
April 24	Tandem disk		
April 30	Tandem disk		
May 7	Field cultivator		
May 15	Plant corn (*PHU* = 1456)	0	.00
June 3	Row cultivator	165	.11
June 17	Row cultivator	343	.24
October 15	Harvest & Kill	1686	1.16
October 29	Tandem disk		
November 5	Chisel		

The number of heat units accumulated for the different operation timings is calculated by summing the heat units for every day starting with the planting date (May 15) and ending with the day the operation takes place. To calculate the fraction of *PHU* at which the operation takes place, the heat units accumulated is divided by the *PHU* for the crop (1456).

Note that the fraction of *PHU* for the harvest operation is 1.16. The fraction is greater than 1.0 because corn is allowed to dry down prior to harvesting. The model will simulate plant growth until the crop reaches maturity (where maturity is defined as *PHU* = 1456). From that point on, plants will not transpire or take up nutrients and water. They will stand in the HRU until converted to residue or harvested.

While the operations after planting have been scheduled by fraction of *PHU*, operations—including planting—which occur during periods when no crop is growing must still be scheduled. To schedule these operations, SWAT keeps track of a second heat index where heat units are summed over the entire year using T_{base} = 0°C. This heat index is solely a function of the climate and is termed the base zero heat index. For the base zero index, the heat units accumulated on a given day are:

$$HU_0 = \overline{T}_{av} \quad \text{when} \quad \overline{T}_{av} > 0°\text{C} \qquad 17.1.3$$

where HU_0 is the number of base zero heat units accumulated on a given day (heat units), and $\overline{T}_{av}$ is the mean daily temperature (°C). The total number of heat units for the year is calculated:

$$PHU_0 = \sum_{d=1}^{365} HU_0 \qquad 17.1.4$$

where PHU_0 is the total base zero heat units (heat units), HU_0 is the number of base zero heat units accumulated on day d where d = 1 on January 1 and 365 on December 31. Unlike the plant PHU which must be provided by the user, PHU_0 is the average calculated by SWAT using long-term weather data provided in the .wgn file.

For the example watershed in Indiana, PHU_0 = 4050. The heat unit fractions for the remaining operations are calculated using this value for potential heat units.

Date	**Operation**	**Base Zero Heat Units Accumulated**	**Plant Heat Units Accumulated**	**Fraction of PHU_0 (PHU_0 = 4050)**	**Fraction of PHU (PHU = 1456)**
April 24	Tandem disk	564		.14	
April 30	Tandem disk	607		.15	
May 7	Field cultivator	696		.17	
May 15	Plant corn (PHU = 1456)	826	0	.20	
June 3	Row cultivator	1136	165		.11
June 17	Row cultivator	1217	343		.24
October 15	Harvest & Kill	3728	1686		1.16
October 29	Tandem disk	3860		.95	
November 5	Chisel	3920		.97	

As stated previously, SWAT always keeps track of base zero heat units. The base zero heat unit scheduling is used any time there are no plants growing in the HRU (before and including the plant operation and after the kill operation). Once plant growth is initiated, the model switches to plant heat unit scheduling until the plant is killed.

The following heat unit fractions have been found to provide reasonable timings for the specified operations:

0.15	planting	fraction of PHU_0
1.0	harvest/kill for crops with no dry-down	fraction of PHU
1.2	harvest/kill for crops with dry-down	fraction of PHU
0.6	hay cutting operation	fraction of PHU

Table 17-1: SWAT input variables that pertain to heat units.

Variable Name	Definition	Input File
PHU	PHU: potential heat units for plant that is growing at the beginning of the simulation in an HRU	.mgt
HEAT UNITS	PHU: potential heat units for plant whose growth is initiated with a planting operation.	.mgt
HUSC	Fraction of potential heat units at which operation takes place.	.mgt
T_BASE	T_{base}: Minimum temperature for plant growth (°C)	crop.dat

17.2 DORMANCY

SWAT assumes trees, perennials and cool season annuals can go dormant as the daylength nears the shortest or minimum daylength for the year. During dormancy, plants do not grow.

The beginning and end of dormancy are defined by a threshold daylength. The threshold daylength is calculated:

$$T_{DL,thr} = T_{DL,mn} + t_{dorm} \qquad 17.2.1$$

where $T_{DL,thr}$ is the threshold daylength to initiate dormancy (hrs), $T_{DL,mn}$ is the minimum daylength for the watershed during the year (hrs), and t_{dorm} is the dormancy threshold (hrs). When the daylength becomes shorter than $T_{DL,thr}$ in the fall, plants other than warm season annuals that are growing in the watershed will enter dormancy. The plants come out of dormancy once the daylength exceeds $T_{DL,thr}$ in the spring.

The dormancy threshold, t_{dorm}, varies with latitude.

$$t_{dorm} = 1.0 \qquad \text{if} \quad \phi > 40\,^{\circ}\text{ N or S} \qquad 17.2.2$$

$$t_{dorm} = \frac{\phi - 20}{20} \qquad \text{if} \quad 20\,^{\circ}\text{ N or S} \leq \phi \leq 40\,^{\circ}\text{ N or S} \qquad 17.2.3$$

$$t_{dorm} = 0.0 \qquad \text{if} \quad \phi < 20\,^{\circ}\text{ N or S} \qquad 17.2.4$$

where t_{dorm} is the dormancy threshold used to compare actual daylength to minimum daylength (hrs) and ϕ is the latitude expressed as a positive value (degrees).

At the beginning of the dormant period for trees, leaf biomass is converted to residue and the leaf area index for the tree species is set to the minimum value allowed (defined in the plant growth database). At the beginning of the dormant period for perennials, 95% of the biomass is converted to residue and the leaf area index for the species is set to the minimum value allowed. For cool season annuals, none of the biomass is converted to residue.

17.3 PLANT TYPES

SWAT categorizes plants into seven different types: warm season annual legume, cold season annual legume, perennial legume, warm season annual, cold season annual, perennial and trees. The differences between the different plant types, as modeled by SWAT, are as follows:

1. warm season annual legume:
    - simulate nitrogen fixation
    - root depth varies during growing season due to root growth
2. cold season annual legume:
    - simulate nitrogen fixation
    - root depth varies during growing season due to root growth
    - fall-planted land covers will go dormant when daylength is less than the threshold daylength
3. perennial legume:
    - simulate nitrogen fixation
    - root depth always equal to the maximum allowed for the plant species and soil
    - plant goes dormant when daylength is less than the threshold daylength
4. warm season annual:
    - root depth varies during growing season due to root growth
5. cold season annual:
    - root depth varies during growing season due to root growth
    - fall-planted land covers will go dormant when daylength is less than the threshold daylength

6 perennial:
  - root depth always equal to the maximum allowed for the plant species and soil
  - plant goes dormant when daylength is less than the threshold daylength

7 trees:
  - root depth always equal to the maximum allowed for the plant species and soil
  - partitions new growth between leaves/needles (30%) and woody growth (70%). At the end of each growing season, biomass in the leaf fraction is converted to residue

17.4 NOMENCLATURE

HU	Number of heat units accumulated on a given day where base temperature is dependant on the plant species (heat units)
HU_0	Number of base zero heat units accumulated on a given day (heat units)
PHU	Potential heat units or total heat units required for plant maturity where base temperature is dependant on the plant species (heat units)
PHU_0	Total base zero heat units or potential base zero heat units (heat units)
T_{base}	Plant’s base or minimum temperature for growth (°C)
$T_{DL,mn}$	Minimum daylength for the watershed during the year (hrs)
$T_{DL,thr}$	Threshold daylength to initiate dormancy (hrs)
$\overline{T}_{av}$	Mean air temperature for day (°C)
t_{dorm}	Dormancy threshold (hrs)
ϕ	Latitude expressed as a positive value (degrees)

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CHAPTER 18

EQUATIONS: OPTIMAL GROWTH

For each day of simulation, potential plant growth, i.e. plant growth under ideal growing conditions, is calculated. Ideal growing conditions consist of adequate water and nutrient supply and a favorable climate. Differences in growth between plant species are defined by the parameters contained in the plant growth database.

18.1 POTENTIAL GROWTH

Plant growth is modeled by simulating leaf area development, light interception and conversion of intercepted light into biomass assuming a plant species-specific radiation-use efficiency.

18.1.1 BIOMASS PRODUCTION

The amount of daily solar radiation intercepted by the leaf area of the plant is calculated using Beer's law (Monsi and Saeki, 1953):

$$H_{phosyn} = 0.5 \cdot H_{day} \cdot \left(1 - \exp\left(k_{\ell} \cdot LAI\right)\right) \qquad 18.1.1$$

where H_{phosyn} is the amount of intercepted photosynthetically active radiation on a given day (MJ m^{-2}), H_{day} is the incident total solar (MJ m^{-2}), $0.5 \cdot H_{day}$ is the incident photosynthetically active radiation (MJ m^{-2}), k_{ℓ} is the light extinction coefficient, and *LAI* is the leaf area index. In SWAT, the light extinct coefficient is –0.65 for all plants.

Photosynthetically active radiation is radiation with a wavelength between 400 and 700 mm (McCree, 1972). Direct solar beam radiation contains roughly 45% photosynthetically active radiation while diffuse radiation contains around 60% photosynthetically active radiation (Monteith, 1972; Ross, 1975). The fraction of photosynthetically active radiation will vary from day to day with variation in overcast conditions but studies in Europe and Israel indicate that 50% is a representative mean value (Monteith, 1972; Szeicz, 1974; Stanhill and Fuchs, 1977).

Radiation-use efficiency is the amount of dry biomass produced per unit intercepted solar radiation. The radiation-use efficiency is defined in the plant growth database and is assumed to be independent of the plant's growth stage. The maximum increase in biomass on a given day that will result from the intercepted photosynthetically active radiation is estimated (Monteith, 1977):

$$\Delta bio = RUE \cdot H_{phosyn} \qquad 18.1.2$$

where Δbio is the potential increase in total plant biomass on a given day (kg/ha), RUE is the radiation-use efficiency of the plant (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ), and H_{phosyn} is the amount of intercepted photosynthetically active radiation on a given day (MJ m^{-2}). Equation 18.1.2 assumes that the photosynthetic rate of a canopy is a linear function of radiant energy.

The total biomass on a given day, d, is calculated as:

$$bio = \sum_{i=1}^{d} \Delta bio_i \qquad 18.1.3$$

where bio is the total plant biomass on a given day (kg ha^{-1}), and Δbio_i is the increase in total plant biomass on day i (kg/ha).

18.1.1.1 IMPACT OF CLIMATE ON RADIATION-USE EFFICIENCY

Radiation-use efficiency is sensitive to variations in atmospheric CO_2 concentrations and equations have been incorporated into SWAT to modify the default radiation-use efficiency values in the plant database for climate change studies. The relationship used to adjust the radiation-use efficiency for effects of elevated CO_2 is (Stockle et al., 1992):

$$RUE = \frac{100 \cdot CO_2}{CO_2 + \exp(r_1 - r_2 \cdot CO_2)} \qquad 18.1.4$$

where RUE is the radiation-use efficiency of the plant (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ), CO_2 is the concentration of carbon dioxide in the atmosphere (ppmv), and r_1 and r_2 are shape coefficients.

The shape coefficients are calculated by solving equation 18.1.4 using two known points (RUE_{amb}, CO_{2amb}) and (RUE_{hi}, CO_{2hi}):

$$r_1 = \ln\left[\frac{CO_{2amb}}{(0.01 \cdot RUE_{amb})} - CO_{2amb}\right] + r_2 \cdot CO_{2amb} \qquad 18.1.5$$

$$r_2 = \frac{\left(\ln\left[\frac{CO_{2amb}}{(0.01 \cdot RUE_{amb})} - CO_{2amb}\right] - \ln\left[\frac{CO_{2hi}}{(0.01 \cdot RUE_{hi})} - CO_{2hi}\right]\right)}{CO_{2hi} - CO_{2amb}} \qquad 18.1.6$$

where r_1 is the first shape coefficient, r_2 is the second shape coefficient, CO_{2amb} is the ambient atmospheric CO_2 concentration (ppmv), RUE_{amb} is the radiation-use efficiency of the plant at ambient atmospheric CO_2 concentration (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ), CO_{2hi} is an elevated atmospheric CO_2 concentration (ppmv), RUE_{hi} is the radiation-use efficiency of the plant at the elevated atmospheric CO_2 concentration, CO_{2hi}, (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ). Equation 18.1.4 was developed when the ambient atmospheric CO_2 concentration was 330 ppmv and is valid for carbon dioxide concentrations in the range 330-660 ppmv. Even though the ambient atmospheric concentration of carbon dioxide is now higher than 330 ppmv, this value is still used in the calculation. If the CO_2 concentration used in the simulation is less than 330 ppmv, the model defines $RUE = RUE_{amb}$.

Stockle and Kiniry (1990) have shown that a plant's radiation-use efficiency is affected by vapor pressure deficit. For a plant, a threshold vapor pressure deficit is defined at which the plant's radiation-use efficiency begins to drop in response to the vapor pressure deficit. The adjusted radiation-use efficiency is calculated:

$$RUE = RUE_{vpd=1} - \Delta rue_{dcl} \cdot \left(vpd - vpd_{thr}\right) \quad \text{if } vpd > vpd_{thr} \qquad 18.1.7$$

$$RUE = RUE_{vpd=1} \quad \text{if } vpd \leq vpd_{thr} \qquad 18.1.8$$

where RUE is the radiation-use efficiency adjusted for vapor pressure deficit (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ), $RUE_{vpd=1}$ is the radiation-use efficiency for the plant at a vapor pressure deficit of 1 kPa (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ), Δrue_{dcl} is the rate of decline in radiation-use efficiency per unit increase in vapor pressure deficit (kg/ha·(MJ/m^2)$^{-1}$·kPa^{-1} or (10^{-1} g/MJ)·kPa^{-1}), vpd is the vapor pressure deficit (kPa), and vpd_{thr} is the threshold vapor pressure deficit above which a plant will exhibit reduced radiation-use efficiency (kPa). The radiation-use efficiency value reported for the plant in the plant growth database, RUE_{amb}, or adjusted for elevated carbon dioxide levels (equation 18.1.4) is the value used for $RUE_{vpd=1}$. The threshold vapor pressure deficit for reduced radiation-use efficiency is assumed to be 1.0 kPa for all plants ($vpd_{thr} = 1.0$).

The radiation-use efficiency is never allowed to fall below 27% of RUE_{amb}. This minimum value was based on field observations (Kiniry, personal communication, 2001).

18.1.2 CANOPY COVER AND HEIGHT

The change in canopy height and leaf area through the growing season as modeled by SWAT is illustrated using parameters for Alamo Switchgrass in Figures 18-1 and 18-2.

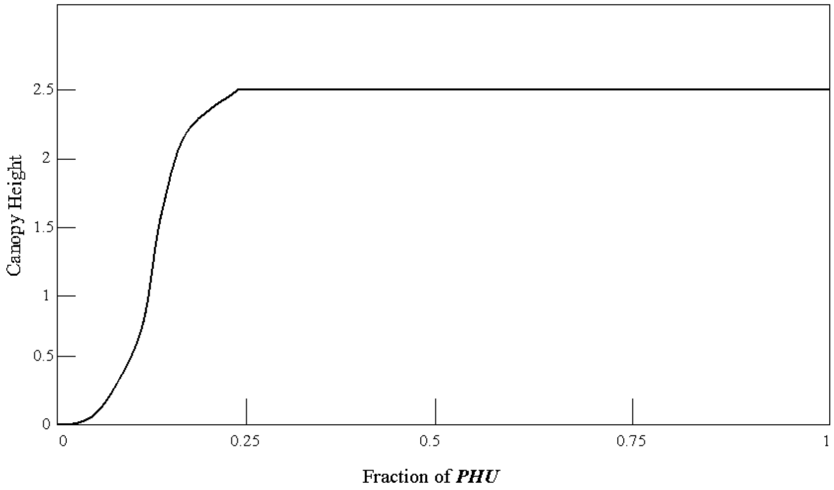

Figure 18-1: Seasonal change in plant canopy height during growing season.

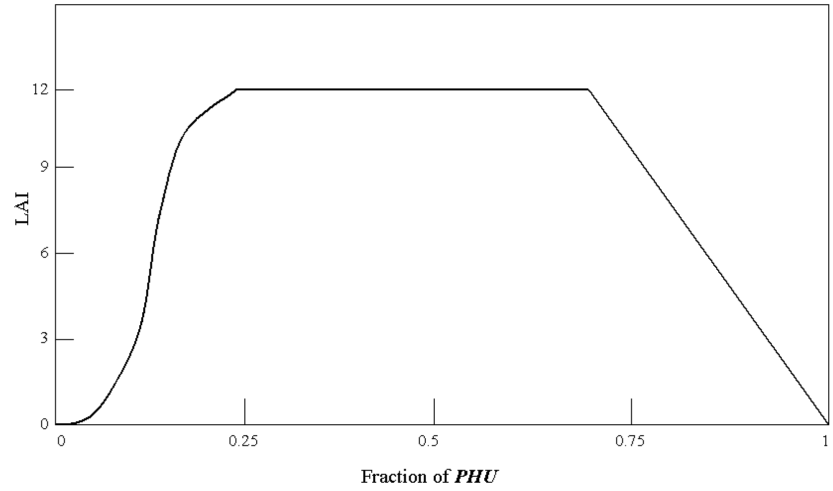

Figure 18-2: Seasonal change in plant leaf area index during growing season.

In the initial period of plant growth, canopy height and leaf area development are controlled by the optimal leaf area development curve:

$$fr_{LAImx} = \frac{fr_{PHU}}{fr_{PHU} + \exp(\ell_1 - \ell_2 \cdot fr_{PHU})} \qquad 18.1.9$$

where fr_{LAImx} is the fraction of the plant's maximum leaf area index corresponding to a given fraction of potential heat units for the plant, fr_{PHU} is the fraction of potential heat units accumulated for the plant on a given day in the growing season, and ℓ_1 and ℓ_2 are shape coefficients. The fraction of potential heat units accumulated by a given date is calculated:

$$fr_{PHU} = \frac{\sum_{i=1}^{d} HU_i}{PHU} \qquad 18.1.10$$

where fr_{PHU} is the fraction of potential heat units accumulated for the plant on day d in the growing season, HU is the heat units accumulated on day i (heat units), and PHU is the total potential heat units for the plant (heat units).

The shape coefficients are calculated by solving equation 18.1.9 using two known points ($fr_{LAI,1}$,$fr_{PHU,1}$) and ($fr_{LAI,2}$,$fr_{PHU,2}$):

$$\ell_1 = \ln\left[\frac{fr_{PHU,1}}{fr_{LAI,1}} - fr_{PHU,1}\right] + \ell_2 \cdot fr_{PHU,1} \qquad 18.1.11$$

$$\ell_2 = \frac{\left(\ln\left[\frac{fr_{PHU,1}}{fr_{LAI,1}} - fr_{PHU,1}\right] - \ln\left[\frac{fr_{PHU,2}}{fr_{LAI,2}} - fr_{PHU,2}\right]\right)}{fr_{PHU,2} - fr_{PHU,1}} \qquad 18.1.12$$

where ℓ_1 is the first shape coefficient, ℓ_2 is the second shape coefficient, $fr_{PHU,1}$ is the fraction of the growing season (i.e. fraction of total potential heat units) corresponding to the 1st point on the optimal leaf area development curve, $fr_{LAI,1}$ is the fraction of the maximum plant leaf area index (i.e. fraction of LAI_{mx}) corresponding to the 1st point on the optimal leaf area development curve, $fr_{PHU,2}$ is the fraction of the growing season corresponding to the 2nd point on the optimal leaf area development curve, and $fr_{LAI,2}$ is the fraction of the maximum plant leaf area index corresponding to the 2nd point on the optimal leaf area development curve.

The canopy height on a given day is calculated:

$$h_c = h_{c,mx} \cdot \sqrt{fr_{LAImx}} \qquad 18.1.13$$

where h_c is the canopy height for a given day (m), $h_{c,mx}$ is the plant's maximum canopy height (m), and fr_{LAImx} is the fraction of the plant's maximum leaf area index corresponding to a given fraction of potential heat units for the plant. As can be seen from Figure 18-1, once the maximum canopy height is reached, h_c will remain constant until the plant is killed.

The amount of canopy cover is expressed as the leaf area index. The leaf area added on day *i* is calculated:

$$\Delta LAI_i = \left(fr_{LAImx,i} - fr_{LA\mathrm{Im}x,i-1} \right) \cdot LAI_{mx} \cdot \left(1 - \exp\left(5 \cdot \left(LAI_{i-1} - LAI_{mx}\right)\right)\right) \qquad 18.1.14$$

And the total leaf area index is calculated:

$$LAI_i = LAI_{i-1} + \Delta LAI_i \qquad 18.1.15$$

where ΔLAI_i is the leaf area added on day *i*, LAI_i and $LAI_{i\text{-}1}$ are the leaf area indices for day *i* and *i*-1 respectiviely, $fr_{LAImx,i}$ and $fr_{LAImx,i\text{-}1}$ are the fraction of the plant's maximum leaf area index calculated with equation 18.1.9 for day *i* and *i*-1, and LAI_{mx} is the maximum leaf area index for the plant.

Leaf area index is defined as the area of green leaf per unit area of land (Watson, 1947). As shown in Figure 18-2, once the maximum leaf area index is reached, *LAI* will remain constant until leaf senescence begins to exceed leaf growth. Once leaf senescence becomes the dominant growth process, the leaf area index is calculated:

$$LAI = 16 \cdot LAI_{mx} \cdot \left(1 - fr_{PHU}\right)^2 \qquad fr_{PHU} > fr_{PHU,sen} \qquad 18.1.16$$

where *LAI* is the leaf area index for a given day, LAI_{mx} is the maximum leaf area index, fr_{PHU} is the fraction of potential heat units accumulated for the plant on a given day in the growing season, and $fr_{PHU,sen}$ is the fraction of growing season (*PHU*) at which senescence becomes the dominant growth process.

18.1.3 ROOT DEVELOPMENT

The amount of total plant biomass partitioned to the root system is 30-50% in seedlings and decreases to 5-20% in mature plants (Jones, 1985). SWAT varies the fraction of total biomass in roots from 0.40 at emergence to 0.20 at maturity. The daily root biomass fraction is calculated with the equation:

$$fr_{root} = 0.40 - 0.20 \cdot fr_{PHU} \qquad 18.1.17$$

where fr_{root} is the fraction of total biomass partitioned to roots on a given day in the growing season, and fr_{PHU} is the fraction of potential heat units accumulated for the plant on a given day in the growing season.

Calculation of root depth varies according to plant type. SWAT assumes perennials and trees have roots down to the maximum rooting depth defined for the soil throughout the growing season:

$$z_{root} = z_{root,mx} \qquad 18.1.18$$

where z_{root} is the depth of root development in the soil on a given day (mm), and $z_{root,mx}$ is the maximum depth for root development in the soil (mm). The simulated root depth for annuals varies linearly from 0.0 mm at the beginning of the growing season to the maximum rooting depth at fr_{PHU} = 0.40 using the equation:

$$z_{root} = 2.5 \cdot fr_{PHU} \cdot z_{root,mx} \qquad \text{if } fr_{PHU} \leq 0.40 \qquad 18.1.19$$

$$z_{root} = z_{root,mx} \qquad \text{if } fr_{PHU} > 0.40 \qquad 18.1.20$$

where z_{root} is the depth of root development in the soil on a given day (mm), fr_{PHU} is the fraction of potential heat units accumulated for the plant on a given day in the growing season, and $z_{root,mx}$ is the maximum depth for root development in the soil (mm). The maximum rooting depth is defined by comparing the maximum potential rooting depth for the plant from the plant growth database (RDMX in crop.dat), and the maximum potential rooting depth for the soil from the soil input file (SOL_ZMX in .sol—if no value is provided for this variable the model will set it to the deepest depth specified for the soil profile). The shallower of these two depths is the value used for $z_{root,mx}$.

18.1.4 MATURITY

Plant maturity is reached when the fraction of potential heat units accumulated, fr_{PHU}, is equal to 1.00. Once maturity is reached, the plant ceases to transpire and take up water and nutrients. Simulated plant biomass remains stable until the plant is harvested or killed via a management operation.

Table 18-1: SWAT input variables that pertain to optimal plant growth.

Variable Name	Definition	Input File
BIO_E	RUE_{amb}: Radiation use efficiency in ambient CO_2((kg/ha)/(MJ/m^2))	crop.dat
CO2HI	CO_{2hi}: Elevated CO_2 atmospheric concentration (ppmv)	crop.dat
BIOEHI	RUE_{hi}: Radiation use efficiency at elevated CO_2 atmospheric concentration value for CO2HI ((kg/ha)/(MJ/m^2))	crop.dat
WAVP	Δrue_{dcl}: Rate of decline in radiation-use efficiency per unit increase in vapor pressure deficit (kg/ha·(MJ/m^2)$^{-1}$·kPa^{-1} or (10^{-1} g/MJ)·kPa^{-1})	crop.dat
PHU	PHU: potential heat units for plant growing at beginning of simulation (heat units)	.mgt
HEAT UNITS	PHU: potential heat units for plant whose growth is initiated in a planting operation (heat units)	.mgt
FRGRW1	$fr_{PHU,1}$: Fraction of the growing season corresponding to the 1st point on the optimal leaf area development curve	crop.dat
LAIMX1	$fr_{LAI,1}$: Fraction of the maximum plant leaf area index corresponding to the 1st point on the optimal leaf area development curve	crop.dat
FRGRW2	$fr_{PHU,2}$: Fraction of the growing season corresponding to the 2nd point on the optimal leaf area development curve	crop.dat
LAIMX2	$fr_{LAI,2}$: Fraction of the maximum plant leaf area index corresponding to the 2nd point on the optimal leaf area development curve	crop.dat
CHTMX	$h_{c,mx}$: Plant's potential maximum canopy height (m)	crop.dat
BLAI	LAI_{mx}: Potential maximum leaf area index for the plant	crop.dat
DLAI	$fr_{PHU,sen}$: Fraction of growing season at which senescence becomes the dominant growth process	crop.dat
SOL_ZMX	$z_{root,mx}$: Maximum rooting depth in soil (mm)	.sol
RDMX	$z_{root,mx}$: Maximum rooting depth for plant (mm)	crop.dat

18.2 WATER UPTAKE BY PLANTS

The potential water uptake from the soil surface to any depth in the root zone is estimated with the function:

$$w_{up,z} = \frac{E_t}{\left[1 - \exp(-\beta_w)\right]} \cdot \left[1 - \exp\left(-\beta_w \cdot \frac{z}{z_{root}}\right)\right] \qquad 18.2.1$$

where $w_{up,z}$ is the potential water uptake from the soil surface to a specified depth, z, on a given day (mm H_2O), E_t is the maximum plant transpiration on a given day (mm H_2O), β_w is the water-use distribution parameter, z is the depth from the soil surface (mm), and z_{root} is the depth of root development in the soil (mm). The potential water uptake from any soil layer can be calculated by solving equation

18.2.1 for the depth at the top and bottom of the soil layer and taking the difference.

$$w_{up,ly} = w_{up,zl} - w_{up,zu} \qquad 18.2.2$$

where $w_{up,ly}$ is the potential water uptake for layer *ly* (mm H_2O), $w_{up,zl}$ is the potential water uptake for the profile to the lower boundary of the soil layer (mm H_2O), and $w_{up,zu}$ is the potential water uptake for the profile to the upper boundary of the soil layer (mm H_2O).

Since root density is greatest near the soil surface and decreases with depth, the water uptake from the upper layers is assumed to be much greater than that in the lower layers. The water-use distribution parameter, β_w, is set to 10 in SWAT. With this value, 50% of the water uptake will occur in the upper 6% of the root zone. Figure 18-3 graphically displays the uptake of water at different depths in the root zone.

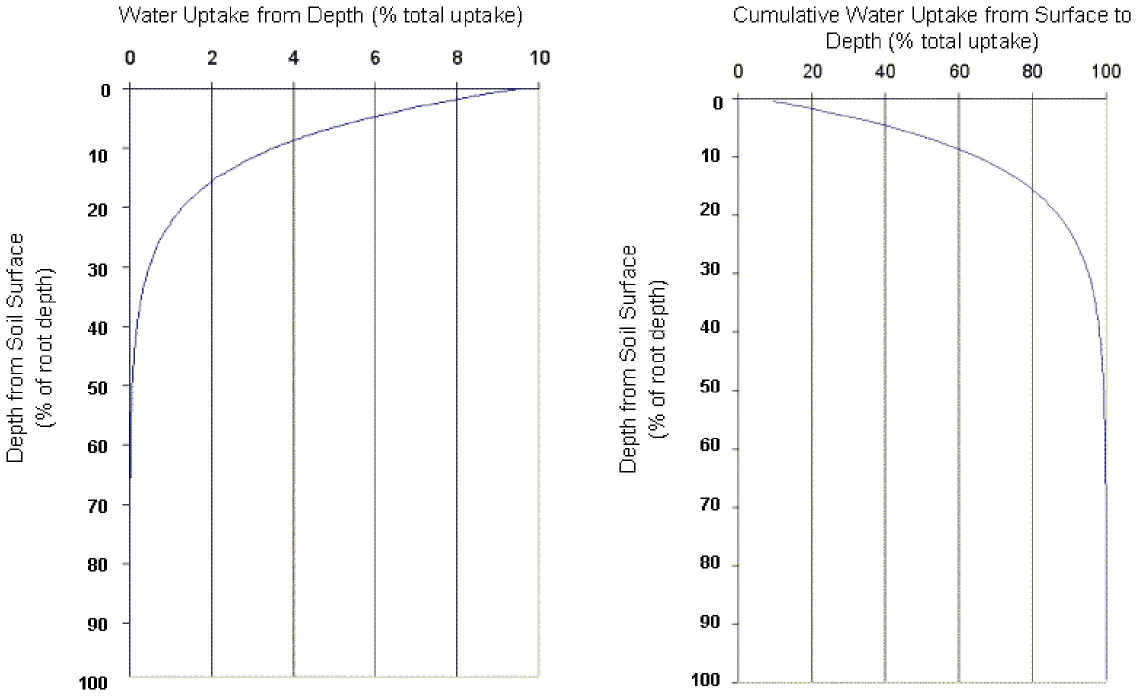

Figure 18-3: Depth distribution of water uptake

The amount of water uptake that occurs on a given day is a function of the amount of water required by the plant for transpiration, E_t, and the amount of water available in the soil, SW. Equations 18.2.1 and 18.2.2 calculate potential water uptake solely as a function of water demand for transpiration and the depth distribution defined in equation 18.2.1. SWAT modifies the initial potential water uptake from a given soil layer to reflect soil water availability in the following ways.

If upper layers in the soil profile do not contain enough water to meet the potential water uptake calculated with equation 18.2.2, users may allow lower layers to compensate. The equation used to calculate the adjusted potential water uptake is:

$$w'_{up,ly} = w_{up,ly} + w_{demand} \cdot epco \qquad 18.2.3$$

where $w'_{up,ly}$ is the adjusted potential water uptake for layer ly (mm H_2O), $w_{up,ly}$ is the potential water uptake for layer ly calculated with equation 18.2.2 (mm H_2O), w_{demand} is the water uptake demand not met by overlying soil layers (mm H_2O), and $epco$ is the plant uptake compensation factor. The plant uptake compensation factor can range from 0.01 to 1.00 and is set by the user. As $epco$ approaches 1.0, the model allows more of the water uptake demand to be met by lower layers in the soil. As $epco$ approaches 0.0, the model allows less variation from the depth distribution described by equation 18.2.1 to take place.

As the water content of the soil decreases, the water in the soil is held more and more tightly by the soil particles and it becomes increasingly difficult for the plant to extract water from the soil. To reflect the decrease in the efficiency of the plant in extracting water from dryer soils, the potential water uptake is modified using the following equations:

$$w''_{up,ly} = w'_{up,ly} \cdot \exp\left[5 \cdot \left(\frac{SW_{ly}}{(.25 \cdot AWC_{ly})} - 1\right)\right] \quad \text{when } SW_{ly} < (.25 \cdot AWC_{ly}) \qquad 18.2.4$$

$$w''_{up,ly} = w'_{up,ly} \quad \text{when } SW_{ly} \geq (.25 \cdot AWC_{ly}) \qquad 18.2.5$$

where $w''_{up,ly}$ is the potential water uptake adjusted for initial soil water content (mm H_2O), $w'_{up,ly}$ is the adjusted potential water uptake for layer ly (mm H_2O), SW_{ly} is the amount of water in the soil layer on a given day (mm H_2O), and AWC_{ly} is the available water capacity for layer ly (mm H_2O). The available water capacity is calculated:

$$AWC_{ly} = FC_{ly} - WP_{ly} \qquad 18.2.6$$

where AWC_{ly} is the available water capacity for layer ly (mm H_2O), FC_{ly} is the water content of layer ly at field capacity (mm H_2O), and WP_{ly} is the water content of layer ly at wilting point (mm H_2O).

Once the potential water uptake has been modified for soil water conditions, the actual amount of water uptake from the soil layer is calculated:

$$w_{actualup,ly} = \min\left[w''_{up,ly}, \left(SW_{ly} - WP_{ly}\right)\right] \qquad 18.2.7$$

where $w_{actualup,ly}$ is the actual water uptake for layer ly (mm H_2O), SW_{ly} is the amount of water in the soil layer on a given day (mm H_2O), and WP_{ly} is the water content of layer ly at wilting point (mm H_2O). The total water uptake for the day is calculated:

$$w_{actualup} = \sum_{ly=1}^{n} w_{actualup,ly} \qquad 18.2.8$$

where $w_{actualup}$ is the total plant water uptake for the day (mm H_2O), $w_{actualup,ly}$ is the actual water uptake for layer ly (mm H_2O), and n is the number of layers in the soil profile. The total plant water uptake for the day calculated with equation 18.2.8 is also the actual amount of transpiration that occurs on the day.

$$E_{t,act} = w_{actualup} \qquad 18.2.9$$

where $E_{t,act}$ is the actual amount of transpiration on a given day (mm H_2O) and $w_{actualup}$ is the total plant water uptake for the day (mm H_2O).

Table 18-2: SWAT input variables that pertain to plant water uptake.

Variable Name	**Definition**	**Input File**
EPCO	*epco*: Plant uptake compensation factor	.bsn, .hru

18.3 NUTRIENT UPTAKE BY PLANTS

SWAT monitors plant uptake of nitrogen and phosphorus.

18.3.1 NITROGEN UPTAKE

Plant nitrogen uptake is controlled by the plant nitrogen equation. The plant nitrogen equation calculates the fraction of nitrogen in the plant biomass as a function of growth stage given optimal growing conditions.

$$fr_N = \left(fr_{N,1} - fr_{N,3}\right) \cdot \left[1 - \frac{fr_{PHU}}{fr_{PHU} + \exp\left(n_1 - n_2 \cdot fr_{PHU}\right)}\right] + fr_{N,3} \qquad 18.3.1$$

where fr_N is the fraction of nitrogen in the plant biomass on a given day, $fr_{N,1}$ is the normal fraction of nitrogen in the plant biomass at emergence, $fr_{N,3}$ is the normal fraction of nitrogen in the plant biomass at maturity, fr_{PHU} is the fraction of potential heat units accumulated for the plant on a given day in the growing season, and n_1 and n_2 are shape coefficients.

The shape coefficients are calculated by solving equation 18.3.1 using two known points ($fr_{N,2}$, $fr_{PHU,50\%}$) and ($fr_{N,3}$, $fr_{PHU,100\%}$):

$$n_1 = \ln\left[\frac{fr_{PHU,50\%}}{\left(1 - \frac{\left(fr_{N,2} - fr_{N,3}\right)}{\left(fr_{N,1} - fr_{N,3}\right)}\right)} - fr_{PHU,50\%}\right] + n_2 \cdot fr_{PHU,50\%} \qquad 18.3.2$$

$$n_2 = \frac{\left(\ln\left[\frac{fr_{PHU,50\%}}{\left(1 - \frac{\left(fr_{N,2} - fr_{N,3}\right)}{\left(fr_{N,1} - fr_{N,3}\right)}\right)} - fr_{PHU,50\%}\right] - \ln\left[\frac{fr_{PHU,100\%}}{\left(1 - \frac{\left(fr_{N,\sim 3} - fr_{N,3}\right)}{\left(fr_{N,1} - fr_{N,3}\right)}\right)} - fr_{PHU,100\%}\right]\right)}{fr_{PHU,100\%} - fr_{PHU,50\%}} \qquad 18.3.3$$

where n_1 is the first shape coefficient, n_2 is the second shape coefficient, $fr_{N,1}$ is the normal fraction of nitrogen in the plant biomass at emergence, $fr_{N,2}$ is the normal fraction of nitrogen in the plant biomass at 50% maturity, $fr_{N,3}$ is the normal fraction of nitrogen in the plant biomass at maturity, $fr_{N,\sim 3}$ is the normal fraction of nitrogen in the plant biomass near maturity, $fr_{PHU,50\%}$ is the fraction of potential heat units accumulated for the plant at 50% maturity ($fr_{PHU,50\%}=0.5$), and $fr_{PHU,100\%}$ is the fraction of potential heat units accumulated for the plant at maturity ($fr_{PHU,100\%}=1.0$). The normal fraction of nitrogen in the plant biomass near maturity ($fr_{N,\sim3}$) is used in equation 18.3.3 to ensure that the denominator term $\left(1-\frac{\left(fr_{N,\sim3}-fr_{N,3}\right)}{\left(fr_{N,1}-fr_{N,3}\right)}\right)$ does not equal 1. The model assumes $\left(fr_{N,\sim3}-fr_{N,3}\right)=0.00001$.

To determine the mass of nitrogen that should be stored in the plant biomass on a given day, the nitrogen fraction is multiplied by the total plant biomass:

$$bio_{N,opt}=fr_N\cdot bio \qquad 18.3.4$$

where $bio_{N,opt}$ is the optimal mass of nitrogen stored in plant material for the current growth stage (kg N/ha), fr_N is the optimal fraction of nitrogen in the plant biomass for the current growth stage, and bio is the total plant biomass on a given day (kg ha^{-1}).

The plant nitrogen demand for a given day is determined by taking the difference between the nitrogen content of the plant biomass expected for the plant's growth stage and the actual nitrogen content:

$$N_{up}=bio_{N,opt}-bio_N \qquad 18.3.5$$

where N_{up} is the potential nitrogen uptake (kg N/ha), $bio_{N,opt}$ is the optimal mass of nitrogen stored in plant material for the current growth stage (kg N/ha), and bio_N is the actual mass of nitrogen stored in plant material (kg N/ha).

The depth distribution of nitrogen uptake is calculated with the function:

$$N_{up,z}=\frac{N_{up}}{\left[1-\exp(-\beta_n)\right]}\cdot\left[1-\exp\left(-\beta_n\cdot\frac{z}{z_{root}}\right)\right] \qquad 18.3.6$$

where $N_{up,z}$ is the potential nitrogen uptake from the soil surface to depth z (kg N/ha), N_{up} is the potential nitrogen uptake (kg N/ha), β_n is the nitrogen uptake distribution parameter, z is the depth from the soil surface (mm), and z_{root} is the depth of root development in the soil (mm). Note that equation 18.3.6 is similar in form to the depth distribution for water uptake described by equation 18.2.1. The potential nitrogen uptake for a soil layer is calculated by solving equation 18.3.6 for the depth at the upper and lower boundaries of the soil layer and taking the difference.

$$N_{up,ly} = N_{up,zl} - N_{up,zu} \tag{18.3.7}$$

where $N_{up,ly}$ is the potential nitrogen uptake for layer *ly* (kg N/ha), $N_{up,zl}$ is the potential nitrogen uptake from the soil surface to the lower boundary of the soil layer (kg N/ha), and $N_{up,zu}$ is the potential nitrogen uptake from the soil surface to the upper boundary of the soil layer (kg N/ha).

Root density is greatest near the surface, and nitrogen uptake in the upper portion of the soil will be greater than in the lower portion. The depth distribution of nitrogen uptake is controlled by β_n, the nitrogen uptake distribution parameter, a variable users are allowed to adjust. Figure 18-4 illustrates nitrogen uptake as a function of depth for four different uptake distribution parameter values.

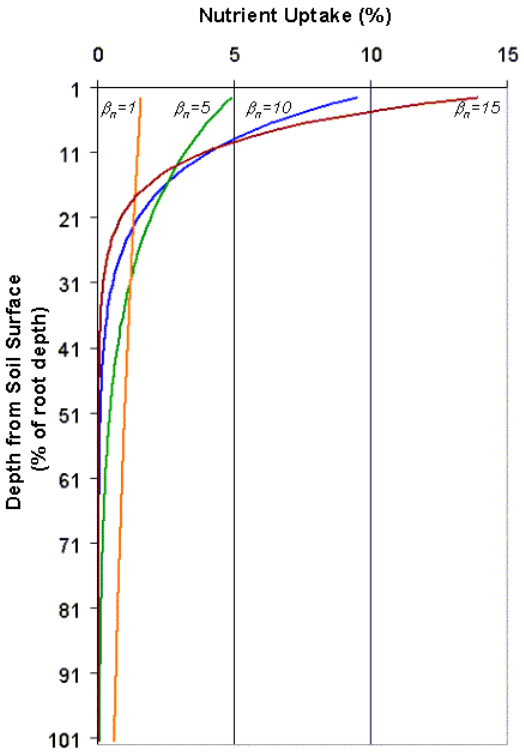

Figure 18-4: Depth distribution of nitrogen uptake

Nitrogen removed from the soil by plants is taken from the nitrate pool. The importance of the nitrogen uptake distribution parameter lies in its control over the maximum amount of nitrate removed from the upper layers. Because the top 10 mm of the soil profile interacts with surface runoff, the nitrogen uptake distribution parameter will influence the amount of nitrate available for transport in surface runoff. The model allows lower layers in the root zone to fully compensate for lack of nitrate in the upper layers, so there should not be significant changes in nitrogen stress with variation in the value used for β_n.

The actual amount if nitrogen removed from a soil layer is calculated:

$$N_{actualup,ly} = \min\left[N_{up,ly} + N_{demand}, \quad NO3_{ly}\right] \qquad 18.3.8$$

where $N_{actualup,ly}$ is the actual nitrogen uptake for layer ly (kg N/ha), $N_{up,ly}$ is the potential nitrogen uptake for layer ly (kg N/ha), N_{demand} is the nitrogen uptake demand not met by overlying soil layers (kg N/ha), and $NO3_{ly}$ is the nitrate content of soil layer ly (kg NO_3-N/ha).

18.3.1.1 NITROGEN FIXATION

If nitrate levels in the root zone are insufficient to meet the demand of a legume, SWAT allows the plant to obtain additional nitrogen through nitrogen fixation. Nitrogen fixation is calculated as a function of soil water, soil nitrate content and growth stage of the plant.

$$N_{fix} = N_{demand} \cdot f_{gr} \cdot \min\left(f_{sw}, \quad f_{no3}, \quad 1\right) \qquad 18.3.9$$

where N_{fix} is the amount of nitrogen added to the plant biomass by fixation (kg N/ha), N_{demand} is the plant nitrogen demand not met by uptake from the soil (kg N/ha), f_{gr} is the growth stage factor (0.0-1.0), f_{sw} is the soil water factor (0.0-1.0), and f_{no3} is the soil nitrate factor (0.0-1.0). The maximum amount of nitrogen that can be fixed by the plant on a given day is N_{demand}.

Growth stage exerts the greatest impact on the ability of the plant to fix nitrogen. The growth stage factor is calculated:

$$f_{gr} = 0 \qquad \text{when } fr_{PHU} \leq 0.15 \qquad 18.3.10$$

$$f_{gr} = 6.67 \cdot fr_{PHU} - 1 \qquad \text{when } 0.15 < fr_{PHU} \leq 0.30 \qquad 18.3.11$$

$$f_{gr} = 1 \qquad \text{when } 0.30 < fr_{PHU} \leq 0.55 \qquad 18.3.12$$

$$f_{gr} = 3.75 - 5 \cdot fr_{PHU} \qquad \text{when } 0.55 < fr_{PHU} \leq 0.75 \qquad 18.3.13$$

$$f_{gr} = 0 \qquad \text{when } fr_{PHU} > 0.75 \qquad 18.3.14$$

where f_{gr} is the growth stage factor and fr_{PHU} is the fraction of potential heat units accumulated for the plant on a given day in the growing season. The growth stage factor is designed to reflect the buildup and decline of nitrogen fixing bacteria in the plant roots during the growing season.

The soil nitrate factor inhibits nitrogen fixation as the presence of nitrate in the soil goes up. The soil nitrate factor is calculated:

$$f_{no3} = 1 \qquad \text{when } NO3 \leq 100 \qquad 18.3.15$$

$$f_{no3} = 1.5 - 0.0005 \cdot NO3 \qquad \text{when } 100 < NO3 \leq 300 \qquad 18.3.16$$

$$f_{no3} = 0 \qquad \text{when } NO3 > 300 \qquad 18.3.17$$

where f_{no3} is the soil nitrate factor and $NO3$ is the nitrate content of the soil profile (kg NO_3-N/ha).

The soil water factor inhibits nitrogen fixation as the soil dries out. The soil water factor is calculated:

$$f_{sw} = \frac{SW}{.85 \cdot FC} \qquad 18.3.18$$

where f_{sw} is the soil water factor, SW is the amount of water in soil profile (mm H_2O), and FC is the water content of soil profile at field capacity (mm H_2O).

18.3.2 PHOSPHORUS UPTAKE

Plant phosphorus uptake is controlled by the plant phosphorus equation. The plant phosphorus equation calculates the fraction of phosphorus in the plant biomass as a function of growth stage given optimal growing conditions.

$$fr_P = \left(fr_{P,1} - fr_{P,3}\right) \cdot \left[1 - \frac{fr_{PHU}}{fr_{PHU} + \exp\left(p_1 - p_2 \cdot fr_{PHU}\right)}\right] + fr_{P,3} \qquad 18.3.19$$

where fr_P is the fraction of phosphorus in the plant biomass on a given day, $fr_{P,1}$ is the normal fraction of phosphorus in the plant biomass at emergence, $fr_{P,3}$ is the normal fraction of phosphorus in the plant biomass at maturity, fr_{PHU} is the fraction of potential heat units accumulated for the plant on a given day in the growing season, and p_1 and p_2 are shape coefficients.

The shape coefficients are calculated by solving equation 18.3.19 using two known points ($fr_{P,2}$, $fr_{PHU,50\%}$) and ($fr_{P,3}$, $fr_{PHU,100\%}$):

$$p_1 = \ln\left[\frac{fr_{PHU,50\%}}{\left(1-\frac{(fr_{P,2}-fr_{P,3})}{(fr_{P,1}-fr_{P,3})}\right)} - fr_{PHU,50\%}\right] + p_2 \cdot fr_{PHU,50\%} \qquad 18.3.20$$

$$p_2 = \frac{\left(\ln\left[\frac{fr_{PHU,50\%}}{\left(1-\frac{(fr_{P,2}-fr_{P,3})}{(fr_{P,1}-fr_{P,3})}\right)} - fr_{PHU,50\%}\right] - \ln\left[\frac{fr_{PHU,100\%}}{\left(1-\frac{(fr_{P,\sim3}-fr_{P,3})}{(fr_{P,1}-fr_{P,3})}\right)} - fr_{PHU,100\%}\right]\right)}{fr_{PHU,100\%} - fr_{PHU,50\%}} \qquad 18.3.21$$

where p_1 is the first shape coefficient, p_2 is the second shape coefficient, $fr_{P,1}$ is the normal fraction of phosphorus in the plant biomass at emergence, $fr_{P,2}$ is the normal fraction of phosphorus in the plant biomass at 50% maturity, $fr_{P,3}$ is the normal fraction of phosphorus in the plant biomass at maturity, $fr_{P,\sim3}$ is the normal fraction of phosphorus in the plant biomass near maturity, $fr_{PHU,50\%}$ is the fraction of potential heat units accumulated for the plant at 50% maturity ($fr_{PHU,50\%}$=0.5), and $fr_{PHU,100\%}$ is the fraction of potential heat units accumulated for the plant at maturity ($fr_{PHU,100\%}$=1.0). The normal fraction of phosphorus in the plant biomass near maturity ($fr_{N,\sim3}$) is used in equation 18.3.21 to ensure that the denominator term $\left(1-\frac{(fr_{P,\sim3}-fr_{P,3})}{(fr_{P,1}-fr_{P,3})}\right)$ does not equal 1. The model assumes $(fr_{P,\sim3}-fr_{P,3}) = 0.00001$.

To determine the mass of phosphorus that should be stored in the plant biomass for the growth stage, the phosphorus fraction is multiplied by the total plant biomass:

$$bio_{P,opt} = fr_P \cdot bio \qquad 18.3.22$$

where $bio_{P,opt}$ is the optimal mass of phosphorus stored in plant material for the current growth stage (kg P/ha), fr_P is the optimal fraction of phophorus in the plant biomass for the current growth stage, and *bio* is the total plant biomass on a given day (kg ha^{-1}).

The plant phosphorus demand for a given day is a function of the difference between the phosphorus content of the plant biomass expected for the plant's growth stage and the actual phosphorus content:

$$P_{up} = 1.5 \cdot \left(bio_{P,opt} - bio_P \right) \qquad 18.3.23$$

where P_{up} is the potential phosphorus uptake (kg P/ha), $bio_{P,opt}$ is the optimal mass of phosphorus stored in plant material for the current growth stage (kg P/ha), and bio_P is the actual mass of phosphorus stored in plant material (kg P/ha). The difference between the phosphorus content of the plant biomass expected for the plant's growth stage and the actual phosphorus content is multiplied by 1.5 to simulate luxury phosphorus uptake.

The depth distribution of phosphorus uptake is calculated with the function:

$$P_{up,z} = \frac{P_{up}}{\left[1 - \exp\left(-\beta_p\right)\right]} \cdot \left[1 - \exp\left(-\beta_p \cdot \frac{z}{z_{root}}\right)\right] \qquad 18.3.24$$

where $P_{up,z}$ is the potential phosphorus uptake from the soil surface to depth z (kg P/ha), P_{up} is the potential phosphorus uptake (kg P/ha), β_P is the phosphorus uptake distribution parameter, z is the depth from the soil surface (mm), and z_{root} is the depth of root development in the soil (mm). The potential phosphorus uptake for a soil layer is calculated by solving equation 18.3.24 for the depth at the upper and lower boundaries of the soil layer and taking the difference.

$$P_{up,ly} = P_{up,zl} - P_{up,zu} \qquad 18.3.25$$

where $P_{up,ly}$ is the potential phosphorus uptake for layer ly (kg P/ha), $P_{up,zl}$ is the potential phosphorus uptake from the soil surface to the lower boundary of the soil layer (kg P/ha), and $P_{up,zu}$ is the potential phosphorus uptake from the soil surface to the upper boundary of the soil layer (kg P/ha).

Root density is greatest near the surface, and phosphorus uptake in the upper portion of the soil will be greater than in the lower portion. The depth distribution of phosphorus uptake is controlled by β_p, the phosphorus uptake distribution parameter, a variable users are allowed to adjust. The illustration of nitrogen uptake as a function of depth for four different uptake distribution parameter values in Figure 18-4 is valid for phosphorus uptake as well.

Phosphorus removed from the soil by plants is taken from the solution phosphorus pool. The importance of the phosphorus uptake distribution parameter lies in its control over the maximum amount of solution P removed from the upper layers. Because the top 10 mm of the soil profile interacts with surface runoff, the phosphorus uptake distribution parameter will influence the amount of labile phosphorus available for transport in surface runoff. The model allows lower layers in the root zone to fully compensate for lack of solution P in the upper layers, so there should not be significant changes in phosphorus stress with variation in the value used for β_p.

The actual amount if phosphorus removed from a soil layer is calculated:

$$P_{actualup,ly} = \min\left[P_{up,ly} + P_{demand}, \quad P_{solution,ly}\right] \qquad 18.3.26$$

where $P_{actualup,ly}$ is the actual phosphorus uptake for layer *ly* (kg P/ha), $P_{up,ly}$ is the potential phosphorus uptake for layer *ly* (kg P/ha), P_{demand} is the phosphorus uptake demand not met by overlying soil layers (kg P/ha), and $P_{solution,ly}$ is the phosphorus content of the soil solution in layer *ly* (kg P/ha).

Table 18-3: SWAT input variables that pertain to plant nutrient uptake.

Variable Name	Definition	Input File
BN(1)	$fr_{N,1}$: Normal fraction of N in the plant biomass at emergence	crop.dat
BN(2)	$fr_{N,2}$: Normal fraction of N in the plant biomass at 50% maturity	crop.dat
BN(3)	$fr_{N,3}$: Normal fraction of N in the plant biomass at maturity	crop.dat
UBN	β_n: Nitrogen uptake distribution parameter	.bsn
BP(1)	$fr_{P,1}$: Normal fraction of P in the plant biomass at emergence	crop.dat
BP(2)	$fr_{P,2}$: Normal fraction of P in the plant biomass at 50% maturity	crop.dat
BP(3)	$fr_{P,3}$: Normal fraction of P in the plant biomass at maturity	crop.dat
UBP	β_p: Phosphorus uptake distribution parameter	.bsn

18.4 CROP YIELD

When a harvest or harvest/kill operation is performed, a portion of the plant biomass is removed from the HRU as yield. The nutrients and plant material contained in the yield are assumed to be lost from the system (i.e. the watershed) and will not be added to residue and organic nutrient pools in the soil with the remainder of the plant material. In contrast, a kill operation converts all biomass to residue.

The fraction of the above-ground plant dry biomass removed as dry economic yield is called the harvest index. For the majority of crops, the harvest index will be between 0.0 and 1.0. However, plants whose roots are harvested, such as sweet potatoes, may have a harvest index greater than 1.0.

The economic yield of most commercial crops is the reproductive portion of the plant. Decades of crop breeding have lead to cultivars and hybrids having maximized harvest indices. Often, the harvest index is relatively stable across a range of environmental conditions.

SWAT calculates harvest index each day of the plant’s growing season using the relationship:

$$HI = HI_{opt} \cdot \frac{100 \cdot fr_{PHU}}{\left(100 \cdot fr_{PHU} + \exp\left[11.1 - 10 \cdot fr_{PHU}\right]\right)} \qquad 18.4.1$$

where HI is the potential harvest index for a given day, HI_{opt} is the potential harvest index for the plant at maturity given ideal growing conditions, and fr_{PHU} is the fraction of potential heat units accumulated for the plant on a given day in the growing season. The variation of the optimal harvest index during the growing season is illustrated in Figure 18-5.

The crop yield is calculated as:

$$yld = bio_{ag} \cdot HI \qquad \text{when } HI \leq 1.00 \qquad 18.4.2$$

$$yld = bio \cdot \left(1 - \frac{1}{\left(1 + HI\right)}\right) \qquad \text{when } HI > 1.00 \qquad 18.4.3$$

where yld is the crop yield (kg/ha), bio_{ag} is the aboveground biomass on the day of harvest (kg ha^{-1}), HI is the harvest index on the day of harvest, and bio is the total plant biomass on the day of harvest (kg ha^{-1}). The aboveground biomass is calculated:

$$bio_{ag} = \left(1 - fr_{root}\right) \cdot bio \qquad 18.4.4$$

where fr_{root} is the fraction of total biomass in the roots the day of harvest, and bio is the total plant biomass on the day of harvest (kg ha^{-1}).

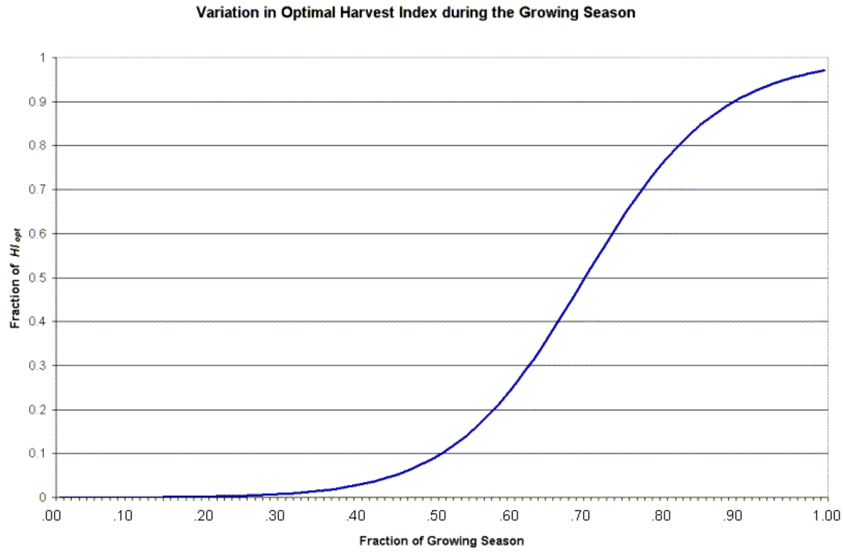

Figure 18-5: Variation in optimal harvest index (HI_i/HI_{opt}) with fraction of growing season (fr_{PHU})

The amount of nutrients removed in the yield are calculated:

$$yld_N = fr_{N,yld} \cdot yld \qquad 18.4.5$$

$$yld_P = fr_{P,yld} \cdot yld \qquad 18.4.6$$

where yld_N is the amount of nitrogen removed in the yield (kg N/ha), yld_P is the amount of phosphorus removed in the yield (kg P/ha), $fr_{N,yld}$ is the fraction of nitrogen in the yield, $fr_{P,yld}$ is the fraction of phosphorus in the yield, and yld is the crop yield (kg/ha).

If the harvest index override is used in the harvest only operation, the model assumes that a significant portion of the plant biomass is being removed in addition to the seed. Therefore, instead of using the nitrogen and phosphorus yield fractions from the plant growth database, the model uses the total biomass nitrogen and phosphorus fractions to determine the amount of nitrogen and phosphorus removed:

$$yld_N = fr_N \cdot yld \qquad 18.4.7$$

$$yld_P = fr_P \cdot yld \qquad 18.4.8$$

where yld_N is the amount of nitrogen removed in the yield (kg N/ha), yld_P is the amount of phosphorus removed in the yield (kg P/ha), fr_N is the fraction of nitrogen in the plant biomass calculated with equation 18.3.1, fr_P is the fraction of phosphorus in the plant biomass calculated with equation 18.3.19, and yld is the crop yield (kg/ha).

Table 18-4: SWAT input variables that pertain to crop yield.

Variable Name	Definition	Input File
HVSTI	HI_{opt}: Potential harvest index for the plant at maturity given ideal growing conditions	crop.dat
CNYLD	$fr_{N,yld}$: Fraction of nitrogen in the yield	crop.dat
CPYLD	$fr_{P,yld}$: Fraction of phosphorus in the yield	crop.dat

18.5 NOMENCLATURE

AWC_{ly}	Available water capacity for layer *ly* (mm H_2O)
CO_2	Concentration of carbon dioxide in the atmosphere (ppmv)
CO_{2amb}	Ambient atmospheric CO_2 concentration (330 ppmv)
CO_{2hi}	Elevated atmospheric CO_2 concentration (ppmv)
E_t	Maximum transpiration rate (mm d^{-1})
$E_{t,act}$	Actual amount of transpiration on a given day (mm H_2O)
FC	Water content of soil profile at field capacity (mm H_2O)
FC_{ly}	Water content of layer *ly* at field capacity (mm H_2O)
H_{day}	Solar radiation reaching ground on current day of simulation (MJ m^{-2} d^{-1})
H_{phosyn}	Intercepted photosynthetically active radiation on a given day (MJ m^{-2})
HI	Potential harvest index for a given day
HI_{opt}	Potential harvest index for the plant at maturity given ideal growing conditions
HU	Number of heat units accumulated on a given day (heat units)
LAI	Leaf area index of the canopy
LAI_{mx}	Maximum leaf area index for the plant
$N_{actualup,ly}$	Actual nitrogen uptake for layer *ly* (kg N/ha)
N_{demand}	Nitrogen uptake demand not met by overlying soil layers (kg N/ha)
N_{fix}	Amount of nitrogen added to the plant biomass by fixation (kg N/ha)
N_{up}	Potential nitrogen uptake (kg N/ha)
$N_{up,ly}$	Potential nitrogen uptake for layer *ly* (kg N/ha)
$N_{up,z}$	Potential nitrogen uptake from the soil surface to depth *z* (kg N/ha)
$N_{up,zl}$	Potential nitrogen uptake from the soil surface to the lower boundary of the soil layer (kg N/ha)

$N_{up,zu}$	Potential nitrogen uptake from the soil surface to the upper boundary of the soil layer (kg N/ha)
$NO3$	Nitrate content of the soil profile (kg NO_3-N/ha)
$NO3_{ly}$	Nitrate content of soil layer *ly* (kg NO_3-N/ha)
$P_{actualup,ly}$	Actual phosphorus uptake for layer *ly* (kg P/ha)
P_{demand}	Phosphorus uptake demand not met by overlying soil layers (kg P/ha)
P_{up}	Potential phosphorus uptake (kg P/ha)
$P_{up,ly}$	Potential phosphorus uptake for layer *ly* (kg P/ha)
$P_{up,z}$	Potential phosphorus uptake from the soil surface to depth *z* (kg P/ha)
$P_{up,zl}$	Potential phosphorus uptake from the soil surface to the lower boundary of the soil layer (kg P/ha)
$P_{up,zu}$	Potential phosphorus uptake from the soil surface to the upper boundary of the soil layer (kg P/ha)
PHU	Potential heat units or total heat units required for plant maturity (heat units)
$P_{solution,ly}$	Phosphorus content of soil solution in layer *ly* (kg P/ha)
RUE	Radiation-use efficiency of the plant (kg/ha·(MJ/m^{2})$^{-1}$ or 10^{-1} g/MJ)
RUE_{amb}	Radiation-use efficiency of the plant at ambient atmospheric CO_2 concentration (kg/ha·(MJ/m^{2})$^{-1}$ or 10^{-1} g/MJ)
RUE_{hi}	Radiation-use efficiency of the plant at the elevated atmospheric CO_2 concentration, CO_{2hi}, (kg/ha·(MJ/m^{2})$^{-1}$ or 10^{-1} g/MJ)
$RUE_{vpd=1}$	Radiation-use efficiency for the plant at a vapor pressure deficit of 1 kPa (kg/ha·(MJ/m^{2})$^{-1}$ or 10^{-1} g/MJ)
SW	Amount of water in soil profile (mm H_2O)
SW_{ly}	Soil water content of layer *ly* (mm H_2O)
WP_{ly}	Water content of layer *ly* at wilting point (mm H_2O).

bio	Total plant biomass on a given day (kg/ha)
bio_{ag}	Aboveground biomass on the day of harvest (kg ha^{-1})
bio_N	Actual mass of nitrogen stored in plant material (kg N/ha)
$bio_{N,opt}$	Optimal mass of nitrogen stored in plant material for the growth stage (kg N/ha)
bio_P	Actual mass of phosphorus stored in plant material (kg P/ha)
$bio_{P,opt}$	Optimal mass of phosphorus stored in plant material for the current growth stage (kg P/ha)
$epco$	Plant uptake compensation factor
f_{gr}	Growth stage factor in nitrogen fixation equation
f_{no3}	Soil nitrate factor in nitrogen fixation equation
f_{sw}	Soil water factor in nitrogen fixation equation
$fr_{LAI,1}$	Fraction of the maximum plant leaf area index corresponding to the 1st point on the optimal leaf area development curve
$fr_{LAI,2}$	Fraction of the maximum plant leaf area index corresponding to the 2nd point on the optimal leaf area development curve
fr_{LAImx}	Fraction of the plant's maximum leaf area index corresponding to a given fraction of potential heat units for the plant
fr_N	Optimal fraction of nitrogen in the plant biomass for current growth stage
$fr_{N,1}$	Normal fraction of nitrogen in the plant biomass at emergence
$fr_{N,2}$	Normal fraction of nitrogen in the plant biomass at 50% maturity

$fr_{N,3}$	Normal fraction of nitrogen in the plant biomass at maturity
$fr_{N,\sim3}$	Normal fraction of nitrogen in the plant biomass near maturity
$fr_{N,yld}$	Fraction of nitrogen in the yield
fr_P	Fraction of phosphorus in the plant biomass
$fr_{P,1}$	Normal fraction of phosphorus in the plant biomass at emergence
$fr_{P,2}$	Normal fraction of phosphorus in the plant biomass at 50% maturity
$fr_{P,3}$	Normal fraction of phosphorus in the plant biomass at maturity
$fr_{P,\sim3}$	Normal fraction of phosphorus in the plant biomass near maturity
$fr_{P,yld}$	Fraction of phosphorus in the yield
fr_{PHU}	Fraction of potential heat units accumulated for the plant on a given day in the growing season
$fr_{PHU,1}$	Fraction of the growing season corresponding to the 1st point on the optimal leaf area development curve
$fr_{PHU,2}$	Fraction of the growing season corresponding to the 2nd point on the optimal leaf area development curve
$fr_{PHU,50\%}$	Fraction of potential heat units accumulated for the plant at 50% maturity ($fr_{PHU,50\%}=0.5$)
$fr_{PHU,100\%}$	Fraction of potential heat units accumulated for the plant at maturity ($fr_{PHU,100\%}=1.0$)
$fr_{PHU,sen}$	Fraction of growing season at which senescence becomes the dominant growth process
fr_{root}	Fraction of total biomass in the roots on a given day in the growing season
h_c	Canopy height (cm)
$h_{c,mx}$	Plant's maximum canopy height (m)
k_ℓ	Light extinction coefficient
n_1	First shape coefficient in plant nitrogen equation
n_2	Second shape coefficient in plant nitrogen equation
p_1	First shape coefficient in plant phosphorus equation
p_2	Second shape coefficient in plant phosphorus equation
r_1	First shape coefficient for radiation-use efficiency curve
r_2	Second shape coefficient for radiation-use efficiency curve
vpd	Vapor pressure deficit (kPa)
vpd_{thr}	Threshold vapor pressure deficit above which a plant will exhibit reduced radiation-use efficiency (kPa)
$w_{actualup}$	Total plant water uptake for the day (mm H_2O)
$w_{actualup,ly}$	Actual water uptake for layer ly (mm H_2O)
w_{demand}	Water uptake demand not met by overlying soil layers (mm H_2O)
$w_{up,ly}$	Potential water uptake for layer ly (mm H_2O)
$w'_{up,ly}$	Adjusted potential water uptake for layer ly (mm H_2O)
$w''_{up,ly}$	Potential water uptake when the soil water content is less than 25% of plant available water (mm H_2O)
$w_{up,z}$	Potential water uptake from the soil surface to a specified depth, z, on a given day (mm H_2O)
$w_{up,zl}$	is the potential water uptake for the profile to the lower boundary of the soil layer (mm H_2O)

$w_{up,zu}$	is the potential water uptake for the profile to the upper boundary of the soil layer (mm H_2O)
yld	Crop yield (kg/ha)
yld_N	Amount of nitrogen removed in the yield (kg N/ha)
yld_P	Amount of phosphorus removed in the yield (kg P/ha)
z	Depth below soil surface (mm)
z_{root}	Depth of root development in the soil (mm)
$z_{root,mx}$	Maximum depth for root development in the soil (mm)
β_n	Nitrogen uptake distribution parameter
β_p	Phosphorus uptake distribution parameter
β_w	Water-use distribution parameter
ΔLAI_i	Leaf area added on day i
Δbio	Potential increase in total plant biomass on a given day (kg/ha)
Δrue_{dcl}	Rate of decline in radiation-use efficiency per unit increase in vapor pressure deficit $(\text{kg/ha}\cdot(\text{MJ/m}^2)^{-1}\cdot\text{kPa}^{-1}$ or $(10^{-1}\ \text{g/MJ})\cdot\text{kPa}^{-1})$
ℓ_1	First shape coefficient for optimal leaf area development curve
ℓ_2	Second shape coefficient for optimal leaf area development curve

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CHAPTER 19

EQUATIONS: ACTUAL GROWTH

Actual growth varies from potential growth due to extreme temperatures, water deficiencies and nutrient deficiencies. This chapter reviews growth constraints as well as overrides that the user may implement to ignore growth constraints.

19.1 GROWTH CONSTRAINTS

Plant growth may be reduced due to extreme temperatures, and insufficient water, nitrogen or phosphorus. The amount of stress for each of these four parameters is calculated on a daily basis using the equations summarized in the following sections.

19.1.1 WATER STRESS

Water stress is simulated by comparing actual and potential plant transpiration:

$$wstrs = 1 - \frac{E_{t,act}}{E_t} = 1 - \frac{w_{actualup}}{E_t} \qquad 19.1.1$$

where *wstrs* is the water stress for a given day, E_t is the maximum plant transpiration on a given day (mm H_2O), $E_{t,act}$ is the actual amount of transpiration on a given day (mm H_2O) and $w_{actualup}$ is the total plant water uptake for the day (mm H_2O). The calculation of maximum transpiration is reviewed in Chapter 7 and the determination of actual plant water uptake/transpiration is reviewed in Chapter 18.

19.1.2 TEMPERATURE STRESS

Temperature stress is a function of the daily average air temperature and the optimal temperature for plant growth. Near the optimal temperature the plant will not experience temperature stress. However as the air temperature diverges from the optimal the plant will begin to experience stress. The equations used to determine temperature stress are:

$$tstrs = 1 \qquad \text{when } \bar{T}_{av} \leq T_{base} \qquad 19.1.2$$

$$tstrs = 1 - \exp\left[\frac{-0.1054 \cdot \left(T_{opt} - \bar{T}_{av}\right)^2}{\left(\bar{T}_{av} - T_{base}\right)^2}\right] \qquad \text{when } T_{base} < \bar{T}_{av} \leq T_{opt} \qquad 19.1.3$$

$$tstrs = 1 - \exp\left[\frac{-0.1054 \cdot \left(T_{opt} - \bar{T}_{av}\right)^2}{\left(2 \cdot T_{opt} - \bar{T}_{av} - T_{base}\right)^2}\right] \qquad \text{when } T_{opt} < \bar{T}_{av} \leq 2 \cdot T_{opt} - T_{base} \qquad 19.1.4$$

$$tstrs = 1 \qquad \text{when } \bar{T}_{av} > 2 \cdot T_{opt} - T_{base} \qquad 19.1.5$$

where *tstrs* is the temperature stress for a given day expressed as a fraction of optimal plant growth, $\overline{T}_{av}$ is the mean air temperature for day (°C), T_{base} is the plant's base or minimum temperature for growth (°C), and T_{opt} is the plant's optimal temperature for growth (°C). Figure 19-1 illustrates the impact of mean daily air temperature on plant growth for a plant with a base temperature of 0°C and an optimal temperature of 15°C.

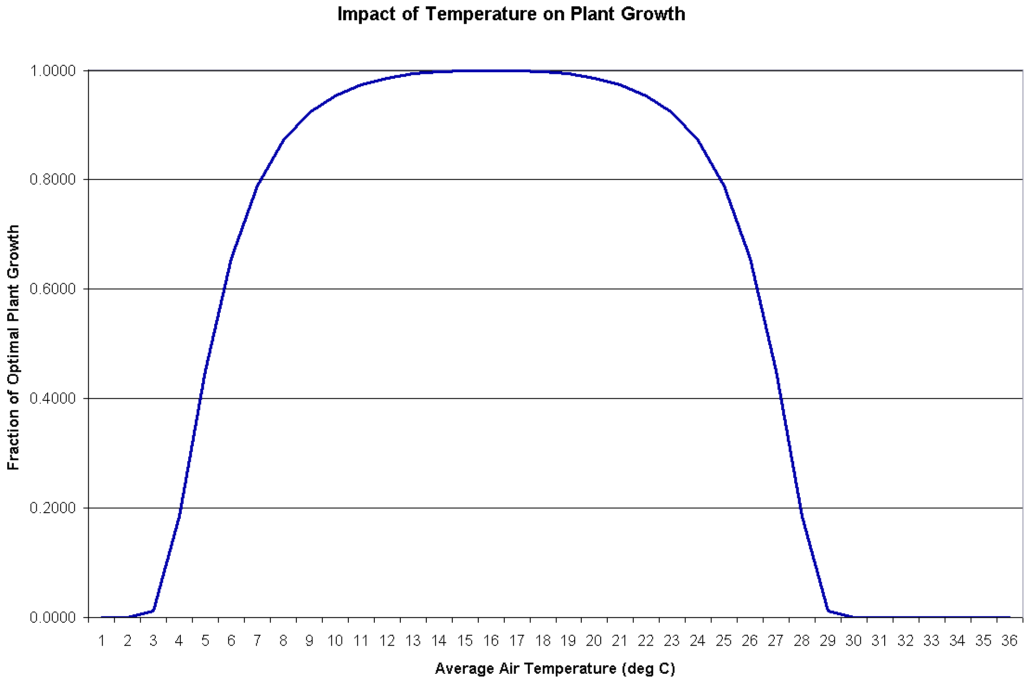

Figure 19-1: Impact of mean air temperature on plant growth for a plant with T_{base}= 0°C and T_{opt}=15°C

19.1.3 NITROGEN STRESS

Nitrogen stress is calculated only for non-legumes. SWAT never allows legumes to experience nitrogen stress.

Nitrogen stress is quantified by comparing actual and optimal plant nitrogen levels. Nitrogen stress varies non-linearly between 0.0 at optimal nitrogen content and 1.0 when the nitrogen content of the plant is 50% or less of the optimal value. Nitrogen stress is computed with the equation:

$$nstrs = 1 - \frac{\varphi_n}{\varphi_n + \exp[3.535 - 0.02597 \cdot \varphi_n]} \qquad 19.1.6$$

where *nstrs* is the nitrogen stress for a given day, and φ_n is a scaling factor for nitrogen stress. The scaling factor is calculated:

$$\varphi_n = 200 \cdot \left(\frac{bio_N}{bio_{N,opt}} - 0.5 \right) \qquad 19.1.7$$

where $bio_{N,opt}$ is the optimal mass of nitrogen stored in plant material for the current growth stage (kg N/ha) and bio_N is the actual mass of nitrogen stored in plant material (kg N/ha).

19.1.4 PHOSPHORUS STRESS

As with nitrogen, phosphorus stress is quantified by comparing actual and optimal plant phosphorus levels. Phosphorus stress varies non-linearly between 0.0 at optimal phosphorus content and 1.0 when the phosphorus content of the plant is 50% or less of the optimal value. Phosphorus stress is computed with the equation:

$$pstrs = 1 - \frac{\varphi_p}{\varphi_p + \exp\left[3.535 - 0.02597 \cdot \varphi_p\right]} \qquad 19.1.8$$

where *pstrs* is the phosphorus stress for a given day, and φ_p is a scaling factor for phosphorus stress. The scaling factor is calculated:

$$\varphi_p = 200 \cdot \left(\frac{bio_P}{bio_{P,opt}} - 0.5 \right) \qquad 19.1.9$$

where $bio_{P,opt}$ is the optimal mass of phosphorus stored in plant material for the current growth stage (kg N/ha) and bio_P is the actual mass of phosphorus stored in plant material (kg N/ha).

Table 19-1: SWAT input variables that pertain to stress on plant growth.

Variable Name	Definition	Input File
T_BASE	T_{base}: Base temperature for plant growth (°C)	crop.dat
T_OPT	T_{opt}: Optimal temperature for plant growth (°C)	crop.dat

19.2 ACTUAL GROWTH

The plant growth factor quantifies the fraction of potential growth achieved on a given day and is calculated:

$$\gamma_{reg} = 1 - \max(wstrs, \quad tstrs, \quad nstrs, \quad pstrs) \qquad 19.2.3$$

where γ_{reg} is the plant growth factor (0.0-1.0), $wstrs$ is the water stress for a given day, $tstrs$ is the temperature stress for a given day expressed as a fraction of optimal plant growth, $nstrs$ is the nitrogen stress for a given day, and $pstrs$ is the phosphorus stress for a given day.

The potential biomass predicted with equation 18.1.2 is adjusted daily if one of the four plant stress factors is greater than 0.0 using the equation:

$$\Delta bio_{act} = \Delta bio \cdot \gamma_{reg} \qquad 19.2.1$$

where Δbio_{act} is the actual increase in total plant biomass on a given day (kg/ha), Δbio is the potential increase in total plant biomass on a given day (kg/ha), and γ_{reg} is the plant growth factor (0.0-1.0).

The potential leaf area added on a given day is also adjusted daily for plant stress:

$$\Delta LAI_{act,i} = \Delta LAI_i \cdot \sqrt{\gamma_{reg}} \qquad 19.2.2$$

where $\Delta LAI_{act,i}$ is the actual leaf area added on day i, ΔLAI_i is the potential leaf area added on day i that is calculated with equation 18.1.14, and γ_{reg} is the plant growth factor (0.0-1.0).

19.2.1 BIOMASS OVERRIDE

The model allows the user to specify a total biomass that the plant will produce each year. When the biomass override is set in the plant operation (.mgt), the impact of variation in growing conditions from year to year is ignored, i.e. γ_{reg} is always set to 1.00 when biomass override is activated in an HRU.

When a value is defined for the biomass override, the change in biomass is calculated:

$$\Delta bio_{act} = \Delta bio_i \cdot \frac{(bio_{trg} - bio_{i-1})}{bio_{trg}} \qquad 19.2.4$$

where Δbio_{act} is the actual increase in total plant biomass on day i (kg/ha), Δbio_i is the potential increase in total plant biomass on day i calculated with equation 18.1.2 (kg/ha), bio_{trg} is the target biomass specified by the user (kg/ha), and bio_{i-1} is the total plant biomass accumulated on day i-1 (kg/ha).

Table 19-2: SWAT input variables that pertain to actual plant growth.

Variable Name	Definition	Input File
BIO_TARG	bio_{trg}/1000: Biomass target (metric tons/ha)	.mgt

19.3 ACTUAL YIELD

The harvest index predicted with equation 18.4.1 is affected by water deficit using the relationship:

$$HI_{act} = \left(HI - HI_{min}\right) \cdot \frac{\gamma_{wu}}{\gamma_{wu} + \exp\left[6.13 - 0.883 \cdot \gamma_{wu}\right]} + HI_{min} \qquad 19.3.1$$

where HI_{act} is the actual harvest index, HI is the potential harvest index on the day of harvest calculated with equation 18.4.1, HI_{min} is the harvest index for the plant in drought conditions and represents the minimum harvest index allowed for the plant, and γ_{wu} is the water deficiency factor. The water deficiency factor is calculated:

$$\gamma_{wu} = 100 \cdot \frac{\sum_{i=1}^{m} E_a}{\sum_{i=1}^{m} E_o} \qquad 19.3.2$$

where E_a is the actual evapotranspiration on a given day, E_o is the potential evapotranspiration on a given day, i is a day in the plant growing season, and m is the day of harvest if the plant is harvested before it reaches maturity or the last day of the growing season if the plant is harvested after it reaches maturity.

19.3.1 HARVEST INDEX OVERRIDE

In the plant and harvest only operations (.mgt), the model allows the user to specify a target harvest index. The target harvest index set in a plant operation is used when the yield is removed using a harvest/kill operation. The target harvest index set in a harvest only operation is used only when that particular harvest only operation is executed.

When a harvest index override is defined, the override value is used in place of the harvest index calculated by the model in the yield calculations. Adjustments for growth stage and water deficiency are not made.

$$HI_{act} = HI_{trg} \qquad 19.3.3$$

where HI_{act} is the actual harvest index and HI_{trg} is the target harvest index.

19.3.2 HARVEST EFFICIENCY

In the harvest only operation (.mgt), the model allows the user to specify a harvest efficiency. The harvest efficiency defines the fraction of yield biomass removed by the harvesting equipment. The remainder of the yield biomass is converted to residue and added to the residue pool in the top 10 mm of soil. If the harvest efficiency is not set or a 0.00 is entered, the model assumes the user wants to ignore harvest efficiency and sets the fraction to 1.00 so that the entire yield is removed from the HRU.

$$yld_{act} = yld \cdot harv_{eff} \qquad 19.3.4$$

where yld_{act} is the actual yield (kg ha^{-1}), yld is the crop yield calculated with equation 18.4.2 or 18.4.3 (kg ha^{-1}), and $harv_{eff}$ is the efficiency of the harvest operation (0.01-1.00). The remainder of the yield biomass is converted to residue:

$$\Delta rsd = yld \cdot \left(1 - harv_{eff}\right) \qquad 19.3.5$$

$$rsd_{surf,i} = rsd_{surf,i-1} + \Delta rsd \qquad 19.3.6$$

where Δrsd is the biomass added to the residue pool on a given day (kg ha^{-1}), yld is the crop yield calculated with equation 18.4.2 or 18.4.3 (kg ha^{-1}) and $harv_{eff}$ is the efficiency of the harvest operation (0.01-1.00) $rsd_{surf,i}$ is the material in the residue pool for the top 10 mm of soil on day i (kg ha^{-1}), and $rsd_{\mathrm{surf},i\text{-}1}$ is the material in the residue pool for the top 10 mm of soil on day i-1 (kg ha^{-1}).

Table 19-3: SWAT input variables that pertain to actual plant yield.

Variable Name	**Definition**	**Input File**
WSYF	HI_{min}: Harvest index for the plant in drought conditions, the minimum harvest index allowed for the plant	crop.dat
HITAR	HI_{trg}: Harvest index target	.mgt
HIOVR	HI_{trg}: Harvest index target	.mgt
HARVEFF	$harv_{eff}$: Efficiency of the harvest operation	.mgt

19.4 NOMENCLATURE

E_a	Actual amount of evapotranspiration on a given day (mm H_2O)
E_o	Potential evapotranspiration (mm d^{-1})
E_t	Maximum transpiration rate (mm d^{-1})
$E_{t,act}$	Actual amount of transpiration on a given day (mm H_2O)
HI	Potential harvest index for a given day
HI_{act}	Actual harvest index
HI_{min}	Harvest index for the plant in drought conditions and represents the minimum harvest index allowed for the plant
HI_{trg}	Target harvest index
T_{base}	Plant's base or minimum temperature for growth (°C)
T_{opt}	Plant's optimal temperature for growth (°C)
$\bar{T}_{av}$	Mean air temperature for day (°C)

bio_N	Actual mass of nitrogen stored in plant material (kg N/ha)
$bio_{N,opt}$	Optimal mass of nitrogen stored in plant material for the growth stage (kg N/ha)
bio_P	Actual mass of phosphorus stored in plant material (kg P/ha)
$bio_{P,opt}$	Optimal mass of phosphorus stored in plant material for the current growth stage (kg P/ha)
bio_{trg}	Target biomass specified by the user (kg/ha)
$harv_{eff}$	Efficiency of the harvest operation
$nstrs$	Nitrogen stress for a given day
$pstrs$	Phosphorus stress for a given day
$rsd_{surf,i}$	Material in the residue pool for the top 10mm of soil on day i (kg ha^{-1})
$tstrs$	Temperature stress for a given day expressed as a fraction of optimal plant growth
$w_{actualup}$	Total plant water uptake for the day (mm H_2O)
$wstrs$	Water stress for a given day
yld_{act}	Actual yield (kg ha^{-1})

ΔLAI_i	Leaf area added on day i (potential)
$\Delta LAI_{act,i}$	Actual leaf area added on day i
Δbio	Potential increase in total plant biomass on a given day (kg/ha)
Δbio_{act}	Actual increase in total plant biomass on a given day (kg/ha)
Δrsd	Biomass added to the residue pool on a given day (kg ha^{-1})
γ_{reg}	Plant growth factor (0.0-1.0)

γ_{wu}	Water deficiency factor
φ_n	Scaling factor for nitrogen stress equation
φ_p	Scaling factor for phosphorus stress equation

MANAGEMENT PRACTICES

Quantifying the impact of land management and land use on water supply and quality is a primary focus of environmental modeling. SWAT allows very detailed management information to be incorporated into a simulation.

The following three chapters review the methodology used by SWAT to simulate water management, tillage and urban processes.

CHAPTER 20

EQUATIONS: GENERAL MANAGEMENT

Management operations that control the plant growth cycle, the timing of fertilizer and pesticide and the removal of plant biomass are explained in this chapter. Water management and the simulation of urban areas are summarized in subsequent chapters.

20.1 PLANTING/BEGINNING OF GROWING SEASON

The plant operation initiates plant growth. This operation can be used to designate the time of planting for agricultural crops or the initiation of plant growth in the spring for a land cover that requires several years to reach maturity (forests, orchards, etc.).

The plant operation will be performed by SWAT only when no land cover is growing in an HRU. Before planting a new land cover, the previous land cover must be removed with a kill operation or a harvest and kill operation. If two plant operations are placed in the management file and the first land cover is not killed prior to the second plant operation, the second plant operation is ignored by the model.

Information required in the plant operation includes the timing of the operation (month and day or fraction of base zero potential heat units), the total number of heat units required for the land cover to reach maturity, and the specific land cover to be simulated in the HRU. If the land cover is being transplanted, the leaf area index and biomass for the land cover at the time of transplanting must be provided. Also, for transplanted land covers, the total number of heat units for the land cover to reach maturity should be from the period the land cover is transplanted to maturity (not from seed generation). Heat units are reviewed in Chapter 17.

The user has the option of varying the curve number in the HRU throughout the year. New curve number values may be entered in a plant operation, tillage operation and harvest and kill operation. The curve number entered for these operations are for moisture condition II. SWAT adjusts the entered value daily to reflect change in water content.

For simulations where a certain amount of crop yield and biomass is required, the user can force the model to meet this amount by setting a harvest index target and a biomass target. These targets are effective only if a harvest and kill operation is used to harvest the crop.

Table 20-1: SWAT input variables that pertain to planting.

Variable Name	Definition	Input File
Variables in plant operation line:		
MONTH/DAY or HUSC	Timing of planting operation.	.mgt
MGT_OP	Operation code. MGT_OP = 1 for plant operation	.mgt
HEAT UNITS	PHU : Total heat units required for plant maturity (heat units)	.mgt
NCR	Plant/land cover code from crop.dat	.mgt
Optional inputs:		
HITAR	HI_{trg}: Target harvest index	.mgt
BIO_TARG	bio_{trg}: Target biomass specified by the user (kg/ha)	.mgt
ALAINIT	LAI: Leaf area index of the canopy for transplanted species	.mgt
BIOINIT	bio: Total plant biomass on a given day (kg/ha)	.mgt
CNOP	CN_2: Moisture condition II curve number	.mgt
Variables in second line of .mgt file		
IGRO	Land cover status code	.mgt
Inputs for plants growing at the beginning of the simulation		
NCRP	Plant/land cover code from crop.dat	.mgt
ALAI	LAI: Leaf area index of the canopy	.mgt
BIO_MS	bio_{trg}: Target biomass specified by the user (kg/ha)	.mgt
PHU	PHU : Total heat units required for plant maturity (heat units)	.mgt

20.2 HARVEST OPERATION

The harvest operation will remove plant biomass without killing the plant. This operation is most commonly used to cut hay or grass.

The only information required by the harvest operation is the date. However, a harvest index override and a harvest efficiency can be set.

When no harvest index override is specified, SWAT uses the plant harvest index from the plant growth database to set the fraction of biomass removed. The plant harvest index in the plant growth database is set to the fraction of the plant biomass partitioned into seed for agricultural crops and a typical fraction of biomass removed in a cutting for hay. If the user prefers a different fraction of biomass to be removed, the harvest index override should be set to the desired value.

A harvest efficiency may also be defined for the operation. This value specifies the fraction of harvested plant biomass removed from the HRU. The remaining fraction is converted to residue on the soil surface. If the harvest efficiency is left blank or set to zero, the model assumes this feature is not being used and removes 100% of the harvested biomass (no biomass is converted to residue).

After biomass is removed in a harvest operation, the plant's leaf area index and accumulated heat units are set back by the fraction of biomass removed. Reducing the number of accumulated heat units shifts the plant's development to an earlier period in which growth is usually occurring at a faster rate.

Table 20-2: SWAT input variables that pertain to harvest.

Variable Name	Definition	Input File
Variables in harvest operation line:		
MONTH/DAY or HUSC	Timing of harvest operation.	.mgt
MGT_OP	Operation code. MGT_OP = 7 for harvest operation	.mgt
Optional inputs:		
HIOVR	HI_{trg}: Harvest index override or target harvest index	.mgt
HARVEFF	$harv_{eff}$: Efficiency of the harvest operation	.mgt

20.3 GRAZING OPERATION

The grazing operation simulates plant biomass removal and manure deposition over a specified period of time. This operation is used to simulate pasture or range grazed by animals.

Information required in the grazing operation includes the time during the year at which grazing begins (month and day or fraction of plant potential heat units), the length of the grazing period, the amount of biomass removed daily, the amount of manure deposited daily, and the type of manure deposited. The amount of biomass trampled is an optional input.

Biomass removal in the grazing operation is similar to that in the harvest operation. However, instead of a fraction of biomass being specified, an absolute amount to be removed every day is given. In some conditions, this can result in a reduction of the plant biomass to a very low level that will result in increased erosion in the HRU. To prevent this, a minimum plant biomass for grazing may be specified (BIO_MIN in the second line of the management file). When the plant biomass falls below the amount specified for BIO_MIN, the model will not graze, trample, or apply manure in the HRU on that day.

If the user specifies an amount of biomass to be removed daily by trampling, this biomass is converted to residue.

Nutrient fractions of the manure applied during grazing must be stored in the fertilizer database. The manure nutrient loadings are added to the topmost 10 mm of soil. This is the portion of the soil with which surface runoff interacts.

After biomass is removed by grazing and/or trampling, the plant's leaf area index and accumulated heat units are set back by the fraction of biomass removed.

Table 20-3: SWAT input variables that pertain to grazing.

Variable Name	Definition	Input File
Variables in grazing operation line:		
MONTH/DAY or HUSC	Time grazing operation is initiated (1st day of grazing)	.mgt
MGT_OP	Operation code. MGT_OP = 9 for grazing operation	.mgt
NDGRAZ	Number of days of grazing.	.mgt
BMEAT	*bio*: Dry weight plant biomass consumed daily (kg/ha)	.mgt
IGFTYP	Manure code from fert.dat	.mgt
WMANURE	*fert*: Amount of manure applied—dry weight (kg/ha)	.mgt
Optional inputs:		
BMTRMP	*bio*: Dry weight plant biomass trampled daily (kg/ha)	.mgt
Variables in second line of .mgt file		
BIO_MIN	*bio*: Minimum plant biomass for grazing to occur (kg/ha)	.mgt

20.4 HARVEST & KILL OPERATION

The harvest and kill operation stops plant growth in the HRU. The fraction of biomass specified in the land cover's harvest index (in the plant growth database) is removed from the HRU as yield. The remaining fraction of plant biomass is converted to residue on the soil surface.

The only information required by the harvest and kill operation is the timing of the operation (month and day or fraction of plant potential heat units). The user also has the option of updating the moisture condition II curve number in this operation.

Table 20-4: SWAT input variables that pertain to harvest & kill.

Variable Name	Definition	Input File
Variables in harvest & kill operation line:		
MONTH/DAY or HUSC	Timing of harvest and kill operation.	.mgt
MGT_OP	Operation code. MGT_OP = 5 for harvest/kill operation	.mgt
Optional inputs:		
CNOP	CN_2: Moisture condition II curve number	.mgt

20.5 KILL/END OF GROWING SEASON

The kill operation stops plant growth in the HRU. All plant biomass is converted to residue.

The only information required by the kill operation is the timing of the operation (month and day or fraction of plant potential heat units).

Table 20-5: SWAT input variables that pertain to kill.

Variable Name	Definition	Input File
Variables in kill operation line:		
MONTH/DAY or HUSC	Timing of kill operation.	.mgt
MGT_OP	Operation code. MGT_OP = 8 for kill operation	.mgt

20.6 TILLAGE

The tillage operation redistributes residue, nutrients, pesticides and bacteria in the soil profile. Information required in the tillage operation includes the timing of the operation (month and day or fraction of base zero potential heat units), and the type of tillage operation.

The user has the option of varying the curve number in the HRU throughout the year. New curve number values may be entered in a plant operation, tillage operation and harvest and kill operation. The curve number entered for these operations are for moisture condition II. SWAT adjusts the entered value daily to reflect change in water content.

The mixing efficiency of the tillage implement defines the fraction of a residue/nutrient/pesticide/bacteria pool in each soil layer that is redistributed through the depth of soil that is mixed by the implement. To illustrate the redistribution of constituents in the soil, assume a soil profile has the following distribution of nitrate.

Layer #	Depth of Layer	NO_3 Content
surface layer	0-10 mm	50 kg/ha
1	10-100 mm	25 kg/ha
2	100-400 mm	20 kg/ha
3	400-1050 mm	10 kg/ha
4	1050-2000 mm	10 kg/ha

If this soil is tilled with a field cultivator, the soil will be mixed to a depth of 100 mm with 30% efficiency. The change in the distribution of nitrate in the soil is:

Layer #	**Depth of Layer**	**Initial NO_3**	**Unmixed NO_3 (70%)**	**Mixed NO_3 (30%)**	**Redistribution of Mixed NO_3**	**Final NO_3**
surface layer	0-10 mm	50 kg/ha	35 kg/ha	15 kg/ha	22.5×10mm/100mm = 2.25 kg/ha	37.25 kg/ha
1	10-100 mm	25 kg/ha	17.5 kg/ha	7.5 kg/ha	22.5×90mm/100mm = 20.25 kg/ha	37.75 kg/ha
2	100-400 mm	20 kg/ha	20 kg/ha			20 kg/ha
3	400-1050 mm	10 kg/ha	10 kg/ha			10 kg/ha
4	1050-2000 mm	10 kg/ha	10 kg/ha			10 kg/ha
			Total mixed:	22.5 kg/ha		

Because the soil is mixed to a depth of 100 mm by the implement, only the nitrate in the surface layer and layer 1 is available for redistribution. To calculated redistribution, the depth of the layer is divided by the tillage mixing depth and multiplied by the total amount of nitrate mixed. To calculate the final nitrate content, the redistributed nitrate is added to the unmixed nitrate for the layer.

All nutrient/pesticide/bacteria/residue pools are treated in the same manner as the nitrate example above. Bacteria mixed into layers below the surface layer is assumed to die.

20.6.1 BIOLOGICAL MIXING

Biological mixing is the redistribution of soil constituents as a result of the activity of biota in the soil (e.g. earthworms, etc.). Studies have shown that biological mixing can be significant in systems where the soil is only infrequently disturbed. In general, as a management system shifts from conventional tillage to conservation tillage to no-till there will be an increase in biological mixing. SWAT allows biological mixing to occur to a depth of 300 mm (or the bottom of the soil profile if it is shallower than 300 mm). The efficiency of biological mixing is defined by the user. The redistribution of nutrients by biological mixing is calculated using the same methodology as that used for a tillage operation.

Table 20-6: SWAT input variables that pertain to tillage.

Variable Name	Definition	Input File
Variables in tillage operation line:		
MONTH/DAY or HUSC	Timing of planting operation.	.mgt
MGT_OP	Operation code. MGT_OP = 6 for tillage operation	.mgt
TILLAGE_ID	Tillage implement code from till.dat	.mgt
Optional inputs:		
CNOP	CN_2: Moisture condition II curve number	.mgt
Variables in second line of .mgt file		
BIOMIX	Biological mixing efficiency	.mgt
Variable in tillage database:		
EFFMIX	Mixing efficiency of tillage operation.	till.dat
DEPTIL	Depth of mixing by tillage operation.	till.dat

20.7 FERTILIZER APPLICATION

The fertilizer operation applies fertilizer or manure to the soil.

Information required in the fertilizer operation includes the timing of the operation (month and day or fraction of plant potential heat units), the type of fertilizer/manure applied, the amount of fertilizer/manure applied, and the depth distribution of fertilizer application.

SWAT assumes surface runoff interacts with the top 10 mm of soil. Nutrients contained in this surface layer are available for transport to the main channel in surface runoff. The fertilizer operation allows the user to specify the fraction of fertilizer that is applied to the top 10 mm. The remainder of the fertilizer is added to the first soil layer defined in the HRU .sol file.

In the fertilizer database, the weight fraction of different types of nutrients and bacteria are defined for the fertilizer. The amount of nutrient added to the different pools in the soil are calculated:

$$NO3_{fert} = fert_{minN} \cdot \left(1 - fert_{NH4}\right) \cdot fert \qquad 20.7.1$$

$$NH4_{fert} = fert_{minN} \cdot fert_{NH4} \cdot fert \qquad 20.7.2$$

$$orgN_{frsh,fert} = 0.5 \cdot fert_{orgN} \cdot fert \qquad 20.7.3$$

$$orgN_{act,fert} = 0.5 \cdot fert_{orgN} \cdot fert \qquad 20.7.4$$

$$P_{solution,fert} = fert_{minP} \cdot fert \qquad 20.7.5$$

$$orgP_{frsh,fert} = 0.5 \cdot fert_{orgP} \cdot fert \qquad 20.7.6$$

$$orgP_{hum,fert} = 0.5 \cdot fert_{orgP} \cdot fert \qquad 20.7.7$$

$$bact_{lpsol,fert} = fert_{lpbact} \cdot k_{bact} \cdot fert \qquad 20.7.8$$

$$bact_{lpsorb,fert} = fert_{lpbact} \cdot \left(1 - k_{bact}\right) \cdot fert \qquad 20.7.9$$

$$bact_{psol,fert} = fert_{pbact} \cdot k_{bact} \cdot fert \qquad 20.7.10$$

$$bact_{psorb,fert} = fert_{pbact} \cdot \left(1 - k_{bact}\right) \cdot fert \qquad 20.7.11$$

where $NO3_{fert}$ is the amount of nitrate added to the soil in the fertilizer (kg N/ha), $NH4_{fert}$ is the amount of ammonium added to the soil in the fertilizer (kg N/ha), $orgN_{frsh,fert}$ is the amount of nitrogen in the fresh organic pool added to the soil in the fertilizer (kg N/ha), $orgN_{act,fert}$ is the amount of nitrogen in the active organic pool added to the soil in the fertilizer (kg N/ha), $P_{solution,fert}$ is the amount of phosphorus in the solution pool added to the soil in the fertilizer (kg P/ha), $orgP_{frsh,fert}$ is the amount of phosphorus in the fresh organic pool added to the soil in the fertilizer (kg P/ha), $orgP_{hum,fert}$ is the amount of phosphorus in the humus organic pool added to the soil in the fertilizer (kg P/ha), $bact_{lpsol,fert}$ is the amount of less persistent bacteria in the solution pool added to the soil in the fertilizer (# bact/ha), $bact_{lpsorb,fert}$ is the amount of less persistent bacteria in the sorbed pool added to the soil in fertilizer (# bact/ha), $bact_{psol,fert}$ is the amount of persistent bacteria in the solution pool added to the soil in the fertilizer (# bact/ha), $bact_{psorb,fert}$ is the amount of persistent bacteria in the sorbed pool added to the soil in fertilizer (# bact/ha), $fert_{minN}$ is the fraction of mineral N in the fertilizer, $fert_{NH4}$ is the fraction of mineral N in the fertilizer that is ammonium, $fert_{orgN}$ is the fraction of organic N in the fertilizer, $fert_{minP}$ is the fraction of mineral P in the fertilizer, $fert_{orgP}$ is the fraction of organic P in the fertilizer, $fert_{lpbact}$ is the concentration of less persistent bacteria in the fertilizer (# bact/kg fert), $fert_{pbact}$ is the concentration of persistent bacteria in the fertilizer (# bact/kg fert), k_{bact} is the bacterial partition coefficient, and $fert$ is the amount of fertilizer applied to the soil (kg/ha).

Table 20-7: SWAT input variables that pertain to fertilizer application.

Variable Name	Definition	Input File
Variables in fertilizer operation line:		
MONTH/DAY or HUSC	Timing of fertilizer operation.	.mgt
MGT_OP	Operation code. MGT_OP = 3 for fertilizer operation	.mgt
FERT_ID	Type of fertilizer/manure applied (code from fert.dat).	.mgt
FRT_KG	*fert*: Amount of fertilizer/manure applied (kg/ha)	.mgt
FRT_LY1	Fraction of fertilizer applied to top 10 mm	.mgt
Variables in fertilizer database:		
FMINN	$fert_{minN}$: Fraction of mineral nitrogen in the fertilizer	fert.dat
FMINP	$fert_{minP}$: Fraction of mineral P in the fertilizer	fert.dat
FORGN	$fert_{orgN}$: Fraction of organic N in the fertilizer	fert.dat
FORGP	$fert_{orgP}$: Fraction of organic P in the fertilizer	fert.dat
FNH3N	$fert_{NH4}$: Fraction of mineral N in the fertilizer that is ammonium	fert.dat
BACTPDB	$fert_{pbact}$: Concentration of persistent bacteria in manure (# bact/kg)	fert.dat
BACTLPDB	$fert_{lpbact}$: Concentration of less-persistent bacteria in manure (# bact/kg)	fert.dat
BACTKDDB	k_{bact}: Bacterial partition coefficient	fert.dat

20.8 AUTO-APPLICATION OF FERTILIZER

Fertilization in an HRU may be scheduled by the user or automatically applied by SWAT. When the user selects auto-application of fertilizer in an HRU, a nitrogen stress threshold must be specified. The nitrogen stress threshold is a fraction of potential plant growth. Anytime actual plant growth falls below this threshold fraction due to nitrogen stress, the model will automatically apply fertilizer to the HRU. The user specifies the type of fertilizer, the fraction of total fertilizer applied to the soil surface, the maximum amount of fertilizer that can be applied during the year, the maximum amount of fertilizer that can be applied in any one application, and the application efficiency.

To determine the amount of fertilizer applied, an estimate of the amount of nitrogen that will be removed in the yield is needed. For the first year of simulation, the model has no information about the amount of nitrogen removed from the soil by the plant. The nitrogen yield estimate is initially assigned a value using the following equations:

$$yld_{est,N} = 350 \cdot fr_{N,yld} \cdot RUE \qquad \text{if } HI_{opt} < 1.0 \qquad 20.8.1$$

$$yld_{est,N} = 1000 \cdot fr_{N,yld} \cdot RUE \qquad \text{if } HI_{opt} \geq 1.0 \qquad 20.8.2$$

where $yld_{est,N}$ is the nitrogen yield estimate (kg N/ha), $fr_{N,yld}$ is the fraction of nitrogen in the yield, RUE is the radiation-use efficiency of the plant (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ), and HI_{opt} is the potential harvest index for the plant at maturity given ideal growing conditions. The nitrogen yield estimate is updated at the end of every simulation year using the equation:

$$yld_{est,N} = \frac{yld_{est,Nprev} \cdot yr_{sim} + yld_{yr,N}}{yr_{sim} + 1} \qquad 20.8.3$$

where $yld_{est,N}$ is the nitrogen yield estimate update for the current year (kg N/ha), $yld_{est,Nprev}$ is the nitrogen yield estimate from the previous year (kg N/ha), yr_{sim} is the year of simulation, $yld_{yr,N}$ is the nitrogen yield target for the current year (kg N/ha). The nitrogen yield target for the current year is calculated at the time of harvest using the equation:

$$yld_{yr,N} = bio_{ag} \cdot fr_N \cdot fert_{eff} \qquad 20.8.4$$

where $yld_{yr,N}$ is the nitrogen yield target for the current year (kg N/ha), bio_{ag} is the aboveground biomass on the day of harvest (kg ha^{-1}), fr_N is the fraction of nitrogen in the plant biomass calculated with equation 18.3.1, and $fert_{eff}$ is the fertilizer application efficiency assigned by the user. The fertilizer application efficiency allows the user to modify the amount of fertilizer applied as a function of plant demand. If the user would like to apply additional fertilizer to adjust for loss in runoff, $fert_{eff}$ will be set to a value greater than 1. If the user would like to apply just enough fertilizer to meet the expected demand, $fert_{eff}$ will be set to 1. If the user would like to apply only a fraction of the demand, $fert_{eff}$ will be set to a value less than 1.

The optimal amount of mineral nitrogen to be applied is calculated:

$$minN_{app} = yld_{est,N} - (NO3 + NH4) - bio_N \qquad 20.8.5$$

where $minN_{app}$ is the amount of mineral nitrogen applied (kg N/ha), $yld_{est,N}$ is the nitrogen yield estimate (kg N/ha), $NO3$ is the nitrate content of the soil profile (kg NO_3-N/ha), $NH4$ is the ammonium content of the soil profile (kg NH_4-N/ha), and bio_N is the actual mass of nitrogen stored in plant material (kg N/ha). If the amount of mineral nitrogen calculated with equation 20.8.5 exceeds the maximum amount allowed for any one application, $minN_{app}$ is reset to the maximum value ($minN_{app} = minN_{app,mx}$). The total amount of nitrogen applied during the year is also compared to the maximum amount allowed for the year. Once the amount applied reaches the maximum amount allowed for the year ($minN_{app,mxyr}$), SWAT will not apply any additional fertilizer regardless of nitrogen stress.

Once the amount of mineral nitrogen applied is determined, the total amount of fertilizer applied is calculated by dividing the mass of mineral nitrogen applied by the fraction of mineral nitrogen in the fertilizer:

$$fert = \frac{minN_{app}}{fert_{minN}} \qquad 20.8.6$$

where $fert$ is the amount of fertilizer applied (kg/ha), $minN_{app}$ is the amount of mineral nitrogen applied (kg N/ha), and $fert_{minN}$ is the fraction of mineral nitrogen in the fertilizer.

The type of fertilizer applied in the HRU is specified by the user. In addition to mineral nitrogen, organic nitrogen and phosphorus and mineral phosphorus are applied to the HRU. The amount of each type of nutrient is calculated from the amount of fertilizer and fraction of the various nutrient types in the fertilizer as summarized in Section 20.7.

While the model does not allow fertilizer to be applied as a function of phosphorus stress, the model does monitor phosphorus stress in the auto-fertilization subroutine. If phosphorus stress causes plant growth to fall below 75% of potential growth, the model ignores the fraction of mineral phosphorus in the fertilizer and applies an amount of mineral phosphorus equal to ($\frac{1}{7} \cdot minN_{app}$).

Table 20-8: SWAT input variables that pertain to auto-fertilization.

Variable Name	Definition	Input File
Variables in auto-fertilizer operation line:		
MONTH/DAY or HUSC	Timing of fertilizer operation.	.mgt
MGT_OP	Operation code. MGT_OP = 11 for auto-fertilizer operation	.mgt
FERT_ID	Type of fertilizer/manure applied (code from fert.dat).	.mgt
AFRT_LY1	Fraction of fertilizer applied to top 10 mm	.mgt
AUTO_NSTR	$nstrs$: Nitrogen stress that triggers fertilizer application	.mgt
AUTO_EFF	$fert_{eff}$: Application efficiency	.mgt
AUTO_NMXS	$minN_{app,mx}$: Maximum amount of mineral N allowed to be applied on any one day (kg N/ha)	.mgt

Table 20-8, cont.: SWAT input variables that pertain to auto-fertilization.

Variable Name	Definition	Input File
AUTO_NMXA	$minN_{app,mxyr}$: Maximum amount of mineral N allowed to be applied during a year (kg N/yr)	.mgt
Other variables:		
CNYLD	$fr_{N,yld}$: Fraction of nitrogen in the yield	crop.dat
BIO_E	RUE: Radiation use efficiency ((kg/ha)/(MJ/m^2))	crop.dat
HVSTI	HI_{opt}: Potential harvest index for the plant at maturity given ideal growing conditions	crop.dat
FMINN	$fert_{minN}$: fraction of mineral N in the fertilizer	fert.dat

20.9 PESTICIDE APPLICATION

The pesticide operation applies pesticide to the HRU.

Information required in the pesticide operation includes the timing of the operation (month and day or fraction of plant potential heat units), the type of pesticide applied, and the amount of pesticide applied.

Field studies have shown that even on days with little or no wind, a portion of pesticide applied to the field is lost. The fraction of pesticide that reaches the foliage or soil surface is defined by the pesticide's application efficiency. The amount of pesticide that reaches the foliage or ground is:

$$pest' = ap_{ef} \cdot pest \qquad 20.9.1$$

where $pest'$ is the effective amount of pesticide applied (kg pst/ha), ap_{ef} is the pesticide application efficiency, and $pest$ is the actual amount of pesticide applied (kg pst/ha).

The amount of pesticide reaching the ground surface and the amount of pesticide added to the plant foliage is calculated as a function of ground cover. The ground cover provided by plants is:

$$gc = \frac{1.99532 - \mathrm{erfc}[1.333 \cdot LAI - 2]}{2.1} \qquad 20.9.2$$

where gc is the fraction of the ground surface covered by plants, erfc is the complementary error function, and LAI is the leaf area index.

1. The figure shows that erf(β) ranges from –1 to +1 while erfc(β) ranges from 0 to +2. The complementary error function takes on a value greater than 1 only for negative values of the argument.

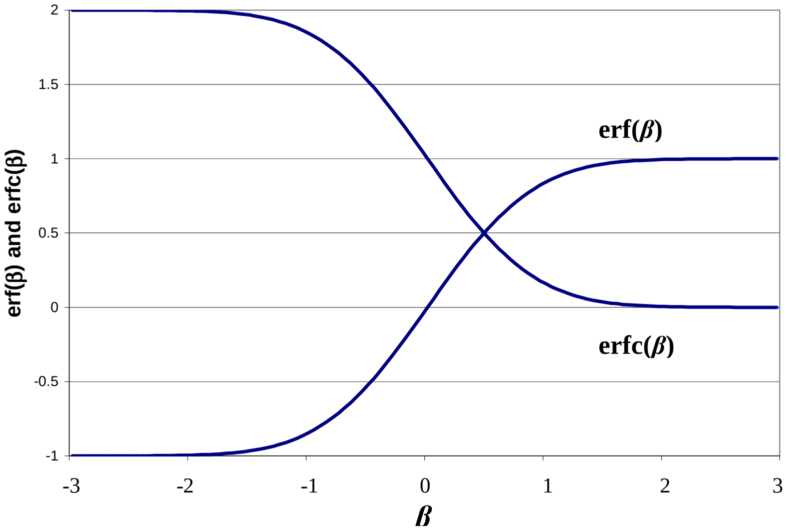

Figure 20-1: erf(β) and erfc(β) plotted versus β

Once the fraction of ground covered by plants is known, the amount of pesticide applied to the foliage is calculated:

$$pest_{fol} = gc \cdot pest' \qquad 20.9.3$$

and the amount of pesticide applied to the soil surface is

$$pest_{surf} = (1 - gc) \cdot pest' \qquad 20.9.4$$

where $pest_{fol}$ is the amount of pesticide applied to foliage (kg pst/ha), $pest_{surf}$ is the amount of pesticide applied to the soil surface (kg pst/ha), gc is the fraction of the ground surface covered by plants, and $pest'$ is the effective amount of pesticide applied (kg pst/ha).

Table 20-9: SWAT input variables that pertain to pesticide application.

Variable Name	Definition	Input File
Variables in pesticide operation line:		
MONTH/DAY or HUSC	Timing of pesticide operation.	.mgt
MGT_OP	Operation code. MGT_OP = 4 for pesticide operation	.mgt
PEST_ID	Type of pesticide applied (code from pest.dat).	.mgt
PST_KG	*pest*: Amount of pesticide applied (kg/ha)	.mgt
Variables in pesticide database:		
AP_EF	ap_{ef}: Pesticide application efficiency	pest.dat

20.10 FILTER STRIPS

Edge-of field filter strips may be defined in an HRU. Sediment, nutrient, pesticide and bacteria loads in surface runoff are reduced as the surface runoff passes through the filter strip.

The filter strip trapping efficiency for bacteria is calculated:

$$trap_{ef,bact} = 1 - \frac{\left(12 + 4.5 \cdot width_{filtstrip}\right)}{100} \qquad 20.10.1$$

where $trap_{ef,bact}$ is the fraction of the bacteria loading trapped by the filter strip, and $width_{filtstrip}$ is the width of the filter strip (m).

The filter strip trapping efficiency for sediment, nutrients and pesticides is calculated:

$$trap_{ef} = 0.367 \cdot \left(width_{filtstrip}\right)^{0.2967} \qquad 20.10.2$$

where $trap_{ef}$ is the fraction of the constituent loading trapped by the filter strip, and $width_{filtstrip}$ is the width of the filter strip (m).

Table 20-10: SWAT input variables that pertain to filter strips.

Variable Name	Definition	Input File
FILTERW	$width_{filtstrip}$: Width of filter strip (m)	.hru

20.11 NOMENCLATURE

CN_2	Moisture condition II curve number
HI_{opt}	Potential harvest index for the plant at maturity given ideal growing conditions
HI_{trg}	Target harvest index
LAI	Leaf area index of the canopy
$NH4$	Ammonium content of the soil profile (kg NH_4-N/ha)
$NH4_{fert}$	Amount of ammonium added to the soil in the fertilizer (kg N/ha)
$NO3$	Nitrate content of the soil profile (kg NO_3-N/ha)
$NO3_{fert}$	Amount of nitrate added to the soil in the fertilizer (kg N/ha)
$P_{solution,fert}$	Amount of phosphorus in the solution pool added to the soil in the fertilizer (kg P/ha)
PHU	Potential heat units or total heat units required for plant maturity where base temperature is dependant on the plant species (heat units)
RUE	Radiation-use efficiency of the plant (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ)
ap_{ef}	Pesticide application efficiency

$bact_{lpsol,fert}$	Amount of less persistent bacteria in the solution pool added to the soil in the fertilizer (# bact/ha)
$bact_{lpsorb,fert}$	Amount of less persistent bacteria in the sorbed pool added to the soil in fertilizer (# bact/ha)
$bact_{psol,fert}$	Amount of persistent bacteria in the solution pool added to the soil in the fertilizer (# bact/ha)
$bact_{psorb,fert}$	Amount of persistent bacteria in the sorbed pool added to the soil in fertilizer (# bact/ha)
bio	Total plant biomass on a given day (kg/ha)
bio_{ag}	Aboveground biomass on the day of harvest (kg ha^{-1})
bio_N	Actual mass of nitrogen stored in plant material (kg N/ha)
bio_{trg}	Target biomass specified by the user (kg/ha)
$fert$	Amount of fertilizer applied (kg/ha)
$fert_{eff}$	Fertilizer application efficiency assigned by the user
$fert_{lpbact}$	Concentration of less persistent bacteria in the fertilizer (# bact/kg fert)
$fert_{minN}$	Fraction of mineral nitrogen in the fertilizer
$fert_{minP}$	Fraction of mineral P in the fertilizer
$fert_{NH4}$	Fraction of mineral N in the fertilizer that is ammonium
$fert_{orgN}$	Fraction of organic N in the fertilizer
$fert_{orgP}$	Fraction of organic P in the fertilizer
$fert_{pbact}$	Concentration of persistent bacteria in the fertilizer (# bact/kg fert)
fr_N	Optimal fraction of nitrogen in the plant biomass for current growth stage
$fr_{N,yld}$	Fraction of nitrogen in the yield
gc	Fraction of the ground surface covered by plants
$harv_{eff}$	Efficiency of the harvest operation
k_{bact}	Bacterial partition coefficient
$minN_{app}$	Amount of mineral nitrogen applied (kg N/ha)
$minN_{app,mx}$	Maximum amount of mineral N allowed to be applied on any one day (kg N/ha)
$minN_{app,mxyr}$	Maximum amount of mineral N allowed to be applied during a year (kg N/ha)
$nstrs$	Nitrogen stress for a given day
$orgN_{act,fert}$	Amount of nitrogen in the active organic pool added to the soil in the fertilizer (kg N/ha)
$orgN_{frsh,fert}$	Amount of nitrogen in the fresh organic pool added to the soil in the fertilizer (kg N/ha)
$orgP_{frsh,fert}$	Amount of phosphorus in the fresh organic pool added to the soil in the fertilizer (kg P/ha)
$orgP_{hum,fert}$	Amount of phosphorus in the humus organic pool added to the soil in the fertilizer (kg P/ha)
$pest$	Actual amount of pesticide applied (kg pst/ha)
$pest'$	Effective amount of pesticide applied (kg pst/ha)
$pest_{fol}$	Amount of pesticide applied to foliage (kg pst/ha)
$pest_{surf}$	Amount of pesticide applied to the soil surface (kg pst/ha)
$trap_{ef}$	Fraction of the constituent loading trapped by the filter strip
$trap_{ef,bact}$	Fraction of the bacteria loading trapped by the filter strip

$width_{filtstrip}$	Width of filter strip (m)
$yld_{est,N}$	Nitrogen yield estimate (kg N/ha)
$yld_{est,Nprev}$	Nitrogen yield estimate from the previous year (kg N/ha)
$yld_{yr,N}$	Nitrogen yield target for the current year (kg N/ha)
yr_{sim}	Year of simulation

20.12 REFERENCES

Domenico, P.A. and F.W. Schwartz. 1990. Physical and chemical hydrology. John Wiley & Sons, New York, NY.

CHAPTER 21

EQUATIONS: WATER MANAGEMENT

Accurately reproducing water management practices can be one of the most complicated portions of data input for the model. Because water management affects the hydrologic balance, it is critical that the model is able to accommodate a variety of management practices. Water management options modeled by SWAT include irrigation, tile drainage, impounded/depressional areas, water transfer, consumptive water use, and loadings from point sources.

21.1 IRRIGATION

Irrigation in an HRU may be scheduled by the user or automatically applied by SWAT. In addition to specifying the timing and application amount, the user must specify the source of irrigation water.

Water applied to an HRU is obtained from one of five types of water sources: a reach, a reservoir, a shallow aquifer, a deep aquifer, or a source outside the watershed. In addition to the type of water source, the model must know the location of the water source (unless the source is outside the watershed). For the reach, shallow aquifer or deep aquifer, SWAT needs to know the subbasin number in which the source is located. If a reservoir is used to supply water, SWAT must know the reservoir number.

If the source of the irrigation water is a reach, SWAT allows additional input parameters to be set. These parameters are used to prevent flow in the reach from being reduced to zero as a result of irrigation water removal. Users may define a minimum in-stream flow, a maximum irrigation water removal amount that cannot be exceeded on any given day, and/or a fraction of total flow in the reach that is available for removal on a given day.

For a given irrigation event, SWAT determines the amount of water available in the source. The amount of water available is compared to the amount of water specified in the irrigation operation. If the amount available is less than the amount specified, SWAT will only apply the available water.

Water applied to an HRU is used to fill the soil layers up to field capacity beginning with the soil surface layer and working downward until all the water applied is used up or the bottom of the profile is reached. If the amount of water specified in an irrigation operation exceeds the amount needed to fill the soil layers up to field capacity water content, the excess water is returned to the source. For HRUs that are defined as potholes or depressional areas, the irrigation water is added to the ponded water overlying the soil surface.

21.1.1 AUTO-APPLICATION OF IRRIGATION

When the user selects auto-application of irrigation water in an HRU, a water stress threshold must be specified. The water stress threshold is a fraction of potential plant growth. Anytime actual plant growth falls below this threshold fraction due to water stress the model will automatically apply water to the HRU. If enough water is available from the irrigation source, the model will add water to the soil until it is at field capacity.

The water stress threshold is usually set somewhere between 0.90 and 0.95.

Table 21-1: SWAT input variables that pertain to irrigation.

Variable Name	Definition	Input File
Variables in irrigation operation line:		
MONTH/DAY or HUSC	Timing of irrigation operation.	.mgt
MGT_OP	Operation code. MGT_OP = 2 for irrigation operation	.mgt
IRR_AMT	Depth of irrigation water applied on HRU (mm)	.mgt
Variables in .hru file		
IRR	Type of water body from which irrigation water is obtained	.hru
IRRNO	Source location	.hru
FLOWMIN	Minimum in-stream flow (m^3/s)	.hru
DIVMAX	Maximum daily irrigation diversion (mm or 10^4 m^3)	.hru
FLOWFR	Fraction of available flow allowed to be used for irrigation	.hru
Variables in auto-irrigation operation line:		
MONTH/DAY or HUSC	Initialization of auto-irrigation	.mgt
MGT_OP	Operation code. MGT_OP = 10 for auto-irrigation	.mgt
AUTO_WSTR	Water stress that triggers irrigation	.mgt

21.2 TILE DRAINAGE

To simulate tile drainage in an HRU, the user must specify the depth from the soil surface to the drains, the amount of time required to drain the soil to field capacity, and the amount of lag between the time water enters the tile till it exits the tile and enters the main channel.

Tile drainage occurs when the soil water content exceeds field capacity. In the soil layer where the tile drains are installed, the amount of water entering the drain on a given day is calculated:

$$tile_{wtr} = \left(SW_{ly} - FC_{ly}\right) \cdot \left(1 - \exp\left[\frac{-24}{t_{drain}}\right]\right) \qquad \text{if } SW_{ly} > FC_{ly} \qquad 21.2.1$$

where $tile_{wtr}$ is the amount of water removed from the layer on a given day by tile drainage (mm H_2O), SW_{ly} is the water content of the layer on a given day (mm H_2O), FC_{ly} is the field capacity water content of the layer (mm H_2O), and t_{drain} is the time required to drain the soil to field capacity (hrs).

Water entering tiles is treated like lateral flow. The flow is lagged using equations reviewed in Chapter 8.

Table 21-2: SWAT input variables that pertain to tile drainage.

Variable Name	Definition	Input File
DDRAIN	Depth to subsurface drain (mm).	.hru
TDRAIN	t_{drain}: Time to drain soil to field capacity (hrs)	.hru
GDRAIN	$tile_{lag}$: Drain tile lag time (hrs)	.hru

21.3 IMPOUNDED/DEPRESSIONAL AREAS

Impounded/depressional areas are simulated as a water body overlying a soil profile in an HRU. This type of ponded system is needed to simulate the growth of rice, cranberries or any other plant that grows in a waterlogged system. The simulation and management operations pertaining to impounded/depressional areas is reviewed in Chapter 27.

21.4 WATER TRANSFER

While water is most typically removed from a water body for irrigation purposes, SWAT also allows water to be transferred from one water body to another. This is performed with a transfer command in the watershed configuration file.

The transfer command can be used to move water from any reservoir or reach in the watershed to any other reservoir or reach in the watershed. The user must input the type of water source, the location of the source, the type of water body receiving the transfer, the location of the receiving water body, and the amount of water transferred.

Three options are provided to specify the amount of water transferred: a fraction of the volume of water in the source; a volume of water left in the source; or the volume of water transferred. The transfer is performed every day of the simulation.

The transfer of water from one water body to another can be accomplished using other methods. For example, water could be removed from one water body via consumptive water use and added to another water body using point source files.

Table 21-3: SWAT input variables that pertain to water transfer.

Variable Name	Definition	Input File
DEP_TYPE	Water source type	.fig
DEP_NUM	Water source location	.fig
DEST_TYPE	Destination type	.fig
DEST_NUM	Destination location	.fig
TRANS_AMT	Amount of water transferred	.fig
TRANS_CODE	Rule code governing water transfer.	.fig

21.5 CONSUMPTIVE WATER USE

Consumptive water use is a management tool that removes water from the basin. Water removed for consumptive use is considered to be lost from the system. SWAT allows water to be removed from the shallow aquifer, the deep aquifer, the reach or the pond within any subbasin in the watershed. Water also may be removed from reservoirs for consumptive use.

Consumptive water use is allowed to vary from month to month. For each month in the year, an average daily volume of water removed from the source is specified. For reservoirs, the user may also specify a fraction of the water removed that is lost during removal. The water lost in the removal process becomes outflow from the reservoir.

Table 21-4: SWAT input variables that pertain to consumptive water use.

Variable Name	**Definition**	**Input File**
WUPND(1-12)	Average daily water removal from pond in subbasin (10^4 m^3)	.wus
WURCH(1-12)	Average daily water removal from reach in subbasin (10^4 m^3)	.wus
WUSHAL(1-12)	Average daily water removal from shallow aquifer in subbasin (10^4 m^3)	.wus
WUDEEP(1-12)	Average daily water removal from deep aquifer in subbasin (10^4 m^3)	.wus
WURESN(1-12)	Average daily water removal from reservoir (10^4 m^3)	.res
WURTNF	Fraction of water removal lost in transfer and returned as reservoir outflow.	.res

21.6 POINT SOURCE LOADINGS

SWAT directly simulates the loading of water, sediment and other constituents off of land areas in the watershed. To simulate the loading of water and pollutants from sources not associated with a land area (e.g. sewage treatment plants), SWAT allows point source information to be read in at any point along the channel network. The point source loadings may be summarized on a daily, monthly, yearly, or average annual basis.

Files containing the point source loads are created by the user. The loads are read into the model and routed through the channel network using recday, recmon, recyear, or reccnst commands in the watershed configuration file. SWAT will read in water, sediment, organic N, organic P, nitrate, soluble P, ammonium, nitrite, metal, and bacteria data from the point source files. Chapter 31 reviews the format of the command lines in the watershed configuration file while Chapter 43 reviews the format of the point source files.

21.7 NOMENCLATURE

SW_{ly}	Water content of the layer on a given day (mm H_2O)
FC_{ly}	Field capacity water content of the layer (mm H_2O)
t_{drain}	Time required to drain the soil to field capacity (hrs)
$tile_{wtr}$	Amount of water removed from the layer on a given day by tile drainage (mm H_2O)

CHAPTER 22

EQUATIONS: URBAN AREAS

Most large watersheds and river basins contain areas of urban land use. Estimates of the quantity and quality of runoff in urban areas are required for comprehensive management analysis. SWAT calculates runoff from urban areas with the SCS curve number method or the Green & Ampt equation. Loadings of sediment and nutrients are determined using one of two options. The first is a set of linear regression equations developed by the USGS (Driver and Tasker, 1988) for estimating storm runoff volumes and constituent loads. The other option is to simulate the buildup and washoff mechanisms, similar to SWMM - Storm Water Management Model (Huber and Dickinson, 1988).

22.1 CHARACTERISTICS OF URBAN AREAS

Urban areas differ from rural areas in the fraction of total area that is impervious. Construction of buildings, parking lots and paved roads increases the impervious cover in a watershed and reduces infiltration. With development, the spatial flow pattern of water is altered and the hydraulic efficiency of flow is increased through artificial channels, curbing, and storm drainage and collection systems. The net effect of these changes is an increase in the volume and velocity of runoff and larger peak flood discharges.

Impervious areas can be differentiated into two groups: the area that is hydraulically connected to the drainage system and the area that is not directly connected. As an example, assume there is a house surrounded by a yard where runoff from the roof flows into the yard and is able to infiltrate into the soil. The rooftop is impervious but it is not hydraulically connected to the drainage system. In contrast, a parking lot whose runoff enters a storm water drain is hydraulically connected. Table 22-1 lists typical values for impervious and directly connected impervious fractions in different urban land types.

Table 22-1: Range and average impervious fractions for different urban land types.

Urban Land Type	**Average total impervious**	**Range total impervious**	**Average directly connected impervious**	**Range directly connected impervious**
Residential-High Density (> 8 unit/acre or unit/2.5 ha)	.60	.44 - .82	.44	.32 - .60
Residential-Medium Density (1-4 unit/acre or unit/2.5 ha)	.38	.23 - .46	.30	.18 - .36
Residential-Med/Low Density (> 0.5-1 unit/acre or unit/2.5 ha)	.20	.14 - .26	.17	.12 - .22
Residential-Low Density (< 0.5 unit/acre or unit/2.5 ha)	.12	.07 - .18	.10	.06 - .14
Commercial	.67	.48 - .99	.62	.44 - .92
Industrial	.84	.63 - .99	.79	.59 - .93
Transportation	.98	.88 - 1.00	.95	.85 – 1.00
Institutional	.51	.33 - .84	.47	.30 - .77

During dry periods, dust, dirt and other pollutants build up on the impervious areas. When precipitation events occur and runoff from the impervious areas is generated, the runoff will carry the pollutants as it moves through the drainage system and enters the channel network of the watershed.

22.2 SURFACE RUNOFF FROM URBAN AREAS

In urban areas, surface runoff is calculated separately for the directly connected impervious area and the disconnected impervious/pervious area. For directly connected impervious areas, a curve number of 98 is always used. For disconnected impervious/pervious areas, a composite curve number is calculated and used in the surface runoff calculations. The equations used to calculate the composite curve number for disconnected impervious/pervious areas are (Soil Conservation Service Engineering Division, 1986):

$$CN_c = \frac{CN_p \cdot \left(1 - imp_{tot} + \frac{imp_{dcon}}{2}\right) + 98 \cdot \left(\frac{imp_{dcon}}{2}\right)}{1 - imp_{con}} \quad \text{if } imp_{tot} \leq 0.30 \qquad 22.2.1$$

$$CN_c = \frac{CN_p \cdot (1 - imp_{tot}) + 98 \cdot imp_{dcon}}{1 - imp_{con}} \quad \text{if } imp_{tot} > 0.30 \qquad 22.2.2$$

where CN_c is the composite moisture condition II curve number, CN_p is the pervious moisture condition II curve number, imp_{tot} is the fraction of the HRU area that is impervious (both directly connected and disconnected), imp_{con} is the fraction of the HRU area that is impervious and hydraulically connected to the drainage system, imp_{dcon} is the fraction of the HRU area that is impervious but not hydraulically connected to the drainage system.

Table 22-2: SWAT input variables that pertain to surface runoff calculations in urban areas.

Variable Name	Definition	Input File
CN2	CN_p: SCS moisture condition II curve number for pervious areas	.mgt
CNOP	CN_p: SCS moisture condition II curve number for pervious areas specified in plant, harvest/kill and tillage operation	.mgt
FIMP	imp_{tot}: fraction of urban land type area that is impervious	urban.dat
FCIMP	imp_{con}: fraction of urban land type area that is connected impervious	urban.dat

22.3 USGS REGRESSION EQUATIONS

The linear regression models incorporated into SWAT are those described by Driver and Tasker (1988). The regression models were developed from a national urban water quality database that related storm runoff loads to urban physical, land use, and climatic characteristics. USGS developed these equations to predict loadings in ungaged urban watersheds.

The regression models calculate loadings as a function of total storm rainfall, drainage area and impervious area. The general equation is

$$Y = \frac{\beta_0 \cdot \left(R_{day}/25.4\right)^{\beta_1} \cdot \left(DA/2.59\right)^{\beta_2} \cdot \left(imp_{tot} \cdot 100 + 1\right)^{\beta_3} \cdot \beta_4}{2.205} \qquad 22.3.1$$

where Y is the total constituent load (kg), R_{day} is precipitation on a given day (mm H_2O), DA is the HRU drainage area (km^2), imp_{tot} is the fraction of the total area that is impervious, and the β variables are regression coefficients. The regression equations were developed in English units, so conversion factors were incorporated to adapt the equations to metric units: 25.4 mm/inch, 2.59 km^2/mi^2, and 2.205 lb/kg.

USGS derived three different sets of regression coefficients that are based on annual precipitation. Category I coefficients are used in watersheds with less than 508 mm of annual precipitation. Category II coefficients are used in watersheds with annual precipitation between 508 and 1016 mm. Category III coefficients are used in watersheds with annual precipitation greater than 1016 mm. SWAT determines the annual precipitation category for each subbasin by summing the monthly precipitation totals provided in the weather generator input file.

Regression coefficients were derived to estimate suspended solid load, total nitrogen load, total phosphorus load and carbonaceous oxygen demand (COD). SWAT calculates suspended solid, total nitrogen, and total phosphorus loadings (the carbonaceous oxygen demand is not currently calculated). Regression coefficients for these constituents are listed in Table 22-3.

Once total nitrogen and phosphorus loads are calculated, they are partitioned into organic and mineral forms using the following relationships from Northern Virginia Planning District Commission (1979). Total nitrogen loads consist of 70 percent organic nitrogen and 30 percent mineral (nitrate). Total phosphorus loads are divided into 75 percent organic phosphorus and 25 percent orthophosphate.

Table 22-3: Urban regression coefficients (from Driver and Tasker, 1988).

Loading	Precipitation Category	β_0	β_1	β_2	β_3	β_4
suspended solids	I	1778.0	0.867	0.728	0.157	2.367
	II	812.0	1.236	0.436	0.202	1.938
	III	97.7	1.002	1.009	0.837	2.818
total nitrogen	I	20.20	0.825	1.070	0.479	1.258
	II	4.04	0.936	0.937	0.692	1.373
	III	1.66	0.703	0.465	0.521	1.845
total phosphorus	I	1.725	0.884	0.826	0.467	2.130
	II	0.697	1.008	0.628	0.469	1.790
	III	1.618	0.954	0.789	0.289	2.247
COD	I	407.0	0.626	0.710	0.379	1.518
	II	151.0	0.823	0.726	0.564	1.451
	III	102.0	0.851	0.601	0.528	1.978

I = annual precipitation < 508 mm
II = 508 mm < annual precipitation < 1,016 mm
III = annual precipitation > 1,016 mm

Table 22-4: SWAT input variables that pertain to urban modeling with regression equations.

Variable Name	Definition	Input File
IURBAN	Urban simulation code	.hru
URBLU	Urban land type identification number from urban database	.hru
FIMP	Fraction of HRU that is impervious. imp_{tot} = FIMP · 100	urban.dat
PRECIPITATION	R_{day}: Precipitation on a given day (mm H_2O)	.pcp
HRU_FR	Fraction of total watershed area in HRU	.hru
DA_KM	Area of watershed (km^2)	.bsn
PCPMM(mon)	Average amount of precipitation falling in month (mm H_2O)	.wgn

22.4 BUILD UP/WASH OFF

In an impervious area, dust, dirt and other constituents are built up on street surfaces in periods of dry weather preceding a storm. Build up may be a function of time, traffic flow, dry fallout and street sweeping. During a storm runoff event, the material is then washed off into the drainage system. Although the build up/wash off option is conceptually appealing, the reliability and credibility of the simulation may be difficult to establish without local data for calibration and validation (Huber and Dickinson, 1988).

When the build up/wash off option is used in SWAT, the urban hydrologic response unit (HRU) is divided into pervious and impervious areas. Management operations other than sweep operations are performed in the pervious portion of the HRU. Sweep operations impact build up of solids in the impervious portion of the HRU. For the pervious portion of the HRU, sediment and nutrient loadings are calculated using the methodology summarized in Chapters 13 and 14. The impervious portion of the HRU uses the build up/wash off algorithm to determine sediment and nutrient loadings.

The build up/wash off algorithm calculates the build up and wash off of solids. The solids are assumed to possess a constant concentration of organic and mineral nitrogen and phosphorus where the concentrations are a function of the urban land type.

Build up of solids is simulated on dry days with a Michaelis-Menton equation:

$$SED = \frac{SED_{mx} \cdot td}{\left(t_{half} + td\right)} \qquad 22.4.1$$

where SED is the solid build up (kg/curb km) td days after the last occurrence of SED = 0 kg/curb km, SED_{mx} is the maximum accumulation of solids possible for the urban land type (kg/curb km), and t_{half} is the length of time needed for solid build up to increase from 0 kg/curb km to ½ SED_{mx} (days). A dry day is defined as a day with surface runoff less than 0.1 mm. An example build-up curve is shown in Figure 22-1. As can be seen from the plot, the Michaelis-Menton function will initially rise steeply and then approach the asymptote slowly.

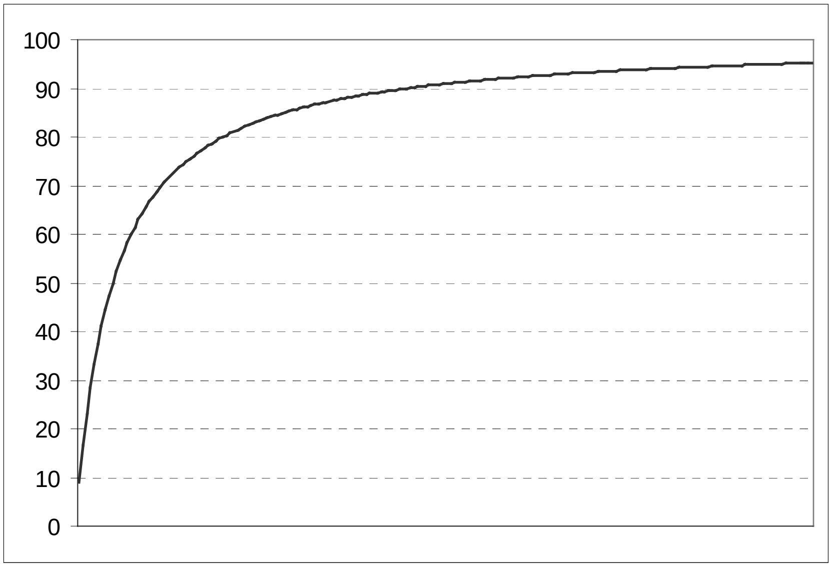

Figure 22-1: Build-up function for solids in urban areas.

The two parameters that determine the shape of this curve are SED_{mx} and t_{half}. These parameters are a function of the urban land type.

Wash off is the process of erosion or solution of constituents from an impervious surface during a runoff event. An exponential relationship is used to simulate the wash off process (Huber and Dickinson, 1988):

$$Y_{sed} = SED_0 \cdot \left(1 - e^{-kk \cdot t}\right) \qquad 22.4.2$$

where Y_{sed} is the cumulative amount of solids washed off at time t (kg/curb km), SED_0 is the amount of solids built up on the impervious area at the beginning of the precipitation event (kg/curb km), and kk is a coefficient.

The coefficient, kk, may be estimated by assuming it is proportional to the peak runoff rate:

$$kk = urb_{coef} \cdot q_{peak} \qquad 22.4.3$$

where urb_{coef} is the wash off coefficient (mm^{-1}) and q_{peak} is the peak runoff rate (mm/hr).

The original default value for urb_{coef} was calculated as 0.18 mm^{-1} by assuming that 13 mm of total runoff in one hour would wash off 90% of the initial surface load. Later estimates of urb_{coef} gave values ranging from 0.002-0.26 mm^{-1}. Huber and Dickinson (1988) noted that values between 0.039 and 0.390 mm^{-1} for urb_{coef} give sediment concentrations in the range of most observed values. They also recommended using this variable to calibrate the model to observed data.

To convert the sediment loading from units of kg/curb km to kg/ha, the amount of sediment removed by wash off is multiplied by the curb length density. The curb length density is a function of the urban land type. Nitrogen and phosphorus loadings from the impervious portion of the urban land area are calculated by multiplying the concentration of nutrient by the sediment loading.

22.4.1 STREET CLEANING

Street cleaning is performed in urban areas to control buildup of solids and trash. While it has long been thought that street cleaning has a beneficial effect on the quality of urban runoff, studies by EPA have found that street sweeping has little impact on runoff quality unless it is performed every day (U.S. Environmental Protection Agency, 1983).

SWAT performs street sweeping operations only when the build up/wash off algorithm is specified for urban loading calculations. Street sweeping is performed only on dry days, where a dry day is defined as a day with less than 0.1 mm of surface runoff. The sweeping removal equation (Huber and Dickinson, 1988) is:

$$SED = SED_0 \cdot \left(1 - fr_{av} \cdot reff\right) \qquad 22.4.4$$

where SED is amount of solids remaining after sweeping (kg/curb km), SED_0 is the amount of solids present prior to sweeping (kg/curb km), fr_{av} is the fraction of the curb length available for sweeping (the availability factor), and $reff$ is the removal efficiency of the sweeping equipment. The availability factor and removal efficiency are specified by the user.

Table 22-5: Removal efficiencies (fraction removed) from street cleaner path (from Pitt, 1979)

Street Cleaning Program and Street Surface Loading Conditions		**Total Solids**	**BOD$_5$**	**COD**	**KN**	**PO$_4$**	**Pesticides**
Vacuum Street Cleaner *(5.5-55 kg/curb km)*							
	1 pass	.31	.24	.16	.26	.08	.33
	2 passes	.45	.35	.22	.37	.12	.50
	3 passes	.53	.41	.27	.45	.14	.59
Vacuum Street Cleaner *(55-280 kg/curb km)*							
	1 pass	.37	.29	.21	.31	.12	.40
	2 passes	.51	.42	.29	.46	.17	.59
	3 passes	.58	.47	.35	.51	.20	.67
Vacuum Street Cleaner *(280-2820 kg/curb km)*							
	1 pass	.48	.38	.33	.43	.20	.57
	2 passes	.60	.50	.42	.54	.25	.72
	3 passes	.63	.52	.44	.57	.26	.75
Mechanical Street Cleaner *(50-500 kg/curb km)*							
	1 pass	.54	.40	.31	.40	.20	.40
	2 passes	.75	.58	.48	.58	.35	.60
	3 passes	.85	.69	.59	.69	.46	.72
Flusher		.30	*a*	*a*	*a*	*a*	*a*
Mechanical Street Cleaner followed by a Flusher		.80	*b*	*b*	*b*	*b*	*b*

a: efficiency fraction estimated .15 to .40
b: efficiency fraction estimated .35 to 1.00

The availability factor, fr_{av}, is the fraction of the curb length that is sweepable. The entire curb length is often not available for sweeping due to the presence of cars and other obstacles.

The removal efficiency of street sweeping is a function of the type of sweeper, whether flushing is a part of the street cleaning process, the quantity of total solids, the frequency of rainfall events and the constituents considered. Removal efficiency can vary depending on the constituent being considered, with efficiencies being greater for particulate constituents. The removal efficiencies for nitrogen and phosphorus are typically less than the solid removal efficiency (Pitt, 1979). Because SWAT assumes a set concentration of nutrient constituents in the solids, the same removal efficiency is in effect used for all constituents. Table 22-5 provides removal efficiencies for various street cleaning programs.

Table 22-6: SWAT input variables that pertain to build up/wash off.

Variable Name	Definition	Input File
IURBAN	Urban simulation code	.hru
URBLU	Urban land type identification number from urban database	.hru
DIRTMX	SED_{mx}: maximum amount of solids allowed to build up on impervious areas (kg/curb km)	urban.dat
THALF	t_{half}: number of days for amount of solids on impervious area to build up from 0 kg/curb km to ½ SED_{mx}	urban.dat
URBCOEF	urb_{coef}: wash off coefficient (mm^{-1})	urban.dat
CURBDEN	curb length density in urban land type (km/ha)	urban.dat
TNCONC	concentration of total nitrogen in suspended solid load (mg N/kg)	urban.dat
TPCONC	concentration of total phosphorus in suspended solid load (mg N/kg)	urban.dat
TNO3CONC	concentration of nitrate in suspended solid load (mg N/kg)	urban.dat
SWEEPEFF	$reff$: removal efficiency of the sweeping equipment	.mgt
AVWSP	fr_{av}: fraction of the curb length that is sweepable.	.mgt

22.5 NOMENCLATURE

CN	Curve number
DA	HRU drainage area (km^2)
R_{day}	Amount of rainfall on a given day (mm H_2O)
SED	Solid build up (kg/curb km)
SED_{mx}	Maximum accumulation of solids possible for the urban land type (kg/curb km)
Y	Total constituent load (kg)
Y_{sed}	Cumulative amount of solids washed off at time t (kg/curb km)

fr_{av}	Fraction of the curb length available for sweeping (the availability factor)
imp_{con}	Fraction of the HRU area that is impervious and hydraulically connected to the drainage system
imp_{dcon}	Fraction of the HRU area that is impervious but not hydraulically connected to the drainage system
imp_{tot}	Fraction of the HRU area that is impervious (both connected and disconnected)
kk	Coefficient in urban wash off equation
q_{peak}	Peak runoff rate (mm/hr)
$reff$	Removal efficiency of the sweeping equipment
t_{half}	Length of time needed for solid build up to increase from 0 kg/curb km to ½ SED_{mx} (days)
urb_{coef}	Wash off coefficient (mm^{-1})
β_0	Coefficient for USGS regression equations for urban loadings
β_1	Coefficient for USGS regression equations for urban loadings
β_2	Coefficient for USGS regression equations for urban loadings
β_3	Coefficient for USGS regression equations for urban loadings
β_4	Coefficient for USGS regression equations for urban loadings

22.6 REFERENCES

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MAIN CHANNEL PROCESSES

Flow in a watershed is classified as overland or channelized. The primary difference between the two flow processes is that water storage and its influence on flow rates is considered in channelized flow. Main channel processes modeled by SWAT include the movement of water, sediment and other constituents (e.g. nutrients, pesticides) in the stream network, in-stream nutrient cycling, and in-stream pesticide transformations. Optional processes include the change in channel dimensions with time due to downcutting and widening.

CHAPTER 23

EQUATIONS: WATER ROUTING

Open channel flow is defined as channel flow with a free surface, such as flow in a river or partially full pipe. SWAT uses Manning's equation to define the rate and velocity of flow. Water is routed through the channel network using the variable storage routing method or the Muskingum river routing method. Both the variable storage and Muskingum routing methods are variations of the kinematic wave model. A detailed discussion of the kinematic wave flood routing model can be found in Chow et al. (1988).

23.1 CHANNEL CHARACTERISTICS

SWAT assumes the main channels, or reaches, have a trapezoidal shape (Figure 23-1).

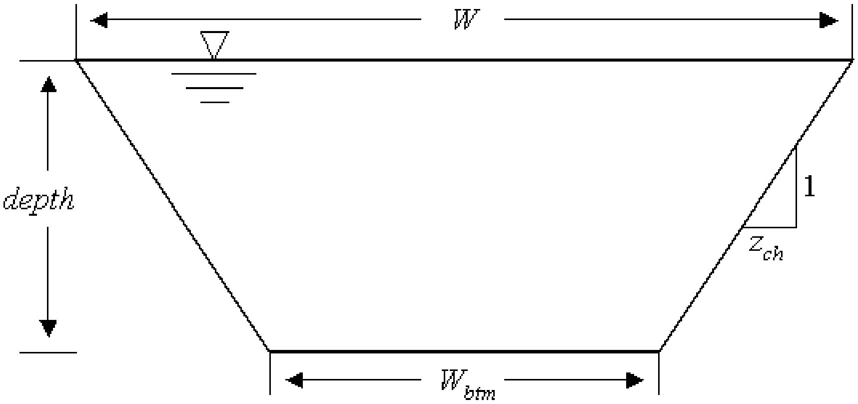

Figure 23-1: Trapezoidal channel dimensions

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. SWAT assumes the channel sides have a 2:1 run to rise ratio ($z_{ch} = 2$). The slope of the channel sides is then ½ or 0.5. The bottom width is calculated from the bankfull width and depth with the equation:

$$W_{btm} = W_{bnkfull} - 2 \cdot z_{ch} \cdot depth_{bnkfull} \qquad 23.1.1$$

where W_{btm} is the bottom width of the channel (m), $W_{bnkfull}$ is the top width of the channel when filled with water (m), z_{ch} is the inverse of the channel side slope, and $depth_{bnkfull}$ is the depth of water in the channel when filled to the top of the bank (m). Because of the assumption that $z_{ch} = 2$, it is possible for the bottom width calculated with equation 23.1.1 to be less than or equal to zero. If this occurs, the model sets $W_{btm} = 0.5 \cdot W_{bnkfull}$ and calculates a new value for the channel side slope run by solving equation 23.1.1 for z_{ch}:

$$z_{ch} = \frac{(W_{bnkfull} - W_{btm})}{2 \cdot depth_{bnkfull}} \qquad 23.1.2$$

For a given depth of water in the channel, the width of the channel at water level is:

$$W = W_{btm} + 2 \cdot z_{ch} \cdot depth \qquad 23.1.3$$

where W is the width of the channel at water level (m), W_{btm} is the bottom width of the channel (m), z_{ch} is the inverse of the channel slope, and *depth* is the depth of water in the channel (m). The cross-sectional area of flow is calculated:

$$A_{ch} = \left(W_{btm} + z_{ch} \cdot depth\right) \cdot depth \qquad 23.1.4$$

where A_{ch} is the cross-sectional area of flow in the channel (m^2), W_{btm} is the bottom width of the channel (m), z_{ch} is the inverse of the channel slope, and *depth* is the depth of water in the channel (m). The wetted perimeter of the channel is defined as

$$P_{ch} = W_{btm} + 2 \cdot depth \cdot \sqrt{1 + z_{ch}^{\ 2}} \qquad 23.1.5$$

where P_{ch} is the wetted perimeter for a given depth of flow (m). The hydraulic radius of the channel is calculated

$$R_{ch} = \frac{A_{ch}}{P_{ch}} \qquad 23.1.6$$

where R_{ch} is the hydraulic radius for a given depth of flow (m), A_{ch} is the cross-sectional area of flow in the channel (m^2), and P_{ch} is the wetted perimeter for a given depth of flow (m). The volume of water held in the channel is

$$V_{ch} = 1000 \cdot L_{ch} \cdot A_{ch} \qquad 23.1.7$$

where V_{ch} is the volume of water stored in the channel (m^3), L_{ch} is the channel length (km), and A_{ch} is the cross-sectional area of flow in the channel for a given depth of water (m^2).

When the volume of water in the reach exceeds the maximum amount that can be held by the channel, the excess water spreads across the flood plain. The flood plain dimensions used by SWAT are shown in Figure 23-2.

Figure 23-2: Illustration of flood plain dimensions.

The bottom width of the floodplain, $W_{btm,fld}$, is $W_{btm,fld} = 5 \cdot W_{bnkfull}$. SWAT assumes the flood plain side slopes have a 4:1 run to rise ratio (z_{fld} = 4). The slope of the flood plain sides is then ¼ or 0.25.

When flow is present in the flood plain, the calculation of the flow depth, cross-sectional flow area and wetting perimeter is a sum of the channel and floodplain components:

$$depth = depth_{bnkfull} + depth_{fld} \qquad 23.1.8$$

$$A_{ch} = \left(W_{btm} + z_{ch} \cdot depth_{bnkfull}\right) \cdot depth_{bnkfull} + \left(W_{btm,fld} + z_{fld} \cdot depth_{fld}\right) \cdot depth_{fld} \qquad 23.1.9$$

$$P_{ch} = W_{btm} + 2 \cdot depth_{bnkfull} \cdot \sqrt{1 + z_{ch}^{2}} + 4 \cdot W_{bnkfull} + 2 \cdot depth_{fld} \cdot \sqrt{1 + z_{fld}^{2}} \qquad 23.1.10$$

where $depth$ is the total depth of water (m), $depth_{bnkfull}$ is the depth of water in the channel when filled to the top of the bank (m), $depth_{fld}$ is the depth of water in the flood plain (m), A_{ch} is the cross-sectional area of flow for a given depth of water (m^2), W_{btm} is the bottom width of the channel (m), z_{ch} is the inverse of the channel side slope, $W_{btm,fld}$ is the bottom width of the flood plain (m), z_{fld} is the inverse of the flood plain side slope, P_{ch} is the wetted perimeter for a given depth of flow (m), and $W_{bnkfull}$ is the top width of the channel when filled with water (m).

Table 23-1: SWAT input variables that pertain to channel dimension calculations.

Variable name	Definition	File Name
CH_W(2)	$W_{bnkfull}$: Width of channel at top of bank (m)	.rte
CH_D	$depth_{bnkfull}$: Depth of water in channel when filled to bank (m)	.rte
CH_L(2)	L_{ch}: Length of main channel (km)	.rte

23.2 FLOW RATE AND VELOCITY

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:

$$q_{ch} = \frac{A_{ch} \cdot R_{ch}^{2/3} \cdot slp_{ch}^{1/2}}{n} \qquad 23.2.1$$

$$v_{c} = \frac{R_{ch}^{2/3} \cdot slp_{ch}^{1/2}}{n} \qquad 23.2.2$$

where q_{ch} is the rate of flow in the channel (m^3/s), A_{ch} is the cross-sectional area of flow in the channel (m^2), R_{ch} is the hydraulic radius for a given depth of flow (m),

slp_{ch} is the slope along the channel length (m/m), n is Manning's "n" coefficient for the channel, and v_c is the flow velocity (m/s).

SWAT routes water as a volume. The daily value for cross-sectional area of flow, A_{ch}, is calculated by rearranging equation 23.1.7 to solve for the area:

$$A_{ch} = \frac{V_{ch}}{1000 \cdot L_{ch}} \qquad 23.2.3$$

where A_{ch} is the cross-sectional area of flow in the channel for a given depth of water (m^2), V_{ch} is the volume of water stored in the channel (m^3), and L_{ch} is the channel length (km). Equation 23.1.4 is rearranged to calculate the depth of flow for a given time step:

$$depth = \sqrt{\frac{A_{ch}}{z_{ch}} + \left(\frac{W_{btm}}{2 \cdot z_{ch}}\right)^2} - \frac{W_{btm}}{2 \cdot z_{ch}} \qquad 23.2.4$$

where $depth$ is the depth of flow (m), A_{ch} is the cross-sectional area of flow in the channel for a given depth of water (m^2), W_{btm} is the bottom width of the channel (m), and z_{ch} is the inverse of the channel side slope. Equation 23.2.4 is valid only when all water is contained in the channel. If the volume of water in the reach segment has filled the channel and is in the flood plain, the depth is calculated:

$$depth = depth_{bnkfull} + \sqrt{\frac{\left(A_{ch} - A_{ch,bnkfull}\right)}{z_{fld}} + \left(\frac{W_{btm,fld}}{2 \cdot z_{fld}}\right)^2} - \frac{W_{btm,fld}}{2 \cdot z_{fld}} \qquad 23.2.5$$

where $depth$ is the depth of flow (m), $depth_{bnkfull}$ is the depth of water in the channel when filled to the top of the bank (m), A_{ch} is the cross-sectional area of flow in the channel for a given depth of water (m^2), $A_{ch,bnkfull}$ is the cross-sectional area of flow in the channel when filled to the top of the bank (m^2), $W_{btm,fld}$ is the bottom width of the flood plain (m), and z_{fld} is the inverse of the flood plain side slope.

Once the depth is known, the wetting perimeter and hydraulic radius are calculated using equations 23.1.5 (or 23.1.10) and 23.1.6. At this point, all values required to calculate the flow rate and velocity are known and equations 23.2.1 and 23.2.2 can be solved.

Table 23-2: SWAT input variables that pertain to channel flow calculations.

Variable name	**Definition**	**File Name**
CH_S(2)	*slp*$_{ch}$: Average channel slope along channel length (m m^{-1})	.rte
CH_N(2)	*n*: Manning's "n" value for the main channel	.rte
CH_L(2)	*L*$_{ch}$: Length of main channel (km)	.rte

23.3 VARIABLE STORAGE ROUTING METHOD

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, storage routing is based on the continuity equation:

$$V_{in} - V_{out} = \Delta V_{stored} \qquad 23.3.1$$

where V_{in} is the volume of inflow during the time step (m^3 H_2O), V_{out} is the volume of outflow during the time step (m^3 H_2O), and ΔV_{stored} is the change in volume of storage during the time step (m^3 H_2O). This equation can be written as

$$\Delta t \cdot \left(\frac{q_{in,1} + q_{in,2}}{2} \right) - \Delta t \cdot \left(\frac{q_{out,1} + q_{out,2}}{2} \right) = V_{stored,2} - V_{stored,1} \qquad 23.3.2$$

where Δt is the length of the time step (s), $q_{in,1}$ is the inflow rate at the beginning of the time step (m^3/s), $q_{in,2}$ is the inflow rate at the end of the time step (m^3/s), $q_{out,1}$ is the outflow rate at the beginning of the time step (m^3/s), $q_{out,2}$ is the outflow rate at the end of the time step (m^3/s), $V_{stored,1}$ is the storage volume at the beginning of the time step (m^3 H_2O), and $V_{stored,2}$ is the storage volume at the end of the time step (m^3 H_2O). Rearranging equation 23.3.2 so that all known variables are on the left side of the equation,

$$q_{in,ave} + \frac{V_{stored,1}}{\Delta t} - \frac{q_{out,1}}{2} = \frac{V_{stored,2}}{\Delta t} + \frac{q_{out,2}}{2} \qquad 23.3.3$$

where $q_{in,ave}$ is the average inflow rate during the time step: $q_{in,ave} = \frac{q_{in,1} + q_{in,2}}{2}$.

Travel time is computed by dividing the volume of water in the channel by the flow rate.

$$TT = \frac{V_{stored}}{q_{out}} = \frac{V_{stored,1}}{q_{out,1}} = \frac{V_{stored,2}}{q_{out,2}} \tag{23.3.4}$$

where TT is the travel time (s), V_{stored} is the storage volume (m^3 H_2O), and q_{out} is the discharge rate (m^3/s).

To obtain a relationship between travel time and the storage coefficient, equation 23.3.4 is substituted into equation 23.3.3:

$$q_{in,ave} + \frac{V_{stored,1}}{\left(\frac{\Delta t}{TT}\right)\cdot\left(\frac{V_{stored,1}}{q_{out,1}}\right)} - \frac{q_{out,1}}{2} = \frac{V_{stored,2}}{\left(\frac{\Delta t}{TT}\right)\cdot\left(\frac{V_{stored,2}}{q_{out,2}}\right)} + \frac{q_{out,2}}{2} \tag{23.3.5}$$

which simplifies to

$$q_{out,2} = \left(\frac{2\cdot\Delta t}{2\cdot TT + \Delta t}\right)\cdot q_{in,ave} + \left(1 - \frac{2\cdot\Delta t}{2\cdot TT + \Delta t}\right)\cdot q_{out,1} \tag{23.3.6}$$

This equation is similar to the coefficient method equation

$$q_{out,2} = SC\cdot q_{in,ave} + (1 - SC)\cdot q_{out,1} \tag{23.3.7}$$

where SC is the storage coefficient. Equation 23.3.7 is the basis for the SCS convex routing method (SCS, 1964) and the Muskingum method (Brakensiek, 1967; Overton, 1966). From equation 23.3.6, the storage coefficient in equation 23.3.7 is defined as

$$SC = \frac{2\cdot\Delta t}{2\cdot TT + \Delta t} \tag{23.3.8}$$

It can be shown that

$$(1 - SC)\cdot q_{out} = SC\cdot\frac{V_{stored}}{\Delta t} \tag{23.3.9}$$

Substituting this into equation 23.3.7 gives

$$q_{out,2} = SC\cdot\left(q_{in,ave} + \frac{V_{stored,1}}{\Delta t}\right) \tag{23.3.10}$$

To express all values in units of volume, both sides of the equation are multiplied by the time step

$$V_{out,2} = SC\cdot\left(V_{in} + V_{stored,1}\right) \tag{23.3.11}$$

23.4 MUSKINGUM ROUTING METHOD

The Muskingum routing method models the storage volume in a channel length as a combination of wedge and prism storages (Figure 23-3).

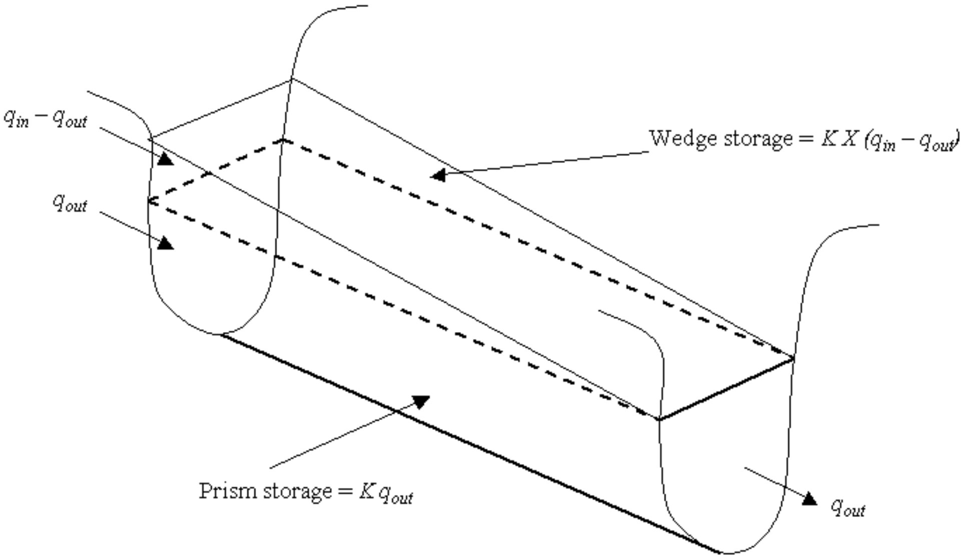

Figure 23-3: Prism and wedge storages in a reach segment (After Chow et al., 1988)

When a flood wave advances into a reach segment, inflow exceeds outflow and a wedge of storage is produced. As the flood wave recedes, outflow exceeds inflow in the reach segment and a negative wedge is produced. In addition to the wedge storage, the reach segment contains a prism of storage formed by a volume of constant cross-section along the reach length.

As defined by Manning's equation (equation 23.2.1), the cross-sectional area of flow is assumed to be directly proportional to the discharge for a given reach segment. Using this assumption, the volume of prism storage can be expressed as a function of the discharge, $K \cdot q_{out}$, where K is the ratio of storage to discharge and has the dimension of time. In a similar manner, the volume of wedge storage can be expressed as $K \cdot X \cdot (q_{in} - q_{out})$, where X is a weighting factor that controls the relative importance of inflow and outflow in determining the storage in a reach. Summing these terms gives a value for total storage

$$V_{stored} = K \cdot q_{out} + K \cdot X \cdot (q_{in} - q_{out}) \qquad 23.4.1$$

where V_{stored} is the storage volume (m^3 H$_2$O), q_{in} is the inflow rate (m^3/s), q_{out} is the discharge rate (m^3/s), K is the storage time constant for the reach (s), and X is the weighting factor. This equation can be rearranged to the form

$$V_{stored} = K \cdot \left(X \cdot q_{in} + (1 - X) \cdot q_{out} \right) \qquad 23.4.2$$

This format is similar to equation 23.3.7.

The weighting factor, X, has a lower limit of 0.0 and an upper limit of 0.5. This factor is a function of the wedge storage. For reservoir-type storage, there is no wedge and $X = 0.0$. For a full-wedge, $X = 0.5$. For rivers, X will fall between 0.0 and 0.3 with a mean value near 0.2.

The definition for storage volume in equation 23.4.2 can be incorporated into the continuity equation (equation 23.3.2) and simplified to

$$q_{out,2} = C_1 \cdot q_{in,2} + C_2 \cdot q_{in,1} + C_3 \cdot q_{out,1} \qquad 23.4.3$$

where $q_{in,1}$ is the inflow rate at the beginning of the time step (m^3/s), $q_{in,2}$ is the inflow rate at the end of the time step (m^3/s), $q_{out,1}$ is the outflow rate at the beginning of the time step (m^3/s), $q_{out,2}$ is the outflow rate at the end of the time step (m^3/s), and

$$C_1 = \frac{\Delta t - 2 \cdot K \cdot X}{2 \cdot K \cdot (1 - X) + \Delta t} \qquad 23.4.4$$

$$C_2 = \frac{\Delta t + 2 \cdot K \cdot X}{2 \cdot K \cdot (1 - X) + \Delta t} \qquad 23.4.5$$

$$C_3 = \frac{2 \cdot K \cdot (1 - X) - \Delta t}{2 \cdot K \cdot (1 - X) + \Delta t} \qquad 23.4.6$$

where $C_1 + C_2 + C_3 = 1$. To express all values in units of volume, both sides of equation 23.4.3 are multiplied by the time step

$$V_{out,2} = C_1 \cdot V_{in,2} + C_2 \cdot V_{in,1} + C_3 \cdot V_{out,1} \qquad 23.4.7$$

To maintain numerical stability and avoid the computation of negative outflows, the following condition must be met:

$$2 \cdot K \cdot X < \Delta t < 2 \cdot K \cdot (1 - X) \qquad 23.4.8$$

The value for the weighting factor, X, is input by the user. The value for the storage time constant is estimated as:

$$K = coef_1 \cdot K_{bnkfull} + coef_2 \cdot K_{0.1bnkfull} \qquad 23.4.9$$

where K is the storage time constant for the reach segment (s), $coef_1$ and $coef_2$ are weighting coefficients input by the user, $K_{bnkfull}$ is the storage time constant calculated for the reach segment with bankfull flows (s), and $K_{0.1bnkfull}$ is the storage time constant calculated for the reach segment with one-tenth of the bankfull flows (s). To calculate $K_{bnkfull}$ and $K_{0.1bnkfull}$, an equation developed by Cunge (1969) is used:

$$K = \frac{1000 \cdot L_{ch}}{c_k} \qquad 23.4.10$$

where K is the storage time constant (s), L_{ch} is the channel length (km), and c_k is the celerity corresponding to the flow for a specified depth (m/s). Celerity is the velocity with which a variation in flow rate travels along the channel. It is defined as

$$c_k = \frac{d}{dA_{ch}}\left(q_{ch}\right) \qquad 23.4.11$$

where the flow rate, q_{ch}, is defined by Manning's equation. Differentiating equation 23.2.1 with respect to the cross-sectional area gives

$$c_k = \frac{5}{3} \cdot \left(\frac{R_{ch}^{2/3} \cdot slp_{ch}^{1/2}}{n} \right) = \frac{5}{3} \cdot v_c \qquad 23.4.12$$

where c_k is the celerity (m/s), R_{ch} is the hydraulic radius for a given depth of flow (m), slp_{ch} is the slope along the channel length (m/m), n is Manning's "n" coefficient for the channel, and v_c is the flow velocity (m/s).

Table 23-3: SWAT input variables that pertain to Muskingum routing.

Variable name	Definition	File Name
MSK_X	X: weighting factor	.bsn
MSK_CO1	$coef_1$: weighting factor for influence of normal flow on storage time constant value	.bsn
MSK_CO2	$coef_2$: weighting factor for influence of low flow on storage time constant	.bsn

23.5 TRANSMISSION LOSSES

The classification of a stream as ephemeral, intermittent or perennial is a function of the amount of groundwater contribution received by the stream. Ephemeral streams contain water during and immediately after a storm event and are dry the rest of the year. Intermittent streams are dry part of the year, but contain flow when the groundwater is high enough as well as during and after a storm event. Perennial streams receive continuous groundwater contributions and flow throughout the year.

During periods when a stream receives no groundwater contributions, it is possible for water to be lost from the channel via transmission through the side and bottom of the channel. Transmission losses are estimated with the equation

$$tloss = K_{ch} \cdot TT \cdot P_{ch} \cdot L_{ch} \qquad 23.5.1$$

where *tloss* are the channel transmission losses (m^3 H_2O), K_{ch} is the effective hydraulic conductivity of the channel alluvium (mm/hr), TT is the flow travel time (hr), P_{ch} is the wetted perimeter (m), and L_{ch} is the channel length (km). Transmission losses from the main channel are assumed to enter bank storage or the deep aquifer.

Typical values for K_{ch} for various alluvium materials are given in Table 23-4. For perennial streams with continuous groundwater contribution, the effective conductivity will be zero.

Table 23-4: Example hydraulic conductivity values for various bed materials (from Lane, 1983).

Bed material group	**Bed material characteristics**	**Hydraulic conductivity**
1 Very high loss rate	Very clean gravel and large sand	> 127 mm/hr
2 High loss rate	Clean sand and gravel, field conditions	51-127 mm/hr
3 Moderately high loss rate	Sand and gravel mixture with low silt-clay content	25-76 mm/hr
4 Moderate loss rate	Sand and gravel mixture with high silt-clay content	6-25 mm/hr
5 Insignificant to low loss rate	Consolidated bed material; high silt-clay content	0.025-2.5 mm/hr

Table 23-5: SWAT input variables that pertain to transmission losses.

Variable name	Definition	File Name
CH_K(2)	K_{ch}: Effective hydraulic conductivity of channel (mm/hr)	.rte
CH_L(2)	L_{ch}: Length of main channel (km)	.rte

23.6 EVAPORATION LOSSES

Evaporation losses from the reach are calculated:

$$E_{ch} = coef_{ev} \cdot E_o \cdot L_{ch} \cdot W \cdot fr_{\Delta t} \qquad 23.6.1$$

where E_{ch} is the evaporation from the reach for the day (m^3 H_2O), $coef_{ev}$ is an evaporation coefficient, E_o is potential evaporation (mm H_2O), L_{ch} is the channel length (km), W is the channel width at water level (m), and $fr_{\Delta t}$ is the fraction of the time step in which water is flowing in the channel.

The evaporation coefficient is a calibration parameter for the user and is allowed to vary between 0.0 and 1.0.

The fraction of the time step in which water is flowing in the channel is calculated by dividing the travel time by the length of the time step.

Table 23-6: SWAT input variables that pertain to evaporation losses.

Variable name	Definition	File Name
EVRCH	$coef_{ev}$: Reach evaporation adjustment factor	.bsn
CH_L(2)	L_{ch}: Length of main channel (km)	.rte

23.7 BANK STORAGE

The amount of water entering bank storage on a given day is calculated:

$$bnk_{in} = tloss \cdot (1 - fr_{trns}) \qquad 23.7.1$$

where bnk_{in} is the amount of water entering bank storage (m^3 H_2O), $tloss$ are the channel transmission losses (m^3 H_2O), and fr_{trns} is the fraction of transmission losses partitioned to the deep aquifer.

Bank storage contributes flow to the main channel or reach within the subbasin. Bank flow is simulated with a recession curve similar to that used for groundwater. The volume of water entering the reach from bank storage is calculated:

$$V_{bnk} = bnk \cdot (1 - \alpha_{bnk}) \qquad 23.7.2$$

where V_{bnk} is the volume of water added to the reach via return flow from bank storage (m^3 H_2O), bnk is the total amount of water in bank storage (m^3 H_2O), and α_{bnk} is the bank flow recession constant or constant of proportionality.

Water may move from bank storage into an adjacent unsaturated zone. SWAT models the movement of water into adjacent unsaturated areas as a function of water demand for evapotranspiration. To avoid confusion with soil evaporation and transpiration, this process has been termed 'revap'. This process is significant in watersheds where the saturated zone is not very far below the surface or where deep-rooted plants are growing. 'Revap' from bank storage is governed by the groundwater revap coefficient defined for the last HRU in the subbasin.

The maximum amount of water than will be removed from bank storage via 'revap' on a given day is:

$$bnk_{revap,mx} = \beta_{rev} \cdot E_o \cdot L_{ch} \cdot W \qquad 23.7.3$$

where $bnk_{revap,mx}$ is the maximum amount of water moving into the unsaturated zone in response to water deficiencies (m^3 H_2O), β_{rev} is the revap coefficient, E_o is the potential evapotranspiration for the day (mm H_2O), L_{ch} is the channel length (km), and W is the width of the channel at water level (m). The actual amount of revap that will occur on a given day is calculated:

$$bnk_{revap} = bnk \qquad \text{if } bnk < bnk_{revap,mx} \qquad 23.7.4$$

$$bnk_{revap} = bnk_{revap,mx} \qquad \text{if } bnk \geq bnk_{revap,mx} \qquad 23.7.5$$

where bnk_{revap} is the actual amount of water moving into the unsaturated zone in response to water deficiencies (m^3 H_2O), $bnk_{revap,mx}$ is the maximum amount of water moving into the unsaturated zone in response to water deficiencies (m^3 H_2O), and bnk is the amount of water in bank storage at the beginning of day i (m^3 H_2O).

Table 23-7: SWAT input variables that pertain to bank storage.

Variable name	Definition	File Name
TRNSRCH	fr_{trns}: Fraction of transmission losses partitioned to the deep aquifer	.bsn
ALPHA_BNK	α_{bnk}: Bank flow recession constant or constant of proportionality	.rte
GW_REVAP	β_{rev}: Revap coefficient	.gw

23.8 CHANNEL WATER BALANCE

Water storage in the reach at the end of the time step is calculated:

$$V_{stored,2} = V_{stored,1} + V_{in} - V_{out} - tloss - E_{ch} + div + V_{bnk} \qquad 23.8.1$$

where $V_{stored,2}$ is the volume of water in the reach at the end of the time step (m^3 H_2O), $V_{stored,1}$ is the volume of water in the reach at the beginning of the time step (m^3 H_2O), V_{in} is the volume of water flowing into the reach during the time step (m^3 H_2O), V_{out} is the volume of water flowing out of the reach during the time step (m^3 H_2O), $tloss$ is the volume of water lost from the reach via transmission through the bed (m^3 H_2O), E_{ch} is the evaporation from the reach for the day (m^3 H_2O), div is the volume of water added or removed from the reach for the day through diversions (m^3 H_2O), and V_{bnk} is the volume of water added to the reach via return flow from bank storage (m^3 H_2O).

SWAT treats the volume of outflow calculated with equation 23.3.11 or 23.4.7 as the net amount of water removed from the reach. As transmission losses, evaporation and other water losses for the reach segment are calculated, the amount of outflow to the next reach segment is reduced by the amount of the loss. When outflow and all losses are summed, the total amount will equal the value obtained from 23.3.11 or 23.4.7.

23.9 NOMENCLATURE

A_{ch}	Cross-sectional area of flow in the channel (m^2)
$A_{ch,bnkfull}$	Cross-sectional area of flow in the channel when filled to the top of the bank (m^2)
C_1	Coefficient in Muskingum flood routing equation
C_2	Coefficient in Muskingum flood routing equation
C_3	Coefficient in Muskingum flood routing equation
E_{ch}	Evaporation from the reach for the day (m^3 H_2O)
E_o	Potential evapotranspiration (mm d^{-1})
K	Storage time constant for the reach (s)
$K_{0.1bnkfull}$	Storage time constant calculated for the reach segment with one-tenth of the bankfull flows (s)
$K_{bnkfull}$	Storage time constant calculated for the reach segment with bankfull flows (s)
K_{ch}	Effective hydraulic conductivity of the channel alluvium (mm/hr)
L_{ch}	Length of main channel (km)
P_{ch}	Wetted perimeter for a given depth of flow (m)
R_{ch}	Hydraulic radius for a given depth of flow (m)
SC	Storage coefficient for variable storage flow routing
TT	Travel time (s)
V_{bnk}	Volume of water added to the reach via return flow from bank storage (m^3 H_2O)
V_{ch}	Volume of water stored in the channel (m^3)
V_{in}	Volume of inflow during the time step (m^3 H_2O)
V_{out}	Volume of outflow during the time step (m^3 H_2O)
V_{stored}	Volume of water stored in water body or channel (m^3 H_2O)
W	Width of channel at water level (m)
$W_{bnkfull}$	Top width of the channel when filled with water (m)
W_{btm}	Bottom width of the channel (m)
$W_{btm,fld}$	Bottom width of the flood plain (m)
X	Weighting factor in Muskingum routing

bnk	Total amount of water in bank storage (m^3 H_2O)
bnk_{in}	Amount of water entering bank storage (m^3 H_2O)
$bnk_{revap,mx}$	Maximum amount of water moving into the unsaturated zone in response to water deficiencies (m^3 H_2O)
c_k	Celerity corresponding to the flow for a specified depth (m/s)
$coef_1$	Weighting coefficient for storage time constant calculation
$coef_2$	Weighting coefficient for storage time constant calculation
$coef_{ev}$	Evaporation coefficient
$depth$	Depth of water in the channel (m)
$depth_{bnkfull}$	Depth of water in the channel when filled to the top of the bank (m)
$depth_{fld}$	Depth of water in the flood plain (m)
div	Volume of water added or removed from the reach for the day through diversions (m^3 H_2O)
fr_{trns}	Fraction of transmission losses partitioned to the deep aquifer

$fr_{\Delta t}$	Fraction of the time step in which water is flowing in the channel
n	Manning's roughness coefficient for the subbasin or channel
q_{ch}	Average channel flow rate (m^3 s^{-1})
q_{in}	Inflow rate (m^3/s)
q_{out}	Outflow rate (m^3/s)
slp_{ch}	Average channel slope along channel length (m m^{-1})
$tloss$	Channel transmission losses (m^3 H_2O)
v_c	Average channel velocity (m s^{-1})
z_{ch}	Inverse of the channel side slope
z_{fld}	Inverse of the flood plain side slope
α_{bnk}	Bank flow recession constant or constant of proportionality
β_{rev}	Revap coefficient
Δt	Length of the time step (s)

23.10 REFERENCES

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CHAPTER 24

EQUATIONS: SEDIMENT ROUTING

Sediment transport in the channel network is a function of two processes, deposition and degradation, operating simultaneously in the reach. SWAT will compute deposition and degradation using the same channel dimensions for the entire simulation. Alternatively, SWAT will simulate downcutting and widening of the stream channel and update channel dimensions throughout the simulation.

24.1 SEDIMENT CHANNEL ROUTING

Previous versions of SWAT used stream power to predict degradation and fall velocity to estimate deposition in the channels (Arnold et al, 1995). Williams (1980) used Bagnold's (1977) definition of stream power to develop a method for determining degradation as a function of channel slope and velocity. In this version, the equations have been 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:

$$v_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}} \qquad 24.1.1$$

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:

$$q_{ch,pk} = prf \cdot q_{ch} \qquad 24.1.2$$

where prf is the peak rate adjustment factor, and q_{ch} is the average rate of flow (m^3/s). Calculation of the average rate of flow, q_{ch}, and the cross-sectional area of flow, A_{ch}, is reviewed in Chapter 23.

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

$$conc_{sed,ch,mx} = c_{sp} \cdot v_{ch,pk}^{\ spexp} \qquad 24.1.3$$

where $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (ton/m^3 or kg/L), 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 1.0 and 2.0 and was set at 1.5 in the original Bagnold stream power equation (Arnold et al., 1995).

The maximum concentration of sediment calculated with equation 24.1.3 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:

$$sed_{dep} = \left(conc_{sed,ch,i} - conc_{sed,ch,mx}\right) \cdot V_{ch} \tag{24.1.4}$$

where sed_{dep} is the amount of sediment deposited in the reach segment (metric tons), $conc_{sed,ch,i}$ is the initial sediment concentration in the reach (kg/L or ton/m^3), $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (kg/L or ton/m^3), and V_{ch} is the volume of water in the reach segment (m^3 H_2O).

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:

$$sed_{deg} = \left(conc_{sed,ch,mx} - conc_{sed,ch,i}\right) \cdot V_{ch} \cdot K_{CH} \cdot C_{CH} \tag{24.1.5}$$

where sed_{deg} is the amount of sediment reentrained in the reach segment (metric tons), $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (kg/L or ton/m^3), $conc_{sed,ch,i}$ is the initial sediment concentration in the reach (kg/L or ton/m^3), V_{ch} is the volume of water in the reach segment (m^3 H_2O), 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:

$$sed_{ch} = sed_{ch,i} - sed_{dep} + sed_{deg} \tag{24.1.6}$$

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), sed_{dep} is the amount of sediment deposited in the reach segment (metric tons), and sed_{deg} is the amount of sediment reentrained in the reach segment (metric tons).

The amount of sediment transported out of the reach is calculated:

$$sed_{out} = sed_{ch} \cdot \frac{V_{out}}{V_{ch}} \tag{24.1.7}$$

where sed_{out} is the amount of sediment transported out of the reach (metric tons), sed_{ch} is the amount of suspended sediment in the reach (metric tons), V_{out} is the volume of outflow during the time step (m^3 H_2O), and V_{ch} is the volume of water in the reach segment (m^3 H_2O).

24.1.1 CHANNEL ERODIBILITY FACTOR

The channel erodibility factor is conceptually similar to the soil erodibility factor used in the USLE equation. Channel erodibility is a function of properties of the bed or bank materials.

Channel erodibility can be measured with a submerged vertical jet device. The basic premise of the test is that erosion of a vegetated or bare channel and local scour beneath an impinging jet are the result of hydraulic stresses, boundary geometry, and the properties of the material being eroded. Hanson (1990) developed a method for determining the erodibility coefficient of channels *in situ* with the submerged vertical jet. Allen et al. (1999) utilized this method to determine channel erodibility factors for thirty sites in Texas.

A submerged, vertical jet of water directed perpendicularly at the channel bed causes erosion of the bed material in the vicinity of the jet impact area (Figure 24-1). Important variables in the erosion process are: the volume of material removed during a jetting event, elevation of the jet above the ground surface, diameter of the jet nozzle, jet velocity, time, mass density of the fluid and coefficient of erodibility.

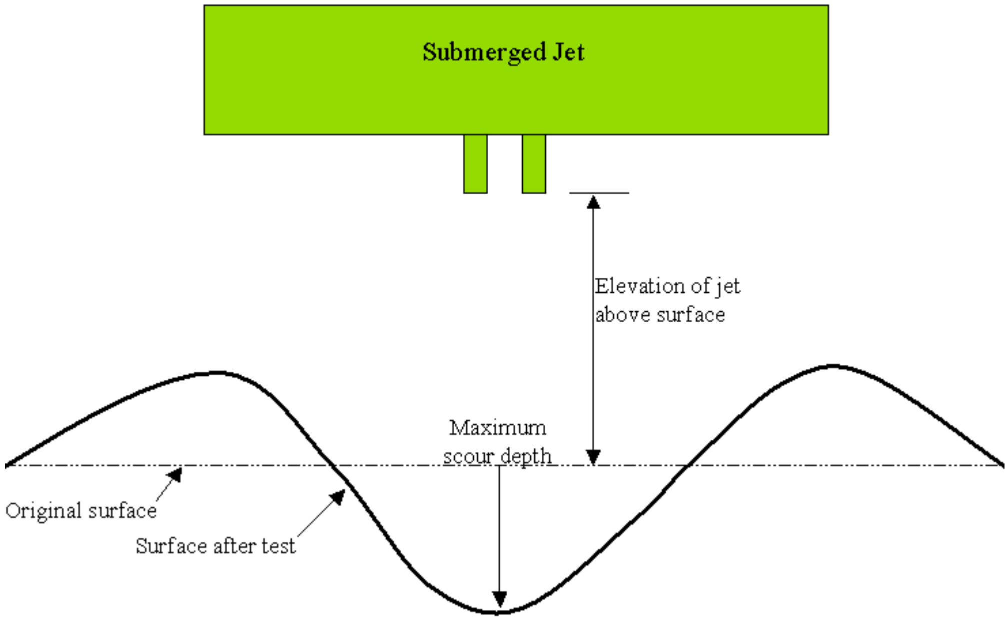

Figure 24-1: Simplified cross-section of submerged jet test (After Allen et al, 1999).

Hanson (1991) defined a jet index, J_i, to relate erodibility to scour created by the submerged jet. The jet index is a function of the depth of scour beneath the jet per unit time and the jet velocity. The jet index is determined by a least squares fit following the procedures outlined in ASTM standard D 5852-95.

Once the jet index is determined, the channel erodibility coefficient is calculated:

$$K_{CH} = 0.003 \cdot \exp\left[385 \cdot J_i\right] \qquad 24.1.8$$

where K_{CH} is the channel erodibility coefficient (cm/h/Pa) and J_i is the jet index. In general, values for channel erodibility are an order of magnitude smaller than values for soil erodibility.

24.1.2 CHANNEL COVER FACTOR

The channel cover factor, C_{CH}, is defined as the ratio of degradation from a channel with a specified vegetative cover to the corresponding degradation from a channel with no vegetative cover. The vegetation affects degradation by reducing the stream velocity, and consequently its erosive power, near the bed surface.

Table 24-1: SWAT input variables that pertain to sediment routing.

Variable Name	Definition	Input File
PRF	*prf*: Peak rate adjustment factor	.bsn
SPCON	c_{sp}: Coefficient in sediment transport equation	.bsn
SPEXP	*spexp*: Exponent in sediment transport equation	.bsn
CH_COV	C_{CH}: Channel cover factor	.rte
CH_EROD	K_{CH}: Channel erodibility factor (cm/hr/Pa)	.rte

24.2 CHANNEL DOWNCUTTING AND WIDENING

While sediment transport calculations have traditionally been made with the same channel dimensions throughout a simulation, SWAT will model channel downcutting and widening. 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}. Channel dimensions are updated using the following equations when the volume of water in the reach exceeds 1.4×10^6 m^3.

The amount of downcutting is calculated (Allen et al., 1999):

$$depth_{dcut} = 358 \cdot depth \cdot slp_{ch} \cdot K_{CH} \qquad 24.2.1$$

where $depth_{dcut}$ is the amount of downcutting (m), $depth$ is the depth of water in channel (m), slp_{ch} is the channel slope (m/m), and K_{CH} is the channel erodibility coefficient (cm/h/Pa).

The new bankfull depth is calculated:

$$depth_{bnkfull} = depth_{bnkfull,i} + depth_{dcut} \qquad 24.2.2$$

where $depth_{bnkfull}$ is the new bankfull depth (m), $depth_{bnkfull,i}$ is the previous bankfull depth, and $depth_{dcut}$ is the amount of downcutting (m).

The new bank width is calculated:

$$W_{bnkfull} = ratio_{WD} \cdot depth_{bnkfull} \qquad 24.2.3$$

where $W_{bnkfull}$ is the new width of the channel at the top of the bank (m), $ratio_{WD}$ is the channel width to depth ratio, and $depth_{bnkfull}$ is the new bankfull depth (m).

The new channel slope is calculated:

$$slp_{ch} = slp_{ch,i} - \frac{depth_{dcut}}{1000 \cdot L_{ch}} \qquad 24.2.4$$

where slp_{ch} is the new channel slope (m/m), $slp_{ch,i}$ is the previous channel slope (m/m), $depth_{bnkfull}$ is the new bankfull depth (m), and L_{ch} is the channel length (km).

Table 24-2: SWAT input variables that pertain to channel downcutting and widening.

Variable Name	**Definition**	**Input File**
IDEG	Channel degradation code	.cod
CH_WDR	$ratio_{WD}$: Channel width to depth ratio	.rte

24.3 NOMENCLATURE

A_{ch}	Cross-sectional area of flow in the channel (m^2)
C_{CH}	Channel cover factor
J_i	Jet index used to calculate channel erodibility
K_{CH}	Channel erodibility factor (cm/hr/Pa)
L_{ch}	Channel length (km)
V_{ch}	Volume of water in the reach segment (m^3 H_2O)
V_{out}	Volume of outflow during the time step (m^3 H_2O)
$W_{bnkfull}$	Top width of the channel when filled with water (m)

c_{sp}	Coefficient in sediment transport equation
$conc_{sed,ch,i}$	Initial sediment concentration in the reach (kg/L or ton/m^3)
$conc_{sed,ch,mx}$	Maximum concentration of sediment that can be transported by the water (kg/L or ton/m^3)
$depth$	Depth of water in channel (m)
$depth_{bnkfull}$	Depth of water in the channel when filled to the top of the bank (m)
$depth_{dcut}$	Amount of downcutting (m)
prf	Peak rate adjustment factor
q_{ch}	Average rate of flow in the channel (m^3/s)
$q_{ch,pk}$	Peak flow rate (m^3/s)
$ratio_{WD}$	Channel width to depth ratio
sed_{ch}	Amount of suspended sediment in the reach (metric tons)
sed_{deg}	Amount of sediment reentrained in the reach segment (metric tons)
sed_{dep}	Amount of sediment deposited in the reach segment (metric tons)
sed_{out}	Amount of sediment transported out of the reach (metric tons)
slp_{ch}	Average channel slope along channel length (m m^{-1})
$spexp$	Exponent in sediment transport equation
$v_{ch,pk}$	Peak channel velocity (m/s)

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CHAPTER 25

EQUATIONS: IN-STREAM NUTRIENT PROCESSES

Parameters which affect water quality and can be considered pollution indicators include nutrients, total solids, biological oxygen demand, nitrates, and microorganisms (Loehr, 1970; Paine, 1973). Parameters of secondary importance include odor, taste, and turbidity (Azevedo and Stout, 1974).

The SWAT in-stream water quality algorithms incorporate constituent interactions and relationships used in the QUAL2E model (Brown and Barnwell, 1987). The documentation provided in this chapter has been taken from Brown and Barnwell (1987). The modeling of in-stream nutrient transformations has been made an optional feature of SWAT. To route nutrient loadings downstream without simulating transformations, the variable IWQ in the input control code (.cod) file should be set to 0. To activate the simulation of in-stream nutrient transformations, this variable should be set to 1.

25.1 ALGAE

During the day, algae increase the stream's dissolved oxygen concentration via photosynthesis. At night, algae reduce the concentration via respiration. As algae grow and die, they form part of the in-stream nutrient cycle. This section summarizes the equations used to simulate algal growth in the stream.

25.1.1 CHLOROPHYLL *a*

Chlorophyll *a* is assumed to be directly proportional to the concentration of phytoplanktonic algal biomass.

$$chla = \alpha_0 \cdot algae \qquad 25.1.1$$

where $chla$ is the chlorophyll *a* concentration (μg chla/L), α_0 is the ratio of chlorophyll *a* to algal biomass (μg chla/mg alg), and $algae$ is the algal biomass concentration (mg alg/L).

25.1.2 ALGAL GROWTH

Growth and decay of algae/chlorophyll *a* is calculated as a function of the growth rate, the respiration rate, the settling rate and the amount of algae present in the stream. The change in algal biomass for a given day is:

$$\Delta algae = \left((\mu_a \cdot algae) - (\rho_a \cdot algae) - \left(\frac{\sigma_1}{depth} \cdot algae \right) \right) \cdot TT \qquad 25.1.2$$

where $\Delta algae$ is the change in algal biomass concentration (mg alg/L), μ_a is the local specific growth rate of algae (day^{-1}), ρ_a is the local respiration or death rate of algae (day^{-1}), σ_1 is the local settling rate for algae (m/day), $depth$ is the depth of water in the channel (m), $algae$ is the algal biomass concentration at the beginning of the day (mg alg/L), and *TT* is the flow travel time in the reach segment (day). The calculation of depth and travel time are reviewed in Chapter 23.

25.1.2.1 LOCAL SPECIFIC GROWTH RATE OF ALGAE

The local specific growth rate of algae is a function of the availability of required nutrients, light and temperature. SWAT first calculates the growth rate at 20°C and then adjusts the growth rate for water temperature. The user has three options for calculating the impact of nutrients and light on growth: multiplicative, limiting nutrient, and harmonic mean.

The multiplicative option multiplies the growth factors for light, nitrogen and phosphorus together to determine their net effect on the local algal growth rate. This option has its biological basis in the mutiplicative effects of enzymatic processes involved in photosynthesis:

$$\mu_{a,20} = \mu_{max} \cdot FL \cdot FN \cdot FP \qquad 25.1.3$$

where $\mu_{a,20}$ is the local specific algal growth rate at 20°C (day^{-1}), μ_{max} is the maximum specific algal growth rate (day^{-1}), *FL* is the algal growth attenuation factor for light, *FN* is the algal growth limitation factor for nitrogen, and *FP* is the algal growth limitation factor for phosphorus. The maximum specific algal growth rate is specified by the user.

The limiting nutrient option calculates the local algal growth rate as limited by light and either nitrogen or phosphorus. The nutrient/light effects are multiplicative, but the nutrient/nutrient effects are alternate. The algal growth rate is controlled by the nutrient with the smaller growth limitation factor. This approach mimics Liebig's law of the minimum:

$$\mu_{a,20} = \mu_{max} \cdot FL \cdot \min(FN, \quad FP) \qquad 25.1.4$$

where $\mu_{a,20}$ is the local specific algal growth rate at 20°C (day^{-1}), μ_{max} is the maximum specific algal growth rate (day^{-1}), *FL* is the algal growth attenuation factor for light, *FN* is the algal growth limitation factor for nitrogen, and *FP* is the algal growth limitation factor for phosphorus. The maximum specific algal growth rate is specified by the user.

The harmonic mean is mathematically analogous to the total resistance of two resistors in parallel and can be considered a compromise between equations 25.1.3 and 25.1.4. The algal growth rate is controlled by a multiplicative relation between light and nutrients, while the nutrient/nutrient interactions are represented by a harmonic mean.

$$\mu_{a,20} = \mu_{max} \cdot FL \cdot \frac{2}{\left(\frac{1}{FN} + \frac{1}{FP} \right)} \qquad 25.1.5$$

where $\mu_{a,20}$ is the local specific algal growth rate at 20°C (day^{-1}), μ_{max} is the maximum specific algal growth rate (day^{-1}), *FL* is the algal growth attenuation factor for light, *FN* is the algal growth limitation factor for nitrogen, and *FP* is the algal growth limitation factor for phosphorus. The maximum specific algal growth rate is specified by the user.

Calculation of the growth limiting factors for light, nitrogen and phosphorus are reviewed in the following sections.

ALGAL GROWTH LIMITING FACTOR FOR LIGHT.

A number of mathematical relationships between photosynthesis and light have been developed. All relationships show an increase in photosynthetic rate with increasing light intensity up to a maximum or saturation value. The algal growth limiting factor for light is calculated using a Monod half-saturation method. In this option, the algal growth limitation factor for light is defined by a Monod expression:

$$FL_z = \frac{I_{phosyn,z}}{K_L + I_{phosyn,z}} \qquad 25.1.6$$

where FL_z is the algal growth attenuation factor for light at depth *z*, $I_{phosyn,z}$ is the photosynthetically-active light intensity at a depth *z* below the water surface (MJ/m^2-hr), and K_L is the half-saturation coefficient for light (MJ/m^2-hr). Photosynthetically-active light is radiation with a wavelength between 400 and 700 nm. The half-saturation coefficient for light is defined as the light intensity at which the algal growth rate is 50% of the maximum growth rate. The half-saturation coefficient for light is defined by the user.

Photosynthesis is assumed to occur throughout the depth of the water column. The variation in light intensity with depth is defined by Beer's law:

$$I_{phosyn,z} = I_{phosyn,hr} \exp\left(-k_{\ell} \cdot z\right) \qquad 25.1.7$$

where $I_{phosyn,z}$ is the photosynthetically-active light intensity at a depth z below the water surface (MJ/m^2-hr), $I_{phosyn,hr}$ is the photosynthetically-active solar radiation reaching the ground/water surface during a specific hour on a given day (MJ/m^2-hr), k_{ℓ} is the light extinction coefficient (m^{-1}), and z is the depth from the water surface (m). Substituting equation 25.1.7 into equation 25.1.6 and integrating over the depth of flow gives:

$$FL = \left(\frac{1}{k_{\ell} \cdot depth}\right) \cdot \ln\left[\frac{K_L + I_{phosyn,hr}}{K_L + I_{phosyn,hr} \exp\left(-k_{\ell} \cdot depth\right)}\right] \qquad 25.1.8$$

where FL is the algal growth attenuation factor for light for the water column, K_L is the half-saturation coefficient for light (MJ/m^2-hr), $I_{phosyn,hr}$ is the photosynthetically-active solar radiation reaching the ground/water surface during a specific hour on a given day (MJ/m^2-hr), k_{ℓ} is the light extinction coefficient (m^{-1}), and *depth* is the depth of water in the channel (m). The photosynthetically-active solar radiation is calculated:

$$I_{phosyn,hr} = I_{hr} \cdot fr_{phosyn} \qquad 25.1.9$$

where I_{hr} is the solar radiation reaching the ground during a specific hour on current day of simulation (MJ m^{-2} h^{-1}), and fr_{phosyn} is the fraction of solar radiation that is photosynthetically active. The calculation of I_{hr} is reviewed in Chapter 2. The fraction of solar radiation that is photosynthetically active is user defined.

For daily simulations, an average value of the algal growth attenuation factor for light calculated over the diurnal cycle must be used. This is calculated using a modified form of equation 25.1.8:

$$FL = 0.92 \cdot fr_{DL} \cdot \left(\frac{1}{k_\ell \cdot depth} \right) \cdot \ln \left[\frac{K_L + \bar{I}_{phosyn,hr}}{K_L + \bar{I}_{phosyn,hr} \exp(-k_\ell \cdot depth)} \right] \quad 25.1.10$$

where fr_{DL} is the fraction of daylight hours, $\bar{I}_{phosyn,hr}$ is the daylight average photosynthetically-active light intensity (MJ/m^2-hr) and all other variables are defined previously. The fraction of daylight hours is calculated:

$$fr_{DL} = \frac{T_{DL}}{24} \quad 25.1.11$$

where T_{DL} is the daylength (hr). $\bar{I}_{phosyn,hr}$ is calculated:

$$\bar{I}_{phosyn,hr} = \frac{fr_{phosyn} \cdot H_{day}}{T_{DL}} \quad 25.1.12$$

where fr_{phosyn} is the fraction of solar radiation that is photosynthetically active, H_{day} is the solar radiation reaching the water surface in a given day (MJ/m^2), and T_{DL} is the daylength (hr). Calculation of H_{day} and T_{DL} are reviewed in Chapter 2.

The light extinction coefficient, k_ℓ, is calculated as a function of the algal density using the nonlinear equation:

$$k_\ell = k_{\ell,0} + k_{\ell,1} \cdot \alpha_0 \cdot algae + k_{\ell,2} \cdot (\alpha_0 \cdot algae)^{2/3} \quad 25.1.13$$

where $k_{\ell,0}$ is the non-algal portion of the light extinction coefficient (m^{-1}), $k_{\ell,1}$ is the linear algal self shading coefficient (m^{-1} (µg-chla/L)$^{-1}$), $k_{\ell,2}$ is the nonlinear algal self shading coefficient (m^{-1} (µg-chla/L)$^{-2/3}$), α_0 is the ratio of chlorophyll *a* to algal biomass (µg chla/mg alg), and *algae* is the algal biomass concentration (mg alg/L).

Equation 25.1.13 allows a variety of algal, self-shading, light extinction relationships to be modeled. When $k_{\ell,1} = k_{\ell,2} = 0$, no algal self-shading is simulated. When $k_{\ell,1} \neq 0$ and $k_{\ell,2} = 0$, linear algal self-shading is modeled. When $k_{\ell,1}$ and $k_{\ell,2}$ are set to a value other than 0, non-linear algal self-shading is modeled. The Riley equation (Bowie et al., 1985) defines $k_{\ell,1} = 0.0088\ \text{m}^{-1}\left(\mu\text{g - chla/L}\right)^{-1}$ and $k_{\ell,2} = 0.054\ \text{m}^{-1}\left(\mu\text{g - chla/L}\right)^{-2/3}$.

ALGAL GROWTH LIMITING FACTOR FOR NUTRIENTS.

The algal growth limiting factor for nitrogen is defined by a Monod expression. Algae are assumed to use both ammonia and nitrate as a source of inorganic nitrogen.

$$FN = \frac{\left(C_{NO3} + C_{NH4}\right)}{\left(C_{NO3} + C_{NH4}\right) + K_N} \qquad 25.1.14$$

where FN is the algal growth limitation factor for nitrogen, C_{NO3} is the concentration of nitrate in the reach (mg N/L), C_{NH4} is the concentration of ammonium in the reach (mg N/L), and K_N is the Michaelis-Menton half-saturation constant for nitrogen (mg N/L).

The algal growth limiting factor for phosphorus is also defined by a Monod expression.

$$FP = \frac{C_{solP}}{C_{solP} + K_P} \qquad 25.1.15$$

where FP is the algal growth limitation factor for phosphorus, C_{solP} is the concentration of phosphorus in solution in the reach (mg P/L), and K_P is the Michaelis-Menton half-saturation constant for phosphorus (mg P/L).

The Michaelis-Menton half-saturation constant for nitrogen and phosphorus define the concentration of N or P at which algal growth is limited to 50% of the maximum growth rate. Users are allowed to set these values. Typical values for K_N range from 0.01 to 0.30 mg N/L while K_P will range from 0.001 to 0.05 mg P/L.

Once the algal growth rate at 20°C is calculated, the rate coefficient is adjusted for temperature effects using a Streeter-Phelps type formulation:

$$\mu_a = \mu_{a,20} \cdot 1.047^{(T_{water}-20)} \qquad 25.1.16$$

where μ_a is the local specific growth rate of algae (day^{-1}), $\mu_{a,20}$ is the local specific algal growth rate at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

25.1.2.2 LOCAL RESPIRATION RATE OF ALGAE

The local respiration or death rate of algae represents the net effect of three processes: the endogenous respiration of algae, the conversion of algal phosphorus to organic phosphorus, and the conversion of algal nitrogen to organic nitrogen. The user defines the local respiration rate of algae at 20°C. The respiration rate is adjusted to the local water temperature using the relationship:

$$\rho_a = \rho_{a,20} \cdot 1.047^{(T_{water}-20)} \qquad 25.1.17$$

where ρ_a is the local respiration rate of algae (day^{-1}), $\rho_{a,20}$ is the local algal respiration rate at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

25.1.2.3 LOCAL SETTLING RATE OF ALGAE

The local settling rate of algae represents the net removal of algae due to settling. The user defines the local settling rate of algae at 20°C. The settling rate is adjusted to the local water temperature using the relationship:

$$\sigma_1 = \sigma_{1,20} \cdot 1.024^{(T_{water}-20)} \qquad 25.1.18$$

where σ_1 is the local settling rate of algae (m/day), $\sigma_{1,20}$ is the local algal settling rate at 20°C (m/day), and T_{water} is the average water temperature for the day (°C).

Table 25-1: SWAT input variables used in algae calculations.

Variable name	Definition	File Name
AI0	α_0: Ratio of chlorophyll *a* to algal biomass (µg chla/mg alg)	.wwq
MUMAX	μ_{max}: Maximum specific algal growth rate (day^{-1})	.wwq
K_L	K_L: Half-saturation coefficient for light (MJ/m^2-hr)	.wwq
TFACT	fr_{phosyn}: Fraction of solar radiation that is photosynthetically active	.wwq
LAMBDA0	$k_{\ell,0}$: Non-algal portion of the light extinction coefficient (m^{-1})	.wwq
LAMBDA1	$k_{\ell,1}$: Linear algal self shading coefficient (m^{-1} (µg-chla/L)$^{-1}$)	.wwq
LAMBDA2	$k_{\ell,2}$: Nonlinear algal self shading coefficient (m^{-1} (µg-chla/L)$^{-2/3}$)	.wwq
K_N	K_N: Michaelis-Menton half-saturation constant for nitrogen (mg N/L)	.wwq
K_P	K_P: Michaelis-Menton half-saturation constant for phosphorus (mg P/L)	.wwq
RHOQ	$\rho_{a,20}$: Local algal respiration rate at 20°C (day^{-1})	.wwq
RS1	$\sigma_{1,20}$: Local algal settling rate at 20°C (m/day)	.swq

25.2 NITROGEN CYCLE

In aerobic water, there is a stepwise transformation from organic nitrogen to ammonia, to nitrite, and finally to nitrate. Organic nitrogen may also be removed from the stream by settling. This section summarizes the equations used to simulate the nitrogen cycle in the stream.

25.2.1 ORGANIC NITROGEN

The amount of organic nitrogen in the stream may be increased by the conversion of algal biomass nitrogen to organic nitrogen. Organic nitrogen concentration in the stream may be decreased by the conversion of organic nitrogen to NH_4^+ or the settling of organic nitrogen with sediment. The change in organic nitrogen for a given day is:

$$\Delta orgN_{str} = \left(\alpha_1 \cdot \rho_a \cdot algae - \beta_{N,3} \cdot orgN_{str} - \sigma_4 \cdot orgN_{str}\right) \cdot TT \qquad 25.2.1$$

where $\Delta orgN_{str}$ is the change in organic nitrogen concentration (mg N/L), α_1 is the fraction of algal biomass that is nitrogen (mg N/mg alg biomass), ρ_a is the local respiration or death rate of algae (day^{-1}), $algae$ is the algal biomass concentration at the beginning of the day (mg alg/L), $\beta_{N,3}$ is the rate constant for hydrolysis of organic nitrogen to ammonia nitrogen (day^{-1}), $orgN_{str}$ is the organic nitrogen concentration at the beginning of the day (mg N/L), σ_4 is the rate coefficient for organic nitrogen settling (day^{-1}), and TT is the flow travel time in the reach segment (day). The fraction of algal biomass that is nitrogen is user-defined. Equation 25.1.17 describes the calculation of the local respiration rate of algae. The calculation of travel time is reviewed in Chapter 23.

The user defines the local rate constant for hydrolysis of organic nitrogen to NH_4^+ at 20°C. The organic nitrogen hydrolysis rate is adjusted to the local water temperature using the relationship:

$$\beta_{N,3} = \beta_{N,3,20} \cdot 1.047^{(T_{water}-20)} \qquad 25.2.2$$

where $\beta_{N,3}$ is the local rate constant for hydrolysis of organic nitrogen to NH_4^+ (day^{-1}), $\beta_{N,3,20}$ is the local rate constant for hydrolysis of organic nitrogen to NH_4^+ at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

The user defines the rate coefficient for organic nitrogen settling at 20°C. The organic nitrogen settling rate is adjusted to the local water temperature using the relationship:

$$\sigma_4 = \sigma_{4,20} \cdot 1.024^{(T_{water}-20)} \qquad 25.2.3$$

where σ_4 is the local settling rate for organic nitrogen (day^{-1}), $\sigma_{4,20}$ is the local settling rate for organic nitrogen at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

25.2.2 AMMONIUM

The amount of ammonium (NH_4^+) in the stream may be increased by the mineralization of organic nitrogen and diffusion of ammonium from the streambed sediments. The ammonium concentration in the stream may be decreased by the conversion of NH_4^+ to NO_2^- or the uptake of NH_4^+ by algae. The change in ammonium for a given day is:

$$\Delta NH4_{str} = \left(\beta_{N,3} \cdot orgN_{str} - \beta_{N,1} \cdot NH4_{str} + \frac{\sigma_3}{(1000 \cdot depth)} - fr_{NH4} \cdot \alpha_1 \cdot \mu_a \cdot algae \right) \cdot TT \qquad 25.2.4$$

where $\Delta NH4_{str}$ is the change in ammonium concentration (mg N/L), $\beta_{N,3}$ is the rate constant for hydrolysis of organic nitrogen to ammonia nitrogen (day^{-1}), $orgN_{str}$ is the organic nitrogen concentration at the beginning of the day (mg N/L), $\beta_{N,1}$ is the rate constant for biological oxidation of ammonia nitrogen (day^{-1}),

$NH4_{str}$ is the ammonium concentration at the beginning of the day (mg N/L), σ_3 is the benthos (sediment) source rate for ammonium (mg N/m^2-day), *depth* is the depth of water in the channel (m), fr_{NH4} is the fraction of algal nitrogen uptake from ammonium pool, α_1 is the fraction of algal biomass that is nitrogen (mg N/mg alg biomass), μ_a is the local growth rate of algae (day^{-1}), *algae* is the algal biomass concentration at the beginning of the day (mg alg/L), and *TT* is the flow travel time in the reach segment (day). The local rate constant for hydrolysis of organic nitrogen to NH_4^+ is calculated with equation 25.2.2. Section 25.1.2.1 describes the calculation of the local growth rate of algae. The calculation of depth and travel time is reviewed in Chapter 23.

The rate constant for biological oxidation of ammonia nitrogen will vary as a function of in-stream oxygen concentration and temperature. The rate constant is calculated:

$$\beta_{N,1} = \beta_{N,1,20} \cdot \left(1 - \exp\left[-0.6 \cdot Ox_{str}\right]\right) \cdot 1.083^{(T_{water}-20)} \qquad 25.2.5$$

where $\beta_{N,1}$ is the rate constant for biological oxidation of ammonia nitrogen (day^{-1}), $\beta_{N,1,20}$ is the rate constant for biological oxidation of ammonia nitrogen at 20°C (day^{-1}), Ox_{str} is the dissolved oxygen concentration in the stream (mg O_2/L), and T_{water} is the average water temperature for the day (°C). The second term on the right side of equation 25.2.5, $\left(1 - \exp\left[-0.6 \cdot Ox_{str}\right]\right)$, is a nitrification inhibition correction factor. This factor inhibits nitrification at low dissolved oxygen concentrations.

The user defines the benthos source rate for ammonium at 20°C. The benthos source rate for ammonium nitrogen is adjusted to the local water temperature using the relationship:

$$\sigma_3 = \sigma_{3,20} \cdot 1.074^{(T_{water}-20)} \qquad 25.2.6$$

where σ_3 is the benthos (sediment) source rate for ammonium (mg N/m^2-day), $\sigma_{3,20}$ is the benthos (sediment) source rate for ammonium nitrogen at 20°C (mg N/m^2-day), and T_{water} is the average water temperature for the day (°C).

The fraction of algal nitrogen uptake from ammonium pool is calculated:

$$fr_{NH4} = \frac{f_{NH4} \cdot NH4_{str}}{\left(f_{NH4} \cdot NH4_{str} + (1 - f_{NH4}) \cdot NO3_{str} \right)} \qquad 25.2.7$$

where fr_{NH4} is the fraction of algal nitrogen uptake from ammonium pool, f_{NH4} is the preference factor for ammonia nitrogen, $NH4_{str}$ is the ammonium concentration in the stream (mg N/L), and $NO3_{str}$ is the nitrate concentration in the stream (mg N/L).

25.2.3 NITRITE

The amount of nitrite (NO_2^-) in the stream will be increased by the conversion of NH_4^+ to NO_2^- and decreased by the conversion of NO_2^- to NO_3^-. The conversion of NO_2^- to NO_3^- occurs more rapidly than the conversion of NH_4^+ to NO_2^-, so the amount of nitrite present in the stream is usually very small. The change in nitrite for a given day is:

$$\Delta NO2_{str} = \left(\beta_{N,1} \cdot NH4_{str} - \beta_{N,2} \cdot NO2_{str}\right) \cdot TT \qquad 25.2.8$$

where $\Delta NO2_{str}$ is the change in nitrite concentration (mg N/L), $\beta_{N,1}$ is the rate constant for biological oxidation of ammonia nitrogen (day^{-1}), $NH4_{str}$ is the ammonium concentration at the beginning of the day (mg N/L), $\beta_{N,2}$ is the rate constant for biological oxidation of nitrite to nitrate (day^{-1}), $NO2_{str}$ is the nitrite concentration at the beginning of the day (mg N/L), and TT is the flow travel time in the reach segment (day). The local rate constant for biological oxidation of ammonia nitrogen is calculated with equation 25.2.5. The calculation of travel time is reviewed in Chapter 23.

The rate constant for biological oxidation of nitrite to nitrate will vary as a function of in-stream oxygen concentration and temperature. The rate constant is calculated:

$$\beta_{N,2} = \beta_{N,2,20} \cdot \left(1 - \exp[-0.6 \cdot Ox_{str}]\right) \cdot 1.047^{(T_{water} - 20)} \qquad 25.2.9$$

where $\beta_{N,2}$ is the rate constant for biological oxidation of nitrite to nitrate (day^{-1}), $\beta_{N,2,20}$ is the rate constant for biological oxidation of nitrite to nitrate at 20°C (day^{-1}), Ox_{str} is the dissolved oxygen concentration in the stream (mg O_2/L), and T_{water} is the average water temperature for the day (°C). The second term on the right side of equation 25.2.9, $\left(1-\exp\left[-0.6\cdot Ox_{str}\right]\right)$, is a nitrification inhibition correction factor. This factor inhibits nitrification at low dissolved oxygen concentrations.

25.2.4 NITRATE

The amount of nitrate ($\mathrm{NO_3^-}$) in the stream may be increased by the oxidation of $\mathrm{NO_2^-}$. The nitrate concentration in the stream may be decreased by the uptake of $\mathrm{NO_3^-}$ by algae. The change in nitrate for a given day is:

$$\Delta NO3_{str} = \left(\beta_{N,2}\cdot NO2_{str} - \left(1- fr_{NH4}\right)\cdot \alpha_1 \cdot \mu_a \cdot algae\right)\cdot TT \qquad 25.2.10$$

where $\Delta NO3_{str}$ is the change in nitrate concentration (mg N/L), $\beta_{N,2}$ is the rate constant for biological oxidation of nitrite to nitrate (day^{-1}), $NO2_{str}$ is the nitrite concentration at the beginning of the day (mg N/L), fr_{NH4} is the fraction of algal nitrogen uptake from ammonium pool, α_1 is the fraction of algal biomass that is nitrogen (mg N/mg alg biomass), μ_a is the local growth rate of algae (day^{-1}), *algae* is the algal biomass concentration at the beginning of the day (mg alg/L), and *TT* is the flow travel time in the reach segment (day). The local rate constant for biological oxidation of nitrite to nitrate is calculated with equation 25.2.9 while the fraction of algal nitrogen uptake from ammonium pool is calculated with equation 25.2.7. Section 25.1.2.1 describes the calculation of the local growth rate of algae. The calculation of travel time is reviewed in Chapter 23.

Table 25-2: SWAT input variables used in in-stream nitrogen calculations.

Variable name	Definition	File Name
AI1	α_1: Fraction of algal biomass that is nitrogen (mg N/mg alg biomass)	.wwq
RHOQ	$\rho_{a,20}$: Local algal respiration rate at 20°C (day^{-1})	.wwq
BC3	$\beta_{N,3,20}$: Local rate constant for hydrolysis of organic nitrogen to $\mathrm{NH_4^+}$ at 20°C (day^{-1} or hr^{-1})	.swq
RS4	$\sigma_{4,20}$: Local settling rate for organic nitrogen at 20°C (day^{-1})	.swq
BC1	$\beta_{N,1,20}$: Rate constant for biological oxidation of ammonia nitrogen at 20°C (day^{-1})	.swq
RS3	$\sigma_{3,20}$: Benthos (sediment) source rate for ammonium nitrogen at 20°C (mg N/m^2-day or mg N/m^2-hr)	.swq
P_N	f_{NH4}: Preference factor for ammonia nitrogen	.wwq
BC2	$\beta_{N,2,20}$: Rate constant for biological oxidation of nitrite to nitrate at 20°C (day^{-1} or hr^{-1})	.swq

25.3 PHOSPHORUS CYCLE

The phosphorus cycle is similar to the nitrogen cycle. The death of algae transforms algal phosphorus into organic phosphorus. Organic phosphorus is mineralized to soluble phosphorus which is available for uptake by algae. Organic phosphorus may also be removed from the stream by settling. This section summarizes the equations used to simulate the phosphorus cycle in the stream.

25.3.1 ORGANIC PHOSPHORUS

The amount of organic phosphorus in the stream may be increased by the conversion of algal biomass phosphorus to organic phosphorus. Organic phosphorus concentration in the stream may be decreased by the conversion of organic phosphorus to soluble inorganic phosphorus or the settling of organic phosphorus with sediment. The change in organic phosphorus for a given day is:

$$\Delta orgP_{str} = \left(\alpha_2 \cdot \rho_a \cdot algae - \beta_{P,4} \cdot orgP_{str} - \sigma_5 \cdot orgP_{str}\right) \cdot TT \qquad 25.3.1$$

where $\Delta orgP_{str}$ is the change in organic phosphorus concentration (mg P/L), α_2 is the fraction of algal biomass that is phosphorus (mg P/mg alg biomass), ρ_a is the local respiration or death rate of algae (day^{-1}), *algae* is the algal biomass concentration at the beginning of the day (mg alg/L), $\beta_{P,4}$ is the rate constant for mineralization of organic phosphorus (day^{-1}), $orgP_{str}$ is the organic phosphorus concentration at the beginning of the day (mg P/L), σ_5 is the rate coefficient for organic phosphorus settling (day^{-1}), and TT is the flow travel time in the reach segment (day). The fraction of algal biomass that is phosphorus is user-defined. Equation 25.1.17 describes the calculation of the local respiration rate of algae. The calculation of travel time is reviewed in Chapter 23.

The user defines the local rate constant for mineralization of organic phosphorus at 20°C. The organic phosphorus mineralization rate is adjusted to the local water temperature using the relationship:

$$\beta_{P,4} = \beta_{P,4,20} \cdot 1.047^{\left(T_{water} - 20\right)} \qquad 25.3.2$$

where $\beta_{P,4}$ is the local rate constant for organic phosphorus mineralization (day^{-1}), $\beta_{P,4,20}$ is the local rate constant for organic phosphorus mineralization at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

The user defines the rate coefficient for organic phosphorus settling at 20°C. The organic phosphorus settling rate is adjusted to the local water temperature using the relationship:

$$\sigma_5 = \sigma_{5,20} \cdot 1.024^{(T_{water}-20)} \qquad 25.3.3$$

where σ_5 is the local settling rate for organic phosphorus (day^{-1}), $\sigma_{5,20}$ is the local settling rate for organic phosphorus at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

25.3.2 INORGANIC/SOLUBLE PHOSPHORUS

The amount of soluble, inorganic phosphorus in the stream may be increased by the mineralization of organic phosphorus and diffusion of inorganic phosphorus from the streambed sediments. The soluble phosphorus concentration in the stream may be decreased by the uptake of inorganic P by algae. The change in soluble phosphorus for a given day is:

$$\Delta solP_{str} = \left(\beta_{P,4} \cdot orgP_{str} + \frac{\sigma_2}{(1000 \cdot depth)} - \alpha_2 \cdot \mu_a \cdot algae \right) \cdot TT \qquad 25.3.4$$

where $\Delta solP_{str}$ is the change in solution phosphorus concentration (mg P/L), $\beta_{P,4}$ is the rate constant for mineralization of organic phosphorus (day^{-1}), $orgP_{str}$ is the organic phosphorus concentration at the beginning of the day (mg P/L), σ_2 is the benthos (sediment) source rate for soluble P (mg P/m^2-day), *depth* is the depth of water in the channel (m), α_2 is the fraction of algal biomass that is phosphorus (mg P/mg alg biomass), μ_a is the local growth rate of algae (day^{-1}), *algae* is the algal biomass concentration at the beginning of the day (mg alg/L), and *TT* is the flow travel time in the reach segment (day). The local rate constant for mineralization of organic phosphorus is calculated with equation 25.3.2. Section 25.1.2.1 describes the calculation of the local growth rate of algae. The calculation of depth and travel time is reviewed in Chapter 23.

The user defines the benthos source rate for soluble P at 20°C. The benthos source rate for soluble phosphorus is adjusted to the local water temperature using the relationship:

$$\sigma_2 = \sigma_{2,20} \cdot 1.074^{(T_{water}-20)} \qquad 25.3.5$$

where σ_2 is the benthos (sediment) source rate for soluble P (mg P/m^2-day), $\sigma_{2,20}$ is the benthos (sediment) source rate for soluble phosphorus at 20°C (mg P/m^2-day), and T_{water} is the average water temperature for the day (°C).

Table 25-3: SWAT input variables used in in-stream phosphorus calculations.

Variable name	Definition	File Name
AI2	α_2: Fraction of algal biomass that is phosphorus (mg P/mg alg biomass)	.wwq
RHOQ	$\rho_{a,20}$: Local algal respiration rate at 20°C (day^{-1})	.wwq
BC4	$\beta_{P,4,20}$: Local rate constant for organic phosphorus mineralization at 20°C (day^{-1})	.swq
RS5	$\sigma_{5,20}$: Local settling rate for organic phosphorus at 20°C (day^{-1})	.swq
RS2	$\sigma_{2,20}$: Benthos (sediment) source rate for soluble phosphorus at 20°C (mg P/m^2-day)	.swq

25.4 CARBONACEOUS BIOLOGICAL OXYGEN DEMAND

The carbonaceous oxygen demand (CBOD) of the water is the amount of oxygen required to decompose the organic material in the water. CBOD is added to the stream with loadings from surface runoff or point sources. Within the stream, two processes are modeled that impact CBOD levels, both of which serve to reduce the carbonaceous biological oxygen demand as the water moves downstream. The change in CBOD within the stream on a given day is calculated:

$$\Delta cbod = -(\kappa_1 \cdot cbod + \kappa_3 \cdot cbod) \cdot TT \qquad 25.4.1$$

where $\Delta cbod$ is the change in carbonaceous biological oxygen demand concentration (mg CBOD/L), κ_1 is the CBOD deoxygenation rate (day^{-1}), *cbod* is the carbonaceous biological oxygen demand concentration (mg CBOD/L), κ_3 is the settling loss rate of CBOD (day^{-1}), and *TT* is the flow travel time in the reach segment (day). The calculation of travel time is reviewed in Chapter 23.

The user defines the carbonaceous deoxygenation rate at 20°C. The CBOD deoxygenation rate is adjusted to the local water temperature using the relationship:

$$\kappa_1 = \kappa_{1,20} \cdot 1.047^{(T_{water}-20)} \qquad 25.4.2$$

where κ_1 is the CBOD deoxygenation rate (day^{-1}), $\kappa_{1,20}$ is the CBOD deoxygenation rate at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

The user defines the settling loss rate of CBOD at 20°C. The settling loss rate is adjusted to the local water temperature using the relationship:

$$\kappa_3 = \kappa_{3,20} \cdot 1.024^{(T_{water}-20)} \qquad 25.4.3$$

where κ_3 is the settling loss rate of CBOD (day^{-1}), $\kappa_{3,20}$ is the settling loss rate of CBOD at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

Table 25-4: SWAT input variables used in in-stream CBOD calculations.

Variable name	Definition	File Name
RK1	$\kappa_{1,20}$: CBOD deoxygenation rate at 20°C (day^{-1})	.swq
RK3	$\kappa_{3,20}$: Settling loss rate of CBOD at 20°C (day^{-1})	.swq

25.5 OXYGEN

An adequate dissolved oxygen concentration is a basic requirement for a healthy aquatic ecosystem. Dissolved oxygen concentrations in streams are a function of atmospheric reareation, photosynthesis, plant and animal respiration, benthic (sediment) demand, biochemical oxygen demand, nitrification, salinity, and temperature. The change in dissolved oxygen concentration on a given day is calculated:

$$\Delta Ox_{str} = (\kappa_2 \cdot (Ox_{sat} - Ox_{str}) + (\alpha_3 \cdot \mu_a - \alpha_4 \cdot \rho_a) \cdot algae - \kappa_1 \cdot cbod - \frac{\kappa_4}{1000 \cdot depth}$$

$$- \alpha_5 \cdot \beta_{N,1} \cdot NH4_{str} - \alpha_6 \cdot \beta_{N,2} \cdot NO2_{str}) \cdot TT \qquad 25.5.1$$

where ΔOx_{str} is the change in dissolved oxygen concentration (mg O_2/L), κ_2 is the reaeration rate for Fickian diffusion (day^{-1}), Ox_{sat} is the saturation oxygen concentration (mg O_2/L), Ox_{str} is the dissolved oxygen concentration in the stream (mg O_2/L), α_3 is the rate of oxygen production per unit of algal photosynthesis (mg O_2/mg alg), μ_a is the local specific growth rate of algae (day^{-1}), α_4 is the rate of oxygen uptake per unit of algae respired (mg O_2/mg alg), ρ_a is the local respiration or death rate of algae (day^{-1}), *algae* is the algal biomass concentration at the beginning of the day (mg alg/L), κ_1 is the CBOD deoxygenation rate (day^{-1}), *cbod* is the carbonaceous biological oxygen demand concentration (mg CBOD/L), κ_4 is the sediment oxygen demand rate (mg O_2/(m^2·day)), *depth* is the depth of water in the channel (m), α_5 is the rate of oxygen uptake per unit NH_4^+ oxidation (mg O_2/mg N), $\beta_{N,1}$ is the rate constant for biological oxidation of ammonia nitrogen (day^{-1}), $NH4_{str}$ is the ammonium concentration at the beginning of the day (mg N/L), α_6 is the rate of oxygen uptake per unit NO_2^- oxidation (mg O_2/mg N), $\beta_{N,2}$ is the rate constant for biological oxidation of nitrite to nitrate (day^{-1}), $NO2_{str}$ is the nitrite concentration at the beginning of the day (mg N/L) and *TT* is the flow travel time in the reach segment (day). The user defines the rate of oxygen production per unit algal photosynthesis, the rate of oxygen uptake per unit algal respiration, the rate of oxygen uptake per unit NH_4^+ oxidation and rate of oxygen uptake per unit NO_2^- oxidation. Section 25.1.2.1 describes the calculation of the local growth rate of algae while equation 25.1.17 describes the calculation of the local respiration rate of algae. The rate constant for biological oxidation of NH_4^+ is calculated with equation 25.2.5 while the rate constant for NO_2^- oxidation is determined with equation 25.2.9. The CBOD deoxygenation rate is calculated using equation 25.4.2. The calculation of depth and travel time are reviewed in Chapter 23.

The user defines the sediment oxygen demand rate at 20°C. The sediment oxygen demand rate is adjusted to the local water temperature using the relationship:

$$\kappa_4 = \kappa_{4,20} \cdot 1.060^{(T_{water}-20)} \qquad 25.5.2$$

where κ_4 is the sediment oxygen demand rate (mg $O_2/(m^2\cdot day)$), $\kappa_{4,20}$ is the sediment oxygen demand rate at 20°C (mg $O_2/(m^2\cdot day)$), and T_{water} is the average water temperature for the day (°C).

25.5.1 OXYGEN SATURATION CONCENTRATION

The amount of oxygen that can be dissolved in water is a function of temperature, concentration of dissolved solids, and atmospheric pressure. An equation developed by APHA (1985) is used to calculate the saturation concentration of dissolved oxygen:

$$Ox_{sat} = \exp\left[-139.34410 + \frac{1.575701\times10^5}{T_{wat,K}} - \frac{6.642308\times10^7}{T_{wat,K}^2} + \frac{1.243800\times10^{10}}{T_{wat,K}^3} - \frac{8.621949\times10^{11}}{T_{wat,K}^4}\right] \qquad 25.5.3$$

where Ox_{sat} is the equilibrium saturation oxygen concentration at 1.00 atm (mg O_2/L), and $T_{wat,K}$ is the water temperature in Kelvin (273.15+°C).

25.5.2 REAERATION

Reaeration occurs by diffusion of oxygen from the atmosphere into the stream and by the mixing of water and air that occurs during turbulent flow.

25.5.2.1 REAERATION BY FICKIAN DIFFUSION

The user defines the reaeration rate at 20°C. The reaeration rate is adjusted to the local water temperature using the relationship:

$$\kappa_2 = \kappa_{2,20}\cdot 1.024^{(T_{water}-20)} \qquad 25.5.4$$

where κ_2 is the reaeration rate (day^{-1}), $\kappa_{2,20}$ is the reaeration rate at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

Numerous methods have been developed to calculate the reaeration rate at 20°C, $\kappa_{2,20}$. A few of the methods are listed below. Brown and Barnwell (1987) provide additional methods.

Using field measurements, Churchill, Elmore and Buckingham (1962) derived the relationship:

$$\kappa_{2,20} = 5.03\cdot v_c^{\ 0.969}\cdot depth^{-1.673} \qquad 25.5.5$$

where $\kappa_{2,20}$ is the reaeration rate at 20°C (day^{-1}), v_c is the average stream velocity (m/s), and *depth* is the average stream depth (m).

O'Connor and Dobbins (1958) incorporated stream turbulence characteristics into the equations they developed. For streams with low velocities and isotropic conditions,

$$\kappa_{2,20} = 294 \cdot \frac{\left(D_m \cdot v_c\right)^{0.5}}{depth^{1.5}} \qquad 25.5.6$$

where $\kappa_{2,20}$ is the reaeration rate at 20°C (day^{-1}), D_m is the molecular diffusion coefficient (m^2/day), v_c is the average stream velocity (m/s), and *depth* is the average stream depth (m). For streams with high velocities and nonisotropic conditions,

$$\kappa_{2,20} = 2703 \cdot \frac{D_m^{\;0.5} \cdot slp^{0.25}}{depth^{1.25}} \qquad 25.5.7$$

where $\kappa_{2,20}$ is the reaeration rate at 20°C (day^{-1}), D_m is the molecular diffusion coefficient (m^2/day), *slp* is the slope of the streambed (m/m), and *depth* is the average stream depth (m). The molecular diffusion coefficient is calculated

$$D_m = 177 \cdot 1.037^{\bar{T}_{water}-20} \qquad 25.5.8$$

where D_m is the molecular diffusion coefficient (m^2/day), and $\bar{T}_{water}$ is the average water temperature (°C).

Owens et al. (1964) developed an equation to determine the reaeration rate for shallow, fast moving streams where the stream depth is 0.1 to 3.4 m and the velocity is 0.03 to 1.5 m/s.

$$\kappa_{2,20} = 5.34 \cdot \frac{v_c^{\;0.67}}{depth^{1.85}} \qquad 25.5.9$$

where $\kappa_{2,20}$ is the reaeration rate at 20°C (day^{-1}), v_c is the average stream velocity (m/s), and *depth* is the average stream depth (m).

25.5.2.2 REAERATION BY TURBULENT FLOW OVER A DAM

Reareation will occur when water falls over a dam, weir, or other structure in the stream. To simulate this form of reaeration, a "structure" command line is added in the watershed configuration file (.fig) at every point along the stream where flow over a structure occurs.

The amount of reaeration that occurs is a function of the oxygen deficit above the structure and a reaeration coefficient:

$$\Delta Ox_{str} = D_a - D_b = D_a\left(1 - \frac{1}{rea}\right) \qquad 25.5.10$$

where ΔOx_{str} is the change in dissolved oxygen concentration (mg O_2/L), D_a is the oxygen deficit above the structure (mg O_2/L), D_b is the oxygen deficit below the structure (mg O_2/L), and *rea* is the reaeration coefficient.

The oxygen deficit above the structure, D_a, is calculated:

$$D_a = Ox_{sat} - Ox_{str} \qquad 25.5.11$$

where Ox_{sat} is the equilibrium saturation oxygen concentration (mg O_2/L), and Ox_{str} is the dissolved oxygen concentration in the stream (mg O_2/L).

Butts and Evans (1983) documents the following relationship that can be used to estimate the reaeration coefficient:

$$rea = 1 + 0.38 \cdot coef_a \cdot coef_b \cdot h_{fall} \cdot \left(1 - 0.11 \cdot h_{fall}\right) \cdot \left(1 + 0.046 \cdot \overline{T}_{water}\right) \qquad 25.5.12$$

where *rea* is the reaeration coefficient, $coef_a$ is an empirical water quality factor, $coef_b$ is an empirical dam aeration coefficient, h_{fall} is the height through which water falls (m), and $\overline{T}_{water}$ is the average water temperature (°C).

The empirical water quality factor is assigned a value based on the condition of the stream:

$coef_a$ = 1.80 in clean water

$coef_a$ = 1.60 in slightly polluted water

$coef_a$ = 1.00 in moderately polluted water

$coef_a$ = 1.00 in moderately polluted water

$coef_a$ = 0.65 in grossly polluted water

The empirical dam aeration coefficient is assigned a value based on the type of structure:

$coef_b$ = 0.70 to 0.90 for flat broad crested weir

$coef_b$ = 1.05 for sharp crested weir with straight slope face

$coef_b$ = 0.80 for sharp crested weir with vertical face

$coef_b$ = 0.05 for sluice gates with submerged discharge

Table 25-5: SWAT input variables used in in-stream oxygen calculations.

Variable name	Definition	File Name
RK2	$\kappa_{2,20}$: Reaeration rate at 20°C (day^{-1})	.swq
AI3	α_3: Rate of oxygen production per unit algal photosynthesis (mg O_2/mg alg)	.wwq
AI4	α_4: Rate of oxygen uptake per unit algal respiration (mg O_2/mg alg)	.wwq
RHOQ	$\rho_{a,20}$: Local algal respiration rate at 20°C (day^{-1})	.wwq
RK1	$\kappa_{1,20}$: CBOD deoxygenation rate at 20°C (day^{-1})	.swq
RK4	$\kappa_{4,20}$: Sediment oxygen demand rate at 20°C (mg $O_2/(m^2 \cdot day)$)	.swq
AI5	α_5: Rate of oxygen uptake per unit NH_4^+ oxidation (mg O_2/mg N)	.wwq
AI6	α_6: Rate of oxygen uptake per unit NO_2 oxidation (mg O_2/mg N)	.wwq
AERATION_COEF	*rea*: Reaeration coefficient	.fig

25.6 NOMENCLATURE

C_{NH4}	Concentration of ammonium in the reach (mg N/L)
C_{NO3}	Concentration of nitrate in the reach (mg N/L)
C_{solP}	Concentration of phosphorus in solution in the reach (mg P/L)
D_a	Oxygen deficit above the structure (mg O_2/L)
D_b	Oxygen deficit below the structure (mg O_2/L)
D_m	Molecular diffusion coefficient for oxygen (m^2/day)
FL	Algal growth attenuation factor for light for the water column
FL_z	Algal growth attenuation factor for light at depth z
FN	Algal growth limitation factor for nitrogen
FP	Algal growth limitation factor for phosphorus
H_{day}	Solar radiation reaching ground on current day of simulation (MJ m^{-2} d^{-1})
I_{hr}	Solar radiation reaching ground during specific hour on current day of simulation (MJ m^{-2} h^{-1})
$I_{phosyn,hr}$	Photosynthetically-active solar radiation reaching ground during specific hour on current day of simulation (MJ m^{-2} h^{-1})
$I_{phosyn,z}$	Photosynthetically-active light intensity at a depth z below the water surface (MJ/m^2-hr)
$\bar{I}_{phosyn,hr}$	Daylight average photosynthetically-active light intensity (MJ/m^2-hr)
K_L	Half-saturation coefficient for light (MJ/m^2-hr)
K_N	Michaelis-Menton half-saturation constant for nitrogen (mg N/L)
K_P	Michaelis-Menton half-saturation constant for phosphorus (mg P/L)

$NH4_{str}$	Ammonium concentration in the stream (mg N/L)
$NO2_{str}$	Nitrite concentration in the stream (mg N/L)
$NO3_{str}$	Nitrate concentration in the stream (mg N/L)
Ox_{sat}	Saturation oxygen concentration (mg O_2/L)
Ox_{str}	Dissolved oxygen concentration in the stream (mg O_2/L)
T_{DL}	Daylength (h)
T_{water}	Average daily water temperature (°C)
$T_{wat,K}$	Water temperature in Kelvin (273.15+°C)
$\overline{T}_{water}$	Average water temperature (°C)
TT	Travel time (day)

$algae$	Algal biomass concentration (mg alg/L)
$cbod$	Carbonaceous biological oxygen demand concentration (mg CBOD/L)
$chla$	Chlorophyll *a* concentration (µg chla/L)
$coef_a$	Empirical water quality factor
$coef_b$	Empirical dam aeration coefficient
$depth$	Depth of water in the channel (m)
f_{NH4}	Preference factor for ammonia nitrogen
fr_{DL}	Fraction of daylight hours
fr_{NH4}	Fraction of algal nitrogen uptake from ammonium pool,
fr_{phosyn}	Fraction of solar radiation that is photosynthetically active
h_{fall}	Height through which water falls (m)
k_ℓ	Light extinction coefficient (m^{-1})
$k_{\ell,0}$	Non-algal portion of the light extinction coefficient (m^{-1})
$k_{\ell,1}$	Linear algal self shading coefficient (m^{-1} $(\mu g\text{-chla/L})^{-1}$)
$k_{\ell,2}$	Nonlinear algal self shading coefficient (m^{-1} $(\mu g\text{-chla/L})^{-2/3}$)
$orgN_{str}$	Organic nitrogen concentration in the stream (mg N/L)
$orgP_{str}$	Organic phosphorus concentration in the stream (mg P/L)
rea	Reaeration coefficient
slp	Slope of the streambed (m/m)
v_c	Average stream velocity (m/s)
z	Depth from the water surface (m)

α_0	Ratio of chlorophyll *a* to algal biomass (µg chla/mg alg)
α_1	Fraction of algal biomass that is nitrogen (mg N/mg alg biomass),
α_2	Fraction of algal biomass that is phosphorus (mg P/mg alg biomass)
α_3	Rate of oxygen production per unit algal photosynthesis (mg O_2/mg alg)
α_4	Rate of oxygen uptake per unit algal respiration (mg O_2/mg alg)
α_5	Rate of oxygen uptake per unit NH_4^+ oxidation (mg O_2/mg N)
α_6	Rate of oxygen uptake per unit NO_2 oxidation (mg O_2/mg N)
$\beta_{N,1}$	Rate constant for biological oxidation of ammonia nitrogen (day^{-1} or hr^{-1})
$\beta_{N,1,20}$	Rate constant for biological oxidation of ammonia nitrogen at 20°C (day^{-1} or hr^{-1})
$\beta_{N,2}$	Rate constant for biological oxidation of nitrite to nitrate (day^{-1} or hr^{-1})

$\beta_{N,2,20}$	Rate constant for biological oxidation of nitrite to nitrate at 20°C (day^{-1} or hr^{-1})
$\beta_{N,3}$	Rate constant for hydrolysis of organic nitrogen to ammonia nitrogen (day^{-1} or hr^{-1})
$\beta_{N,3,20}$	Local rate constant for hydrolysis of organic nitrogen to NH_4^+ at 20°C (day^{-1} or hr^{-1})
$\beta_{P,4}$	Rate constant for mineralization of organic phosphorus (day^{-1} or hr^{-1})
$\beta_{P,4,20}$	Local rate constant for organic phosphorus mineralization at 20°C (day^{-1} or hr^{-1})
$\Delta algae$	Change in algal biomass concentration (mg alg/L)
$\Delta NH4_{str}$	Change in ammonium concentration (mg N/L)
$\Delta NO2_{str}$	Change in nitrite concentration (mg N/L)
$\Delta orgN_{str}$	Change in organic nitrogen concentration (mg N/L)
$\Delta orgP_{str}$	Change in organic phosphorus concentration (mg P/L)
ΔOx_{str}	Change in dissolved oxygen concentration (mg O_2/L)
$\Delta solP_{str}$	Change in solution phosphorus concentration (mg P/L)
κ_1	CBOD deoxygenation rate (day^{-1} or hr^{-1})
$\kappa_{1,20}$	CBOD deoxygenation rate at 20°C (day^{-1} or hr^{-1})
κ_2	Reaeration rate for Fickian diffusion (day^{-1} or hr^{-1})
$\kappa_{2,20}$	Reaeration rate at 20°C (day^{-1} or hr^{-1})
κ_3	Settling loss rate of CBOD (day^{-1} or hr^{-1})
$\kappa_{3,20}$	Settling loss rate of CBOD at 20°C (day^{-1} or hr^{-1})
κ_4	Sediment oxygen demand rate (mg O_2/(m^2·day))
$\kappa_{4,20}$	Sediment oxygen demand rate at 20°C (mg O_2/(m^2·day) or mg O_2/(m^2·hr))
ρ_a	Local respiration rate of algae (day^{-1} or hr^{-1})
$\rho_{a,20}$	Local algal respiration rate at 20°C (day^{-1} or hr^{-1})
σ_1	Local settling rate for algae (m/day or m/hr)
$\sigma_{1,20}$	Local algal settling rate at 20°C (m/day or m/hr)
σ_2	Benthos (sediment) source rate for soluble P (mg P/m^2-day or mg P/m^2-hr)
$\sigma_{2,20}$	Benthos (sediment) source rate for soluble phosphorus at 20°C (mg P/m^2-day or mg P/m^2-hr)
σ_3	Benthos (sediment) source rate for ammonium (mg N/m^2-day or mg N/m^2-hr)
$\sigma_{3,20}$	Benthos (sediment) source rate for ammonium nitrogen at 20°C (mg N/m^2-day or mg N/m^2-hr)
σ_4	Rate coefficient of organic nitrogen settling (day^{-1} or hr^{-1})
$\sigma_{4,20}$	Local settling rate for organic nitrogen at 20°C (day^{-1} or hr^{-1})
σ_5	Rate coefficient for organic phosphorus settling (day^{-1} or hr^{-1})
$\sigma_{5,20}$	Local settling rate for organic phosphorus at 20°C (day^{-1} or hr^{-1})
μ_a	Local specific growth rate of algae (day^{-1} or hr^{-1})
$\mu_{a,20}$	Local specific algal growth rate at 20°C (day^{-1} or hr^{-1})
μ_{max}	Maximum specific algal growth rate (day^{-1} or hr^{-1})

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CHAPTER 26

EQUATIONS: IN-STREAM PESTICIDE TRANSFORMATIONS

SWAT incorporates a simple mass balance developed by Chapra (1997) to model the transformation and transport of pesticides in streams. The model assumes a well-mixed layer of water overlying a sediment layer. Only one pesticide can be routed through the stream network. The pesticide to be routed is defined by the variable IRTPEST in the .bsn file.

26.1 PESTICIDE IN THE WATER

Pesticide in a reach segment is increased through addition of mass in inflow as well as resuspension and diffusion of pesticide from the sediment layer. The amount of pesticide in a reach segment is reduced through removal in outflow as well as degradation, volatilization, settling and diffusion into the underlying sediment.

26.1.1 SOLID-LIQUID PARTITIONING

Pesticides will partition into particulate and dissolved forms. The fraction of pesticide in each phase is a function of the pesticide's partition coefficient and the reach segment's suspended solid concentration:

$$F_d = \frac{1}{1 + K_d \cdot conc_{sed}} \qquad 26.1.1$$

$$F_p = \frac{K_d \cdot conc_{sed}}{1 + K_d \cdot conc_{sed}} = 1 - F_d \qquad 26.1.2$$

where F_d is the fraction of total pesticide in the dissolved phase, F_p is the fraction of total pesticide in the particulate phase, K_d is the pesticide partition coefficient (m^3/g), and $conc_{sed}$ is the concentration of suspended solids in the water (g/m^3).

The pesticide partition coefficient can be estimated from the octanol-water partition coefficient (Chapra, 1997):

$$K_d = 3.085 \times 10^{-8} \cdot K_{ow} \qquad 26.1.3$$

where K_d is the pesticide partition coefficient (m^3/g) and K_{ow} is the pesticide's octanol-water partition coefficient ($\text{mg m}^{-3}_{\text{octanol}} \left(\text{mg m}^{-3}_{\text{water}}\right)^{-1}$). Values for the octanol-water partition coefficient have been published for many chemicals. If a published value cannot be found, it can be estimated from solubility (Chapra, 1997):

$$\log(K_{ow}) = 5.00 - 0.670 \cdot \log(pst'_{sol}) \qquad 26.1.4$$

where pst'_{sol} is the pesticide solubility (µmoles/L). The solubility in these units is calculated:

$$pst'_{sol} = \frac{pst_{sol}}{MW} \cdot 10^3 \qquad 26.1.5$$

where pst'_{sol} is the pesticide solubility (µmoles/L), pst_{sol} is the pesticide solubility (mg/L) and MW is the molecular weight (g/mole).

26.1.2 DEGRADATION

Pesticides in both the particulate and dissolved forms are subject to degradation. The amount of pesticide that is removed from the water via degradation is:

$$pst_{deg,wtr} = k_{p,aq} \cdot pst_{rchwtr} \cdot TT \qquad 26.1.6$$

where $pst_{deg,wtr}$ is the amount of pesticide removed from the water via degradation (mg pst), $k_{p,aq}$ is the rate constant for degradation or removal of pesticide in the water (1/day), pst_{rchwtr} is the amount of pesticide in the water at the beginning of the day (mg pst), and TT is the flow travel time (days). The rate constant is related to the aqueous half-life:

$$k_{p,aq} = \frac{0.693}{t_{1/2,aq}} \qquad 26.1.7$$

where $k_{p,aq}$ is the rate constant for degradation or removal of pesticide in the water (1/day), and $t_{1/2,aq}$ is the aqueous half-life for the pesticide (days).

26.1.3 VOLATILIZATION

Pesticide in the dissolved phase is available for volatilization. The amount of pesticide removed from the water via volatilization is:

$$pst_{vol,wtr} = \frac{v_v}{depth} \cdot F_d \cdot pst_{rchwtr} \cdot TT \qquad 26.1.8$$

where $pst_{vol,wtr}$ is the amount of pesticide removed via volatilization (mg pst), v_v is the volatilization mass-transfer coefficient (m/day), $depth$ is the flow depth (m), F_d is the fraction of total pesticide in the dissolved phase, pst_{rchwtr} is the amount of pesticide in the water (mg pst), and TT is the flow travel time (days).

The volatilization mass-transfer coefficient can be calculated based on Whitman's two-film or two-resistance theory (Whitman, 1923; Lewis and Whitman, 1924 as described in Chapra, 1997). While the main body of the gas and liquid phases are assumed to be well-mixed and homogenous, the two-film theory assumes that a substance moving between the two phases encounters maximum resistance in two laminar boundary layers where transfer is a function of molecular diffusion. In this type of system the transfer coefficient or velocity is:

$$v_v = K_l \cdot \frac{H_e}{H_e + R \cdot T_K \cdot \left(K_l / K_g\right)} \qquad 26.1.9$$

where v_v is the volatilization mass-transfer coefficient (m/day), K_l is the mass-transfer velocity in the liquid laminar layer (m/day), K_g is the mass-transfer velocity in the gaseous laminar layer (m/day), H_e is Henry's constant (atm m^3 mole^{-1}), R is the universal gas constant (8.206×10^{-5} atm m^3 (K mole)$^{-1}$), and T_K is the temperature (K).

For rivers where liquid flow is turbulent, the transfer coefficients are estimated using the surface renewal theory (Higbie, 1935; Danckwerts, 1951; as described by Chapra, 1997). The surface renewal model visualizes the system as consisting of parcels of water that are brought to the surface for a period of time. The fluid elements are assumed to reach and leave the air/water interface randomly, i.e. the exposure of the fluid elements to air is described by a statistical distribution. The transfer velocities for the liquid and gaseous phases are calculated:

$$K_l = \sqrt{r_l \cdot D_l} \qquad K_g = \sqrt{r_g \cdot D_g} \qquad 26.1.10$$

where K_l is the mass-transfer velocity in the liquid laminar layer (m/day), K_g is the mass-transfer velocity in the gaseous laminar layer (m/day), D_l is the liquid molecular diffusion coefficient (m^2/day), D_g is the gas molecular diffusion coefficient (m^2/day), r_l is the liquid surface renewal rate (1/day), and r_g is the gaseous surface renewal rate (1/day).

O'Connor and Dobbins (1956) defined the surface renewal rate as the ratio of the average stream velocity to depth.

$$r_l = \frac{86400 \cdot v_c}{depth} \qquad 26.1.11$$

where r_l is the liquid surface renewal rate (1/day), v_c is the average stream velocity (m/s) and *depth* is the depth of flow (m).

26.1.4 SETTLING

Pesticide in the particulate phase may be removed from the water layer by settling. Settling transfers pesticide from the water to the sediment layer. The amount of pesticide that is removed from the water via settling is:

$$pst_{stl,wtr} = \frac{v_s}{depth} \cdot F_p \cdot pst_{rchwtr} \cdot TT \qquad 26.1.12$$

where $pst_{stl,wtr}$ is the amount of pesticide removed from the water due to settling (mg pst), v_s is the settling velocity (m/day), *depth* is the flow depth (m), F_p is the fraction of total pesticide in the particulate phase, pst_{rchwtr} is the amount of pesticide in the water (mg pst), and TT is the flow travel time (days).

26.1.5 OUTFLOW

Pesticide is removed from the reach segment in outflow. The amount of dissolved and particulate pesticide removed from the reach segment in outflow is:

$$pst_{sol,o} = Q \cdot \frac{F_d \cdot pst_{rchwtr}}{V} \qquad 26.1.13$$

$$pst_{sorb,o} = Q \cdot \frac{F_p \cdot pst_{rchwtr}}{V} \qquad 26.1.14$$

where $pst_{sol,o}$ is the amount of dissolved pesticide removed via outflow (mg pst), $pst_{sorb,o}$ is the amount of particulate pesticide removed via outflow (mg pst), Q is the rate of outflow from the reach segment (m^3 H_2O/day), F_d is the fraction of total pesticide in the dissolved phase, F_p is the fraction of total pesticide in the particulate phase, pst_{rchwtr} is the amount of pesticide in the water (mg pst), and V is the volume of water in the reach segment (m^3 H_2O).

Table 26-1: SWAT input variables that pesticide partitioning.

Variable Name	Definition	Input File
CHPST_KOC	K_d: Pesticide partition coefficient (m^3/g)	.swq
CHPST_REA	$k_{p,aq}$: Rate constant for degradation or removal of pesticide in the water (1/day)	.swq
CHPST_VOL	v_v: Volatilization mass-transfer coefficient (m/day)	.swq
CHPST_STL	v_s: Pesticide settling velocity (m/day)	.swq

26.2 PESTICIDE IN THE SEDIMENT

Pesticide in the sediment layer underlying a reach segment is increased through addition of mass by settling and diffusion from the water. The amount of pesticide in the sediment layer is reduced through removal by degradation, resuspension, diffusion into the overlying water, and burial.

26.2.1 SOLID-LIQUID PARTITIONING

As in the water layer, pesticides in the sediment layer will partition into particulate and dissolved forms. Calculation of the solid-liquid partitioning in the sediment layer requires a suspended solid concentration. The "concentration" of solid particles in the sediment layer is defined as:

$$conc_{sed}^{*} = \frac{M_{sed}}{V_{tot}} \tag{26.2.1}$$

where $conc_{sed}^{*}$ is the "concentration" of solid particles in the sediment layer (g/m^3), M_{sed} is the mass of solid particles in the sediment layer (g) and V_{tot} is the total volume of the sediment layer (m^3).

Mass and volume are also used to define the porosity and density of the sediment layer. In the sediment layer, porosity is the fraction of the total volume in the liquid phase:

$$\phi = \frac{V_{wtr}}{V_{tot}} \tag{26.2.2}$$

where ϕ is the porosity, V_{wtr} is the volume of water in the sediment layer (m^3) and V_{tot} is the total volume of the sediment layer (m^3). The fraction of the volume in the solid phase can then be defined as:

$$1 - \phi = \frac{V_{sed}}{V_{tot}} \tag{26.2.3}$$

where ϕ is the porosity, V_{sed} is the volume of solids in the sediment layer (m^3) and V_{tot} is the total volume of the sediment layer (m^3).

The density of sediment particles is defined as:

$$\rho_s = \frac{M_{sed}}{V_{sed}} \tag{26.2.4}$$

where ρ_s is the particle density (g/m^3), M_{sed} is the mass of solid particles in the sediment layer (g), and V_{sed} is the volume of solids in the sediment layer (m^3).

Solving equation 26.2.3 for V_{tot} and equation 26.2.4 for M_{sed} and substituting into equation 26.2.1 yields:

$$conc^*_{sed} = (1-\phi)\cdot\rho_s \qquad 26.2.5$$

where $conc^*_{sed}$ is the "concentration" of solid particles in the sediment layer (g/m^3), ϕ is the porosity, and ρ_s is the particle density (g/m^3).

Assuming $\phi = 0.5$ and $\rho_s = 2.6 \times 10^6$ g/m^3, the "concentration" of solid particles in the sediment layer is 1.3×10^6 g/m^3.

The fraction of pesticide in each phase is then calculated:

$$F_{d,sed} = \frac{1}{\phi + (1-\phi)\cdot\rho_s\cdot K_d} \qquad 26.2.6$$

$$F_{p,sed} = 1 - F_{d,sed} \qquad 26.2.7$$

where $F_{d,sed}$ is the fraction of total sediment pesticide in the dissolved phase, $F_{p,sed}$ is the fraction of total sediment pesticide in the particulate phase, ϕ is the porosity, ρ_s is the particle density (g/m^3), and K_d is the pesticide partition coefficient (m^3/g). The pesticide partition coefficient used for the water layer is also used for the sediment layer.

26.2.2 DEGRADATION

Pesticides in both the particulate and dissolved forms are subject to degradation. The amount of pesticide that is removed from the sediment via degradation is:

$$pst_{deg,sed} = k_{p,sed}\cdot pst_{rchsed} \qquad 26.2.8$$

where $pst_{deg,sed}$ is the amount of pesticide removed from the sediment via degradation (mg pst), $k_{p,sed}$ is the rate constant for degradation or removal of pesticide in the sediment (1/day), and pst_{rchsed} is the amount of pesticide in the sediment (mg pst). The rate constant is related to the sediment half-life:

$$k_{p,sed} = \frac{0.693}{t_{1/2,sed}} \qquad 26.2.9$$

where $k_{p,sed}$ is the rate constant for degradation or removal of pesticide in the sediment (1/day), and $t_{1/2,sed}$ is the sediment half-life for the pesticide (days).

26.2.3 RESUSPENSION

Pesticide in the sediment layer is available for resuspension. The amount of pesticide that is removed from the sediment via resuspension is:

$$pst_{rsp,wtr} = \frac{v_r}{depth} \cdot pst_{rchsed} \cdot TT \qquad 26.2.10$$

where $pst_{rsp,wtr}$ is the amount of pesticide removed via resuspension (mg pst), v_r is the resuspension velocity (m/day), *depth* is the flow depth (m), pst_{rchsed} is the amount of pesticide in the sediment (mg pst), and *TT* is the flow travel time (days). Pesticide removed from the sediment layer by resuspension is added to the water layer.

26.2.4 DIFFUSION

Pesticide in the dissolved phase is available for diffusion. Diffusion transfers pesticide between the water and sediment layers. The direction of movement is controlled by the pesticide concentration. Pesticide will move from areas of high concentration to areas of low concentration. The amount of pesticide that is transferred between the water and sediment by diffusion is:

$$pst_{dif} = \left| \frac{v_d}{depth} \cdot \left(F_{d,sed} \cdot pst_{rchsed} - F_d \cdot pst_{rchwtr} \right) \cdot TT \right| \qquad 26.2.11$$

where pst_{dif} is the amount of pesticide transferred between the water and sediment by diffusion (mg pst), v_d is the rate of diffusion or mixing velocity (m/day), *depth* is the flow depth (m), $F_{d,sed}$ is the fraction of total sediment pesticide in the dissolved phase, pst_{rchsed} is the amount of pesticide in the sediment (mg pst), F_d is the fraction of total water layer pesticide in the dissolved phase, pst_{rchwtr} is the amount of pesticide in the water (mg pst), and *TT* is the flow duration (days). If $F_{d,sed} \cdot pst_{rchsed} > F_d \cdot pst_{rchwtr}$, pst_{dif} is transferred from the sediment to the water layer. If, $F_{d,sed} \cdot pst_{rchsed} < F_d \cdot pst_{rchwtr}$, pst_{dif} is transferred from the water to the sediment layer.

The diffusive mixing velocity, v_d, can be estimated from the empirically derived formula (Chapra, 1997):

$$v_d = \frac{69.35}{365} \cdot \phi \cdot MW^{-2/3} \qquad 26.2.12$$

where v_d is the rate of diffusion or mixing velocity (m/day), ϕ is the sediment porosity, and MW is the molecular weight of the pesticide compound.

26.2.5 BURIAL

Pesticide in the sediment layer may be lost by burial. The amount of pesticide that is removed from the sediment via burial is:

$$pst_{bur} = \frac{v_b}{D_{sed}} \cdot pst_{rchsed} \qquad 26.2.13$$

where pst_{bur} is the amount of pesticide removed via burial (mg pst), v_b is the burial velocity (m/day), D_{sed} is the depth of the active sediment layer (m), and pst_{rchsed} is the amount of pesticide in the sediment (mg pst).

Table 26-2: SWAT input variables related to pesticide in the sediment.

Variable Name	Definition	Input File
CHPST_KOC	K_d: Pesticide partition coefficient (m^3/g)	.swq
SEDPST_REA	$k_{p,sed}$: Rate constant for degradation or removal of pesticide in the sediment (1/day)	.swq
CHPST_RSP	v_r: Resuspension velocity (m/day)	.swq
SEDPST_ACT	D_{sed}: Depth of the active sediment layer (m)	.swq
CHPST_MIX	v_d: Rate of diffusion or mixing velocity (m/day)	.swq
SEDPST_BRY	v_b: Pesticide burial velocity (m/day)	.swq

26.3 MASS BALANCE

The processes described above can be combined into mass balance equations for the well-mixed reach segment and the well-mixed sediment layer:

$$\Delta pst_{rchwtr} = pst_{in} - \left(pst_{sol,o} + pst_{sorb,o}\right) - pst_{deg,wtr} - pst_{vol,wtr} - pst_{stl,wtr} + pst_{rsp,wtr} \pm pst_{dif} \qquad 26.3.1$$

$$\Delta pst_{rchsed} = -pst_{deg,sed} + pst_{stl,wtr} - pst_{rsp,wtr} - pst_{bur} \pm pst_{dif} \qquad 26.3.2$$

where Δpst_{rchwtr} is the change in pesticide mass in the water layer (mg pst), Δpst_{rchsed} is the change in pesticide mass in the sediment layer (mg pst), pst_{in} is the pesticide added to the reach segment via inflow (mg pst), $pst_{sol,o}$ is the amount of dissolved pesticide removed via outflow (mg pst), $pst_{sorb,o}$ is the amount of particulate pesticide removed via outflow (mg pst), $pst_{deg,wtr}$ is the amount of pesticide removed from the water via degradation (mg pst), $pst_{vol,wtr}$ is the amount of pesticide removed via volatilization (mg pst), $pst_{stl,wtr}$ is the amount of pesticide removed from the water due to settling (mg pst), $pst_{rsp,wtr}$ is the amount of pesticide removed via resuspension (mg pst), pst_{dif} is the amount of pesticide transferred between the water and sediment by diffusion (mg pst), $pst_{deg,sed}$ is the amount of pesticide removed from the sediment via degradation (mg pst), pst_{bur} is the amount of pesticide removed via burial (mg pst)

26.4 NOMENCLATURE

D_g	Gas molecular diffusion coefficient (m^2/day)
D_l	Liquid molecular diffusion coefficient (m^2/day)
D_{sed}	Depth of the active sediment layer (m)
F_d	Fraction of total pesticide in the dissolved phase
$F_{d,sed}$	Fraction of total sediment pesticide in the dissolved phase
F_p	Fraction of total pesticide in the particulate phase
$F_{p,sed}$	Fraction of total sediment pesticide in the particulate phase
H_e	Henry's constant (atm m^3 mole^{-1})
K_d	Pesticide partition coefficient (m^3/g)
K_g	Mass-transfer velocity in the gaseous laminar layer (m/day)
K_l	Mass-transfer velocity in the liquid laminar layer (m/day)
M_{sed}	Mass of solid phase in the sediment layer (g)
MW	Molecular weight of the pesticide compound
Q	Rate of outflow from the reach segment (m^3 H_2O/day)
R	Universal gas constant (8.206×10^{-5} atm m^3 (K mole)$^{-1}$)
V_{sed}	Volume of solids in the sediment layer (m^3)
V_{tot}	Total volume of the sediment layer (m^3)
V_{wtr}	Volume of water in the sediment layer (m^3)
$conc_{sed}$	Concentration of suspended solids in the water (g/m^3)
$conc_{sed}^{*}$	"Concentration" of solid particles in the sediment layer (g/m^3)
$depth$	Depth of flow (m)
$k_{p,aq}$	Rate constant for degradation or removal of pesticide in the water (1/day)
$k_{p,sed}$	Rate constant for degradation or removal of pesticide in the sediment (1/day)
pst_{bur}	Amount of pesticide removed via burial (mg pst)
$pst_{deg,sed}$	Amount of pesticide removed from the sediment via degradation (mg pst)

$pst_{deg,wtr}$	Amount of pesticide removed from the water via degradation (mg pst)
pst_{dif}	Amount of pesticide transferred between the water and sediment by diffusion (mg pst)
pst_{rchsed}	Amount of pesticide in the sediment (mg pst)
pst_{rchwtr}	Amount of pesticide in the water (mg pst)
$pst_{rsp,wtr}$	Amount of pesticide removed from sediment via resuspension (mg pst)
$pst_{sol,o}$	Amount of dissolved pesticide removed via outflow (mg pst)
$pst_{sorb,o}$	Amount of particulate pesticide removed via outflow (mg pst)
$pst_{stl,wtr}$	Amount of pesticide removed from the water due to settling (mg pst)
$pst_{vol,wtr}$	Amount of pesticide removed via volatilization (mg pst)
r_g	Gaseous surface renewal rate (1/day)
r_l	Liquid surface renewal rate (1/day)
$t_{1/2,aq}$	Aqueous half-life for the pesticide (days)
$t_{1/2,sed}$	Sediment half-life for the pesticide (days)
v_b	Pesticide burial velocity (m/day)
v_c	Average stream velocity (m/s)
v_d	Rate of diffusion or mixing velocity (m/day)
v_r	Resuspension velocity (m/day)
v_s	Settling velocity (m/day)
v_v	Volatilization mass-transfer coefficient (m/day)
Δpst_{rchwtr}	Change in pesticide mass in the water layer (mg pst)
Δpst_{rchsed}	Change in pesticide mass in the sediment layer (mg pst)
ϕ	Porosity
ρ_s	Particle density (g/m^3)

26.5 REFERENCES

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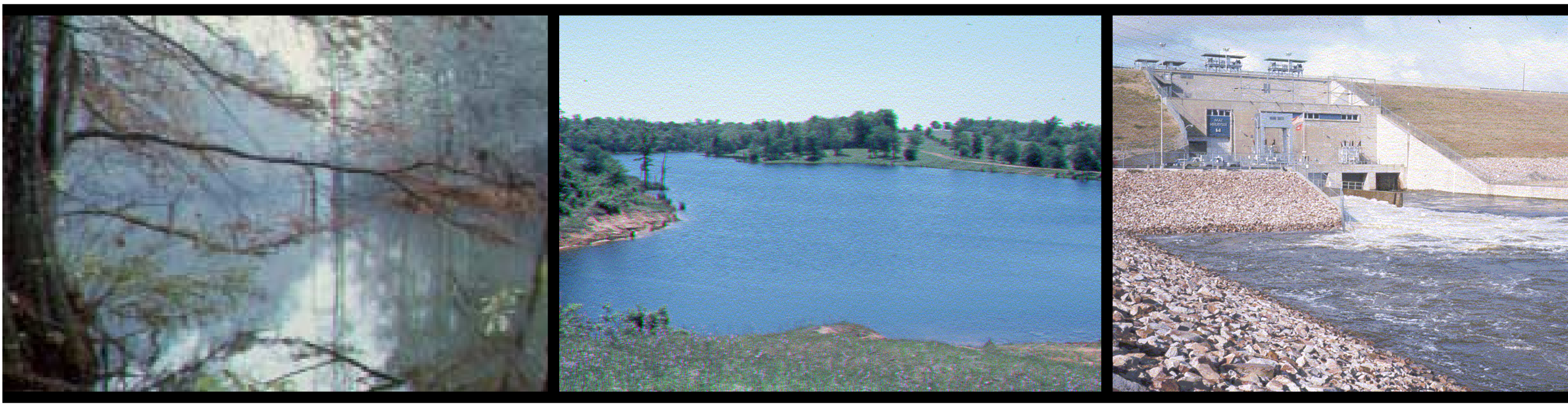

WATER BODIES

Impoundment structures modify the movement of water in the channel network by lowering the peak flow and volume of flood discharges. Because impoundments slow down the flow of water, sediment will fall from suspension, removing nutrient and chemicals adsorbed to the soil particles.

CHAPTER 27

EQUATIONS: IMPOUNDMENT WATER ROUTING

Impoundments play an important role in water supply and flood control. SWAT models four types of water bodies: ponds, wetlands, depressions/potholes, and reservoirs. Ponds, wetlands, and depressions/potholes are located within a subbasin off the main channel. Water flowing into these water bodies must originate from the subbasin in which the water body is located. Reservoirs are located on the main channel network. They receive water from all subbasins upstream of the water body.

27.1 RESERVOIRS

A reservoir is an impoundment located on the main channel network of a watershed. No distinction is made between naturally-occurring and man-made structures. The features of an impoundment are shown in Figure 27.1.

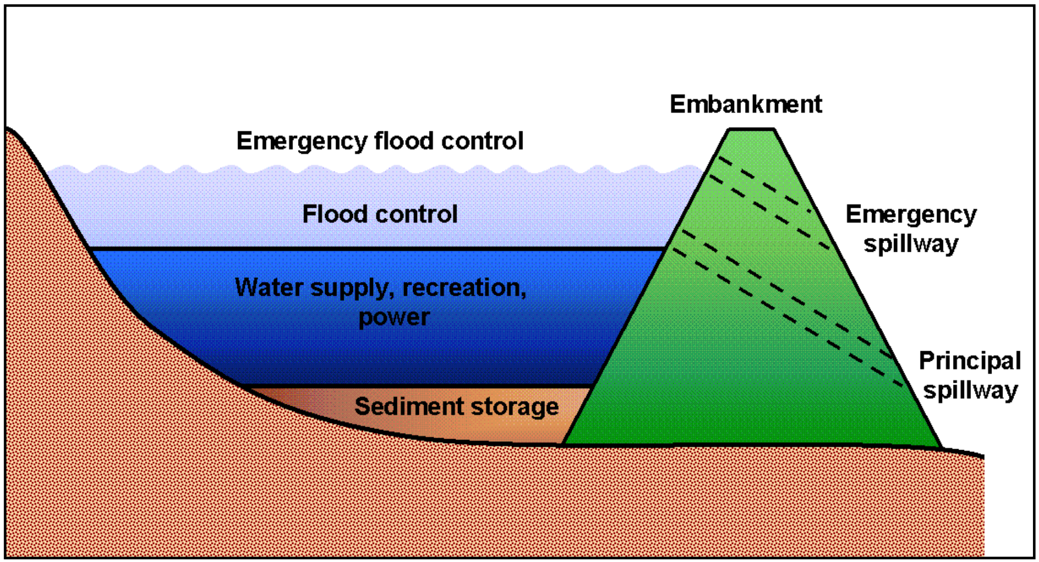

Figure 27.1: Components of a reservoir with flood water detention features (After Ward and Elliot, 1995).

The water balance for a reservoir is:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \qquad 27.1.1$$

where V is the volume of water in the impoundment at the end of the day (m^3 H_2O), V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3 H_2O), V_{flowin} is the volume of water entering the water body during the day (m^3 H_2O), $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), V_{pcp} is the volume of precipitation falling on the water body during the day (m^3 H_2O), V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H_2O), and V_{seep} is the volume of water lost from the water body by seepage (m^3 H_2O).

27.1.1 SURFACE AREA

The surface area of the reservoir is needed to calculate the amount of precipitation falling on the water body as well as the amount of evaporation and seepage. Surface area varies with change in the volume of water stored in the reservoir. The surface area is updated daily using the equation:

$$SA = \beta_{sa} \cdot V^{expsa} \tag{27.1.2}$$

where SA is the surface area of the water body (ha), β_{sa} is a coefficient, V is the volume of water in the impoundment (m^3 H_2O), and *expsa* is an exponent.

The coefficient, β_{sa}, and exponent, *expsa*, are calculated by solving equation 27.1.2 using two known points. The two known points are surface area and volume information provided for the principal and emergency spillways.

$$expsa = \frac{\log_{10}(SA_{em}) - \log_{10}(SA_{pr})}{\log_{10}(V_{em}) - \log_{10}(V_{pr})} \tag{27.1.3}$$

$$\beta_{sa} = \left(\frac{SA_{em}}{V_{em}}\right)^{expsa} \tag{27.1.4}$$

where SA_{em} is the surface area of the reservoir when filled to the emergency spillway (ha), SA_{pr} is the surface area of the reservoir when filled to the principal spillway (ha), V_{em} is the volume of water held in the reservoir when filled to the emergency spillway (m^3 H_2O), and V_{pr} is the volume of water held in the reservoir when filled to the principal spillway (m^3 H_2O).

27.1.2 PRECIPITATION

The volume of precipitation falling on the reservoir during a given day is calculated:

$$V_{pcp} = 10 \cdot R_{day} \cdot SA \tag{27.1.5}$$

where V_{pcp} is the volume of water added to the water body by precipitation during the day (m^3 H_2O), R_{day} is the amount of precipitation falling on a given day (mm H_2O), and SA is the surface area of the water body (ha).

27.1.3 EVAPORATION

The volume of water lost to evaporation on a given day is calculated:

$$V_{evap} = 10 \cdot \eta \cdot E_o \cdot SA \qquad 27.1.6$$

where V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H_2O), η is an evaporation coefficient (0.6), E_o is the potential evapotranspiration for a given day (mm H_2O), and SA is the surface area of the water body (ha).

27.1.4 SEEPAGE

The volume of water lost by seepage through the bottom of the reservoir on a given day is calculated:

$$V_{seep} = 240 \cdot K_{sat} \cdot SA \qquad 27.1.7$$

where V_{seep} is the volume of water lost from the water body by seepage (m^3 H_2O), K_{sat} is the effective saturated hydraulic conductivity of the reservoir bottom (mm/hr), and SA is the surface area of the water body (ha).

27.1.5 OUTFLOW

The volume of outflow may be calculated using one of four different methods: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, controlled outflow with target release.

27.1.5.1 MEASURED DAILY OUTFLOW

When measured daily outflow (IRESCO = 3) is chosen as the method to calculate reservoir outflow, the user must provide a file with the outflow rate for every day the reservoir is simulated in the watershed. The volume of outflow from the reservoir is then calculated:

$$V_{flowout} = 86400 \cdot q_{out} \qquad 27.1.8$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), and q_{out} is the outflow rate (m^3/s).

27.1.5.2 MEASURED MONTHLY OUTFLOW

When measured monthly outflow (IRESCO = 1) is chosen as the method to calculate reservoir outflow, the user must provide a file with the average daily outflow rate for every month the reservoir is simulated in the watershed. The volume of outflow from the reservoir is then calculated using equation 27.1.8.

27.1.5.3 AVERAGE ANNUAL RELEASE RATE FOR UNCONTROLLED RESERVOIR

When the average annual release rate (IRESCO = 0) is chosen as the method to calculate reservoir outflow, the reservoir releases water whenever the reservoir volume exceeds the principal spillway volume, V_{pr}. If the reservoir volume is greater than the principal spillway volume but less than the emergency spillway volume, the amount of reservoir outflow is calculated:

$$V_{flowout} = V - V_{pr} \qquad \text{if } V - V_{pr} < q_{rel} \cdot 86400 \qquad 27.1.9$$

$$V_{flowout} = q_{rel} \cdot 86400 \qquad \text{if } V - V_{pr} > q_{rel} \cdot 86400 \qquad 27.1.10$$

If the reservoir volume exceeds the emergency spillway volume, the amount of outflow is calculated:

$$V_{flowout} = (V - V_{em}) + (V_{em} - V_{pr}) \qquad \text{if } V_{em} - V_{pr} < q_{rel} \cdot 86400 \qquad 27.1.11$$

$$V_{flowout} = (V - V_{em}) + q_{rel} \cdot 86400 \qquad \text{if } V_{em} - V_{pr} > q_{rel} \cdot 86400 \qquad 27.1.12$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), V is the volume of water stored in the reservoir (m^3 H_2O), V_{pr} is the volume of water held in the reservoir when filled to the principal spillway (m^3 H_2O), V_{em} is the volume of water held in the reservoir when filled to the emergency spillway (m^3 H_2O), and q_{rel} is the average daily principal spillway release rate (m^3/s).

27.1.5.4 TARGET RELEASE FOR CONTROLLED RESERVOIR

When target release (IRESCO = 2) is chosen as the method to calculate reservoir outflow, the reservoir releases water as a function of the desired target storage.

The target release approach tries to mimic general release rules that may be used by reservoir operators. Although the method is simplistic and cannot account for all decision criteria, it can realistically simulate major outflow and low flow periods.

For the target release approach, the principal spillway volume corresponds to maximum flood control reservation while the emergency spillway volume corresponds to no flood control reservation. The model requires the beginning and ending month of the flood season. In the non-flood season, no flood control reservation is required, and the target storage is set at the emergency spillway volume. During the flood season, the flood control reservation is a function of soil water content. The flood control reservation for wet ground conditions is set at the maximum. For dry ground conditions, the flood control reservation is set at 50% of the maximum.

The target storage may be specified by the user on a monthly basis or it can be calculated as a function of flood season and soil water content. If the target storage is specified:

$$V_{targ} = starg \qquad 27.1.13$$

where V_{targ} is the target reservoir volume for a given day (m^3 H_2O), and *starg* is the target reservoir volume specified for a given month (m^3 H_2O). If the target storage is not specified, the target reservoir volume is calculated:

$$V_{targ} = V_{em} \qquad \text{if } mon_{fld,beg} < mon < mon_{fld,end} \qquad 27.1.14$$

$$V_{targ} = V_{pr} + \frac{\left(1 - \min\left[\frac{SW}{FC},\ 1\right]\right)}{2} \cdot \left(V_{em} - V_{pr}\right)$$

$$\text{if } mon \leq mon_{fld,beg} \text{ or } mon \geq mon_{fld,end} \qquad 27.1.15$$

where V_{targ} is the target reservoir volume for a given day (m^3 H_2O), V_{em} is the volume of water held in the reservoir when filled to the emergency spillway (m^3 H_2O), V_{pr} is the volume of water held in the reservoir when filled to the principal spillway (m^3 H_2O), SW is the average soil water content in the subbasin (mm H_2O), FC is the water content of the subbasin soil at field capacity (mm H_2O), mon is the month of the year, $mon_{fld,beg}$ is the beginning month of the flood season, and $mon_{fld,end}$ is the ending month of the flood season.

Once the target storage is defined, the outflow is calculated:

$$V_{flowout} = \frac{V - V_{targ}}{ND_{targ}} \qquad 27.1.16$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), V is the volume of water stored in the reservoir (m^3 H_2O), V_{targ} is the target reservoir volume for a given day (m^3 H_2O), and ND_{targ} is the number of days required for the reservoir to reach target storage.

Once outflow is determined using one of the preceding four methods, the user may specify maximum and minimum amounts of discharge that the initial outflow estimate is checked against. If the outflow doesn't meet the minimum discharge or exceeds the maximum specified discharge, the amount of outflow is altered to meet the defined criteria.

$$V_{flowout} = V'_{flowout} \qquad \text{if } q_{rel,mn} \cdot 86400 \leq V'_{flowout} \leq q_{rel,mx} \cdot 86400 \qquad 27.1.17$$

$$V_{flowout} = q_{rel,mn} \cdot 86400 \qquad \text{if } V'_{flowout} < q_{rel,mn} \cdot 86400 \qquad 27.1.18$$

$$V_{flowout} = q_{rel,mx} \cdot 86400 \qquad \text{if } V'_{flowout} > q_{rel,mx} \cdot 86400 \qquad 27.1.19$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), $V'_{flowout}$ is the initial estimate of the volume of water flowing out of the water body during the day (m^3 H_2O), $q_{rel,mn}$ is the minimum average daily outflow for the month (m^3/s), and $q_{rel,mx}$ is the maximum average daily outflow for the month (m^3/s).

Table 27-1: SWAT input variables that pertain to reservoirs.

Variable name	Definition	File Name
RES_ESA	SA_{em}: Surface area of the reservoir when filled to the emergency spillway (ha)	.res
RES_PSA	SA_{pr}: Surface area of the reservoir when filled to the principal spillway (ha)	.res
RES_EVOL	V_{em}: Volume of water held in the reservoir when filled to the emergency spillway (10^4 m^3 H_2O)	.res
RES_PVOL	V_{pr}: Volume of water held in the reservoir when filled to the principal spillway (10^4 m^3 H_2O)	.res
RES_K	K_{sat}: Effective saturated hydraulic conductivity of the reservoir bottom (mm/hr)	.res
IRESCO	Outflow method	.res
RES_OUTFLOW	q_{out}: Outflow rate (m^3/s)	resdayo.dat
RESOUT	q_{out}: Outflow rate (m^3/s)	resmono.dat
RES_RR	q_{rel}: Average daily principal spillway release rate (m^3/s)	.res
STARG(mon)	*starg*: Target reservoir volume specified for a given month (m^3 H_2O)	.res
IFLOD1R	$mon_{fld,beg}$: Beginning month of the flood season	.res
IFLOD2R	$mon_{fld,end}$: Ending month of the flood season	.res
NDTARGR	ND_{targ}: Number of days required for the reservoir to reach target storage	.res
OFLOWMN(mon)	$q_{rel,mn}$: Minimum average daily outflow for the month (m^3/s)	.res
OFLOWMX(mon)	$q_{rel,mx}$: Maximum average daily outflow for the month (m^3/s)	.res

27.2 PONDS/WETLANDS

Ponds and wetlands are water bodies located within subbasins that received inflow from a fraction of the subbasin area. The algorithms used to model these two types of water bodies differ only in the options allowed for outflow calculation.

The water balance for a pond or wetland is:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \qquad 27.2.1$$

where V is the volume of water in the impoundment at the end of the day (m^3 H_2O), V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3 H_2O), V_{flowin} is the volume of water entering the water body during the day (m^3 H_2O), $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), V_{pcp} is the volume of precipitation falling on the water body during the day (m^3 H_2O), V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H_2O), and V_{seep} is the volume of water lost from the water body by seepage (m^3 H_2O).

27.2.1 SURFACE AREA

The surface area of the pond or wetland is needed to calculate the amount of precipitation falling on the water body as well as the amount of evaporation and seepage. Surface area varies with change in the volume of water stored in the impoundment. The surface area is updated daily using the equation:

$$SA = \beta_{sa} \cdot V^{expsa} \qquad 27.2.2$$

where SA is the surface area of the water body (ha), β_{sa} is a coefficient, V is the volume of water in the impoundment (m^3 H$_2$O), and *expsa* is an exponent.

The coefficient, β_{sa}, and exponent, *expsa*, are calculated by solving equation 27.1.2 using two known points. For ponds, the two known points are surface area and volume information provided for the principal and emergency spillways.

$$expsa = \frac{\log_{10}(SA_{em}) - \log_{10}(SA_{pr})}{\log_{10}(V_{em}) - \log_{10}(V_{pr})} \qquad 27.2.3$$

$$\beta_{sa} = \left(\frac{SA_{em}}{V_{em}}\right)^{expsa} \qquad 27.2.4$$

where SA_{em} is the surface area of the pond when filled to the emergency spillway (ha), SA_{pr} is the surface area of the pond when filled to the principal spillway (ha), V_{em} is the volume of water held in the pond when filled to the emergency spillway (m^3 H$_2$O), and V_{pr} is the volume of water held in the pond when filled to the principal spillway (m^3 H$_2$O). For wetlands, the two known points are surface area and volume information provided for the maximum and normal water levels.

$$expsa = \frac{\log_{10}(SA_{mx}) - \log_{10}(SA_{nor})}{\log_{10}(V_{mx}) - \log_{10}(V_{nor})} \qquad 27.2.5$$

$$\beta_{sa} = \left(\frac{SA_{mx}}{V_{mx}}\right)^{expsa} \qquad 27.2.6$$

where SA_{mx} is the surface area of the wetland when filled to the maximum water level (ha), SA_{nor} is the surface area of the wetland when filled to the normal water level (ha), V_{mx} is the volume of water held in the wetland when filled to the maximum water level (m^3 H_2O), and V_{nor} is the volume of water held in the wetland when filled to the normal water level (m^3 H_2O).

27.2.2 PRECIPITATION

The volume of precipitation falling on the pond or wetland during a given day is calculated:

$$V_{pcp} = 10 \cdot R_{day} \cdot SA \qquad 27.2.7$$

where V_{pcp} is the volume of water added to the water body by precipitation during the day (m^3 H_2O), R_{day} is the amount of precipitation falling on a given day (mm H_2O), and SA is the surface area of the water body (ha).

27.2.3 INFLOW

The volume of water entering the pond or wetland on a given day is calculated:

$$V_{flowin} = fr_{imp} \cdot 10 \cdot \left(Q_{surf} + Q_{gw} + Q_{lat}\right) \cdot \left(Area - SA\right) \qquad 27.2.8$$

where V_{flowin} is the volume of water flowing into the water body on a given day (m^3 H_2O), fr_{imp} is the fraction of the subbasin area draining into the impoundment, Q_{surf} is the surface runoff from the subbasin on a given day (mm H_2O), Q_{gw} is the groundwater flow generated in a subbasin on a given day (mm H_2O), Q_{lat} is the lateral flow generated in a subbasin on a given day (mm H_2O), $Area$ is the subbasin area (ha), and SA is the surface area of the water body (ha). The volume of water entering the pond or wetland is subtracted from the surface runoff, lateral flow and groundwater loadings to the main channel.

27.2.4 EVAPORATION

The volume of water lost to evaporation on a given day is calculated:

$$V_{evap} = 10 \cdot \eta \cdot E_o \cdot SA \qquad 27.2.9$$

where V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H_2O), η is an evaporation coefficient (0.6), E_o is the potential evapotranspiration for a given day (mm H_2O), and SA is the surface area of the water body (ha).

27.2.5 SEEPAGE

The volume of water lost by seepage through the bottom of the pond or wetland on a given day is calculated:

$$V_{seep} = 240 \cdot K_{sat} \cdot SA \qquad 27.2.10$$

where V_{seep} is the volume of water lost from the water body by seepage (m^3 H_2O), K_{sat} is the effective saturated hydraulic conductivity of the pond or wetland bottom (mm/hr), and SA is the surface area of the water body (ha).

27.2.6 OUTFLOW

The primary difference between ponds and wetlands is the method in which the outflow is calculated.

27.2.6.1 POND OUTFLOW

Pond outflow is calculated as a function of target storage. The target storage varies based on flood season and soil water content. The target pond volume is calculated:

$$V_{targ} = V_{em} \qquad \text{if } mon_{fld,beg} < mon < mon_{fld,end} \qquad 27.2.11$$

$$V_{targ} = V_{pr} + \frac{\left(1 - \min\left[\frac{SW}{FC},\ 1\right]\right)}{2} \cdot \left(V_{em} - V_{pr}\right)$$

$$\text{if } mon \le mon_{fld,beg} \text{ or } mon \ge mon_{fld,end} \qquad 27.2.12$$

where V_{targ} is the target pond volume for a given day (m^3 H_2O), V_{em} is the volume of water held in the pond when filled to the emergency spillway (m^3 H_2O), V_{pr} is the volume of water held in the pond when filled to the principal spillway (m^3 H_2O), SW is the average soil water content in the subbasin (mm H_2O), FC is the water content of the subbasin soil at field capacity (mm H_2O), mon is the month of the year, $mon_{fld,beg}$ is the beginning month of the flood season, and $mon_{fld,end}$ is the ending month of the flood season.

Once the target storage is defined, the outflow is calculated:

$$V_{flowout} = \frac{V - V_{targ}}{ND_{targ}} \qquad 27.2.13$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), V is the volume of water stored in the pond (m^3 H_2O), V_{targ} is the target pond volume for a given day (m^3 H_2O), and ND_{targ} is the number of days required for the pond to reach target storage.

27.2.6.2 WETLAND OUTFLOW

The wetland releases water whenever the water volume exceeds the normal storage volume, V_{nor}. Wetland outflow is calculated:

$$V_{flowout} = 0 \qquad \text{if } V < V_{nor} \qquad 27.2.14$$

$$V_{flowout} = \frac{V - V_{nor}}{10} \qquad \text{if } V_{nor} \le V \le V_{mx} \qquad 27.2.15$$

$$V_{flowout} = V - V_{mx} \qquad \text{if } V > V_{mx} \qquad 27.2.16$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), V is the volume of water stored in the wetland (m^3 H_2O), V_{mx} is the volume of water held in the wetland when filled to the maximum water level (m^3 H_2O), and V_{nor} is the volume of water held in the wetland when filled to the normal water level (m^3 H_2O).

Table 27-2: SWAT input variables that pertain to ponds and wetlands.

Variable name	Definition	File Name
PND_ESA	SA_{em}: Surface area of the pond when filled to the emergency spillway (ha)	.pnd
PND_PSA	SA_{pr}: Surface area of the pond when filled to the principal spillway (ha)	.pnd
PND_EVOL	V_{em}: Volume of water held in the pond when filled to the emergency spillway (10^4 m^3 H_2O)	.pnd
PND_PVOL	V_{pr}: Volume of water held in the pond when filled to the principal spillway (10^4 m^3 H_2O)	.pnd
WET_MXSA	SA_{mx}: Surface area of the wetland when filled to the maximum water level (ha)	.pnd
WET_NSA	SA_{nor}: Surface area of the wetland when filled to the normal water level (ha)	.pnd
WET_MXVOL	V_{mx}: Volume of water held in the wetland when filled to the maximum water level (m^3 H_2O)	.pnd
WET_NVOL	V_{nor}: Volume of water held in the wetland when filled to the normal water level (m^3 H_2O)	.pnd
PND_FR	fr_{imp}: Fraction of the subbasin area draining into the pond	.pnd
WET_FR	fr_{imp}: Fraction of the subbasin area draining into the wetland	.pnd

Table 27-2, cont.: SWAT input variables that pertain to ponds and wetlands

Variable name	Definition	File Name
PND_K	K_{sat}: Effective saturated hydraulic conductivity of the pond bottom (mm/hr)	.pnd
WET_K	K_{sat}: Effective saturated hydraulic conductivity of the wetland bottom (mm/hr)	.pnd
IFLOD1	$mon_{fld,beg}$: Beginning month of the flood season	.pnd
IFLOD2	$mon_{fld,end}$: Ending month of the flood season	.pnd
NDTARG	ND_{targ}: Number of days required for the reservoir to reach target storage	.pnd

27.3 DEPRESSIONS/POTHOLES

In areas of low relief and/or young geologic development, the drainage network may be poorly developed. Watersheds in these areas may have many closed depressional areas, referred to as potholes. Runoff generated within these areas flows to the lowest portion of the pothole rather than contributing to flow in the main channel. Other systems that are hydrologically similar to potholes include playa lakes and fields that are artifically impounded for rice production. The algorithms reviewed in this section are used to model these types of systems.

To define an HRU as a pothole, the user must set IPOT (.hru) to the HRU number. To initiate water impoundment, a release/impound operation must be placed in the .mgt file. The water balance for a pothole is:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \qquad 27.3.1$$

where V is the volume of water in the impoundment at the end of the day (m^3 H_2O), V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3 H_2O), V_{flowin} is the volume of water entering the water body during the day (m^3 H_2O), $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), V_{pcp} is the volume of precipitation falling on the water body during the day (m^3 H_2O), V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H_2O), and V_{seep} is the volume of water lost from the water body by seepage (m^3 H_2O).

27.3.1 SURFACE AREA

The surface area of the pothole is needed to calculate the amount of precipitation falling on the water body as well as the amount of evaporation and seepage. Surface area varies with change in the volume of water stored in the impoundment. For surface area calculations, the pothole is assumed to be cone-shaped. The surface area is updated daily using the equation:

$$SA = \frac{\pi}{10^4} \cdot \left(\frac{3 \cdot V}{\pi \cdot slp} \right)^{2/3} \qquad 27.3.2$$

where SA is the surface area of the water body (ha), V is the volume of water in the impoundment (m^3 H_2O), and slp is the slope of the HRU (m/m).

27.3.2 PRECIPITATION

The volume of precipitation falling on the pothole during a given day is calculated:

$$V_{pcp} = 10 \cdot R_{day} \cdot SA \qquad 27.3.3$$

where V_{pcp} is the volume of water added to the water body by precipitation during the day (m^3 H_2O), R_{day} is the amount of precipitation falling on a given day (mm H_2O), and SA is the surface area of the water body (ha).

27.3.3 INFLOW

Water entering the pothole on a given day may be contributed from any HRU in the subbasin. To route a portion of the flow from an HRU into a pothole, the variable IPOT (.hru) is set to the number of the HRU containing the pothole and POT_FR (.hru) is set to the fraction of the HRU area that drains into the pothole. This must be done for each HRU contributing flow to the pothole. Water routing from other HRUs is performed only during the period that water impoundment has been activated (release/impound operation in .mgt). Water may also be added to the pothole with an irrigation operation in the management file (.mgt). Chapter 21 reviews the irrigation operation.

The inflow to the pothole is calculated:

$$V_{flowin} = irr + \sum_{hru=1}^{n} \left[fr_{pot,hru} \cdot 10 \cdot \left(Q_{surf,hru} + Q_{gw,hru} + Q_{lat,hru} \right) \cdot area_{hru} \right] \qquad 27.3.4$$

where V_{flowin} is the volume of water flowing into the pothole on a given day (m^3 H_2O), irr is the amount of water added through an irrigation operation on a given day (m^3 H_2O), n is the number of HRUs contributing water to the pothole, $fr_{pot,hru}$

is the fraction of the HRU area draining into the pothole, $Q_{surf,hru}$ is the surface runoff from the HRU on a given day (mm H_2O), $Q_{gw,hru}$ is the groundwater flow generated in the HRU on a given day (mm H_2O), $Q_{lat,hru}$ is the lateral flow generated in the HRU on a given day (mm H_2O), and $area_{hru}$ is the HRU area (ha).

27.3.4 EVAPORATION

The volume of water lost to evaporation on a given day is calculated:

$$V_{evap} = 10 \cdot \left(1 - \frac{LAI}{LAI_{evap}}\right) \cdot E_o \cdot SA \qquad \text{if } LAI < LAI_{evap} \qquad 27.3.5$$

$$V_{evap} = 0 \qquad \text{if } LAI \geq LAI_{evap} \qquad 27.3.6$$

where V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H_2O), LAI is the leaf area index of the plants growing in the pothole, LAI_{evap} is the leaf area index at which no evaporation occurs from the water surface, E_o is the potential evapotranspiration for a given day (mm H_2O), and SA is the surface area of the water body (ha).

27.3.5 SEEPAGE

The volume of water lost by seepage through the bottom of the pothole on a given day is calculated as a function of the water content of the soil profile beneath the pothole.

$$V_{seep} = 240 \cdot K_{sat} \cdot SA \qquad \text{if } SW < 0.5 \cdot FC \qquad 27.3.7$$

$$V_{seep} = 240 \cdot \left(1 - \frac{SW}{FC}\right) \cdot K_{sat} \cdot SA \qquad \text{if } 0.5 \cdot FC \leq SW < FC \qquad 27.3.8$$

$$V_{seep} = 0 \qquad \text{if } SW \geq FC \qquad 27.3.9$$

where V_{seep} is the volume of water lost from the water body by seepage (m^3 H_2O), K_{sat} is the effective saturated hydraulic conductivity of the 1st soil layer in the profile (mm/hr), SA is the surface area of the water body (ha), SW is the soil water content of the profile on a given day (mm H_2O), and FC is the field capacity soil water content (mm H_2O). Water lost from the pothole by seepage is added to the soil profile.

27.3.6 OUTFLOW

Water may be removed from the pothole in three different types of outflow. When the volume of water in the pothole exceeds the maximum storage, the excess water is assumed to overflow and enter the main channel in the subbasin. When the retaining wall or berm is removed (this is done with a release/impound operation in the management file), all water stored in the pothole enters the main channel. The third type of flow from the pothole is via drainage tiles installed in the pothole.

27.3.6.1 OVERFLOW

Pothole outflow caused by overflow is calculated:

$$V_{flowout} = V - V_{pot,mx} \qquad \text{if } V > V_{pot.mx} \qquad 27.3.10$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), V is the volume of water stored in the pothole (m^3 H_2O), and $V_{pot,mx}$ is the maximum amount of water that can be stored in the pothole (m^3 H_2O).

27.3.6.2 RELEASE OPERATION

When a release operation is scheduled, all water in the pothole becomes outflow:

$$V_{flowout} = V \qquad 27.3.11$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), and V is the volume of water stored in the pothole (m^3 H_2O).

27.3.6.3 TILE FLOW

When drainage tiles are installed in a pothole, the pothole will contribute water to the main channel through tile flow. The pothole outflow originating from tile drainage is:

$$V_{flowout} = q_{tile} \cdot 86400 \qquad \text{if } V > q_{tile} \cdot 86400 \qquad 27.3.12$$

$$V_{flowout} = V \qquad \text{if } V \le q_{tile} \cdot 86400 \qquad 27.3.13$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), q_{tile} is the average daily tile flow rate (m^3/s), and V is the volume of water stored in the pothole (m^3 H_2O).

Table 27-3: SWAT input variables that pertain to potholes.

Variable name	**Definition**	**File Name**
IPOT	Number of HRU that is impounding water (that contains the pothole)	.hru
Variables in release/impound operation line:		
MONTH/DAY or HUSC	Timing of release/impound operation.	.mgt
MGT_OP	Operation code. MGT_OP = 13 for release/impound operation	.mgt
IREL_IMP	Release/impound action code: 0: impound, 1: release	.mgt
SLOPE	slp: Slope of the HRU (m/m)	.hru
POT_FR	fr_{pot}: Fraction of the HRU area draining into the pothole	.hru
EVLAI	LAI_{evap}: Leaf area index at which no evaporation occurs from the water surface	.bsn
POT_VOLX	$V_{pot,mx}$: Maximum amount of water that can be stored in the pothole (m^3 H_2O)	.hru
POT_TILE	q_{tile}: Average daily tile flow rate (m^3/s)	.hru

27.4 NOMENCLATURE

$Area$	Subbasin area (ha)
E_o	Potential evapotranspiration for a given day (mm H_2O)
FC	Water content of the soil at field capacity (mm H_2O)
K_{sat}	Effective saturated hydraulic conductivity of the reservoir bottom (mm/hr)
LAI	Leaf area index of the plants growing in the pothole
LAI_{evap}	Leaf area index at which no evaporation occurs from the water surface
ND_{targ}	Number of days required for the reservoir to reach target storage
Q_{gw}	Groundwater flow generated in a subbasin on a given day (mm H_2O)
Q_{lat}	Lateral flow generated in a subbasin on a given day (mm H_2O)
Q_{surf}	Surface runoff from the subbasin on a given day (mm H_2O)
R_{day}	Amount of precipitation falling on a given day (mm H_2O)
SA	Surface area of the water body (ha)
SA_{em}	Surface area of the reservoir or pond when filled to the emergency spillway (ha)
SA_{mx}	Surface area of the wetland when filled to the maximum water level (ha)
SA_{nor}	Surface area of the wetland when filled to the normal water level (ha)
SA_{pr}	Surface area of the reservoir when filled to the principal spillway (ha)
SW	Average soil water content (mm H_2O)
V	Volume of water in the impoundment at the end of the day (m^3 H_2O)
V_{em}	Volume of water held in the reservoir when filled to the emergency spillway (m^3 H_2O)
V_{evap}	Volume of water removed from the water body by evaporation during the day (m^3 H_2O)
V_{flowin}	Volume of water entering the water body during the day (m^3 H_2O)

$V_{flowout}$	Volume of water flowing out of the water body during the day (m^3 H_2O)
$V'_{flowout}$	Initial estimate of the volume of water flowing out of the water body during the day (m^3 H_2O)
V_{mx}	Volume of water held in the wetland when filled to the maximum water level (m^3 H_2O)
V_{nor}	Volume of water held in the wetland when filled to the normal water level (m^3 H_2O)
V_{pcp}	Volume of precipitation falling on the water body during the day (m^3 H_2O)
$V_{pot,mx}$	Maximum amount of water that can be stored in the pothole (m^3 H_2O)
V_{pr}	Volume of water held in the reservoir when filled to the principal spillway (m^3 H_2O)
V_{seep}	Volume of water lost from the water body by seepage (m^3 H_2O)
V_{stored}	Volume of water stored in the water body at the beginning of the day (m^3 H_2O)
V_{targ}	Target reservoir volume for a given day (m^3 H_2O)

$area_{hru}$	HRU area (ha)
$expsa$	Exponent for impoundment surface area calculation
fr_{imp}	Fraction of the subbasin area draining into the impoundment
fr_{pot}	Fraction of the HRU area draining into the pothole
irr	Amount of irrigation water added on a given day (m^3 H_2O)
mon	Month of the year
$mon_{fld,beg}$	Beginning month of the flood season
$mon_{fld,end}$	Ending month of the flood season
q_{out}	Outflow rate (m^3/s)
q_{rel}	Average daily principal spillway release rate (m^3/s)
$q_{rel,mn}$	Minimum average daily outflow for the month (m^3/s)
$q_{rel,mx}$	Maximum average daily outflow for the month (m^3/s)
q_{tile}	Average daily tile flow rate (m^3/s)
slp	Slope of the HRU (m/m)
$starg$	Target reservoir volume specified for a given month (m^3 H_2O)

β_{sa}	Coefficient for impoundment surface area equation
η	Evaporation coefficient (0.6)

27.5 REFERENCES

Ward, A.D. and W.J. Elliot. 1995. Environmental hydrology. Lewis Publishers, CRC Press, Inc., Boca Raton, FL.

CHAPTER 28

EQUATIONS: SEDIMENT IN WATER BODIES

SWAT incorporates a simple mass balance model to simulate the transport of sediment into and out of water bodies. SWAT defines four different types of water bodies: ponds, wetlands, reservoirs and potholes. Sediment processes modeled in ponds, wetlands, reservoirs, and potholes are identical.

When calculating sediment movement through a water body, SWAT assumes the system is completely mixed. In a completely mixed system, as sediment enters the water body it is instantaneously distributed throughout the volume.

28.1 MASS BALANCE

The mass balance equation for sediment in a water body is:

$$sed_{wb} = sed_{wb,i} + sed_{flowin} - sed_{stl} - sed_{flowout} \qquad 28.1.1$$

where sed_{wb} is the amount of sediment in the water body at the end of the day (metric tons), $sed_{wb,i}$ is the amount of sediment in the water body at the beginning of the day (metric tons), sed_{flowin} is the amount of sediment added to the water body with inflow (metric tons), sed_{stl} is the amount of sediment removed from the water by settling (metric tons), $sed_{flowout}$ is the amount of sediment transported out of the water body with outflow (metric tons).

28.2 SETTLING

The amount of suspended solid settling that occurs in the water body on a given day is calculated as a function of concentration. The initial suspended solid concentration is:

$$conc_{sed,i} = \frac{\left(sed_{wb,i} + sed_{flowin}\right)}{\left(V_{stored} + V_{flowin}\right)} \qquad 28.2.1$$

where $conc_{sed,i}$ is the initial concentration of suspended solids in the water (Mg/m^3), $sed_{wb,i}$ is the amount of sediment in the water body at the beginning of the day (metric tons), sed_{flowin} is the amount of sediment added to the water body with inflow (metric tons), V_{stored} is the volume of water stored in water body or channel at the beginning of the day (m^3 H_2O), and V_{flowin} is the volume of water entering water body on given day (m^3 H_2O).

Settling occurs only when the sediment concentration in the water body exceeds the equilibrium sediment concentration specified by the user, $conc_{sed,eq}$. The concentration of sediment in the water body at the end of the day is calculated:

$$conc_{sed,f} = \left(conc_{sed,i} - conc_{sed,eq}\right)\cdot \exp\left[-k_s \cdot t \cdot d_{50}\right] + conc_{sed,eq} \quad \text{if } conc_{sed,i} > conc_{sed,eq} \qquad 28.2.2$$

$$conc_{sed,f} = conc_{sed,i} \quad \text{if } conc_{sed,i} \leq conc_{sed,eq} \qquad 28.2.3$$

where $conc_{sed,f}$ is the final sediment concentration in the water body (Mg/m^3), $conc_{sed,i}$ is the initial concentration of suspended solids in the water body (Mg/m^3), $conc_{sed,eq}$ is the equilibrium concentration of suspended solids in the water body (Mg/m^3), k_s is the decay constant (1/day), t is the length of the time step (1 day), and d_{50} is the median particle size of the inflow sediment (µm). Assuming 99% of the 1 µm size particles settle out of solution within 25 days, k_s is equal to 0.184. The median particle size of the inflow sediment is calculated:

$$d_{50} = \exp\left(0.41 \cdot \frac{m_c}{100} + 2.71 \cdot \frac{m_{silt}}{100} + 5.7 \cdot \frac{m_s}{100}\right) \qquad 28.2.4$$

where d_{50} is the median particle size of the inflow sediment (µm), m_c is percent clay in the surface soil layer in the subbasin, m_{silt} is the percent silt in the surface soil layer in the subbasin, m_s is the percent sand in the surface soil layer in the subbasin.

The amount of sediment settling out of solution on a given day is then calculated:

$$sed_{stl} = \left(conc_{sed,i} - conc_{sed,f}\right) \cdot V \qquad 28.2.5$$

where sed_{stl} is the amount of sediment removed from the water by settling (metric tons), $conc_{sed,i}$ is the initial concentration of suspended solids in the water body (Mg/m^3), $conc_{sed,f}$ is the final sediment concentration in the water body (Mg/m^3), and V is the volume of water in the impoundment (m^3 H_2O).

Table 28-1: SWAT input variables that pertain to sediment settling.

Variable Name	**Definition**	**Input File**
RES_NSED	$conc_{sed,eq}$: Equilibrium sediment concentration in water body (mg/L)	.res
PND_NSED	$conc_{sed,eq}$: Equilibrium sediment concentration in water body (mg/L)	.pnd
WET_NSED	$conc_{sed,eq}$: Equilibrium sediment concentration in water body (mg/L)	.pnd
POT_NSED	$conc_{sed,eq}$: Equilibrium sediment concentration in water body (mg/L)	.hru
CLAY	m_c: Percent clay in the surface soil layer in the subbasin	.sol
SILT	m_{silt}: Percent silt in the surface soil layer in the subbasin	.sol
SAND	m_s: Percent sand in the surface soil layer in the subbasin	.sol

28.3 SEDIMENT OUTFLOW

The amount of sediment transported out of the water body on a given day is calculated as a function of the final concentration. The initial suspended solid concentration is:

$$sed_{flowout} = conc_{sed,f} \cdot V_{flowout} \qquad 28.3.1$$

where $sed_{flowout}$ is the amount of sediment transported out of the water body with outflow (metric tons), $conc_{sed,f}$ is the final sediment concentration in the water body (Mg/m^3), and $V_{flowout}$ is the volume of outflow from the impoundment (m^3 H_2O).

28.4 NOMENCLATURE

V	Volume of water in the impoundment (m^3 H_2O)
V_{flowin}	Volume of water entering water body on given day (m^3 H_2O)
$V_{flowout}$	Volume of outflow from the impoundment (m^3 H_2O)
V_{stored}	Volume of water stored in water body or channel (m^3 H_2O)
$conc_{sed}$	Concentration of suspended solids in the water (Mg/m^3)
$conc_{sed,eq}$	Equilibrium concentration of suspended solids in the water body (Mg/m^3)
d_{50}	Median particle size of the inflow sediment (µm)
k_s	Decay constant (1/day)
t	Length of the time step (1 day)
m_c	Percent clay in the surface soil layer in the subbasin
m_s	Percent sand in the surface soil layer in the subbasin
m_{silt}	Percent silt in the surface soil layer in the subbasin
sed_{flowin}	Amount of sediment added to the water body with inflow (metric tons)
$sed_{flowout}$	Amount of sediment transported out of the water body (metric tons)
sed_{stl}	Amount of sediment removed from the water by settling (metric tons)
sed_{wb}	Sediment in the water body (metric tons)

CHAPTER 29

EQUATIONS: NUTRIENTS IN WATER BODIES

SWAT incorporates a simple empirical model to predict the trophic status of water bodies. For studies that require detailed modeling of lake water quality, SWAT has been linked to distributed lake water quality models such as WASP.

SWAT defines four different types of water bodies: ponds, wetlands, reservoirs and depressional/impounded areas (potholes). Nutrient processes modeled in ponds, wetlands and reservoirs are identical. Nutrient processes are not yet modeled in potholes.

29.1 NUTRIENT TRANSFORMATIONS

When calculating nutrient transformations in a water body, SWAT assumes the system is completely mixed. In a completely mixed system, as nutrients enter the water body they are instantaneously distributed throughout the volume. The assumption of a completely mixed system ignores lake stratification and intensification of phytoplankton in the epilimnion.

The initial amount of nitrogen and phosphorus in the water body on the given day is calculated by summing the mass of nutrient entering the water body on that day with the mass of nutrient already present in the water body.

$$M_{initial} = M_{stored} + M_{flowin} \qquad 29.1.1$$

where $M_{initial}$ is the initial mass of nutrient in the water body for the given day (kg), M_{stored} is the mass of nutrient in the water body at the end of the previous day (kg), and M_{flowin} is the mass of nutrient added to the water body on the given day (kg).

In a similar manner, the initial volume of water in the water body is calculated by summing the volume of water entering the water body on that day with the volume already present in the water body.

$$V_{initial} = V_{stored} + V_{flowin} \qquad 29.1.2$$

where $V_{initial}$ is the initial volume of water in the water body for a given day (m^3 H_2O), V_{stored} is the volume of water in the water body at the end of the previous day (m^3 H_2O), and V_{flowin} is the volume of water entering the water body on the given day (m^3 H_2O).

The initial concentration of nutrients in the water body is calculated by dividing the initial mass of nutrient by the initial volume of water.

Nutrient transformations simulated in ponds, wetlands and reservoirs are limited to the removal of nutrients by settling. Transformations between nutrient pools (e.g. $NO_3 \Leftrightarrow NO_2 \Leftrightarrow NH_4$) are ignored.

Settling losses in the water body can be expressed as a flux of mass across the surface area of the sediment-water interface (Figure 29-1) (Chapra, 1997).

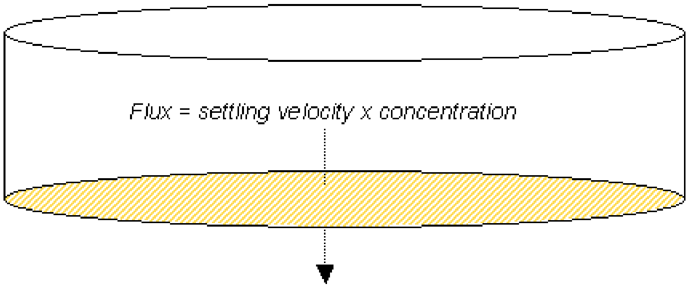

Figure 29-1: Settling losses calculated as flux of mass across the sediment-water interface.

The mass of nutrient lost via settling is calculated by multiplying the flux by the area of the sediment-water interface.

$$M_{settling} = v \cdot c \cdot A_s \cdot dt \qquad 29.1.3$$

where $M_{settling}$ is the mass of nutrient lost via settling on a day (kg), v is the apparent settling velocity (m/day), A_s is the area of the sediment-water interface (m^2), c is the initial concentration of nutrient in the water (kg/m^3 H_2O), and dt is the length of the time step (1 day). The settling velocity is labeled as “apparent” because it represents the net effect of the different processes that deliver nutrients to the water body’s sediments. The water body is assumed to have a uniform depth of water and the area of the sediment-water interface is equivalent to the surface area of the water body.

The apparent settling velocity is most commonly reported in units of m/year and this is how the values are input to the model. For natural lakes, measured phosphorus settling velocities most frequently fall in the range of 5 to 20 m/year although values less than 1 m/year to over 200 m/year have been reported (Chapra, 1997). Panuska and Robertson (1999) noted that the range in apparent settling velocity values for man-made reservoirs tends to be significantly greater than for natural lakes. Higgins and Kim (1981) reported phosphorus apparent settling velocity values from –90 to 269 m/year for 18 reservoirs in Tennessee with a median value of 42.2 m/year. For 27 Midwestern reservoirs, Walker and Kiihner (1978) reported phosphorus apparent settling velocities ranging from –1 to 125 m/year with an average value of 12.7 m/year. ***A negative settling rate indicates that the reservoir sediments are a source of N or P; a positive settling rate indicates that the reservoir sediments are a sink for N or P***.

A number of inflow and impoundment properties affect the apparent settling velocity for a water body. Factors of particular importance include the form of phosphorus in the inflow (dissolved or particulate) and the settling velocity of the particulate fraction. Within the impoundment, the mean depth, potential for sediment resuspension and phosphorus release from the sediment will affect the apparent settling velocity (Panuska and Robertson, 1999). Water bodies with high internal phosphorus release tend to possess lower phosphorus retention and lower phosphorus apparent settling velocities than water bodies with low internal phosphorus release (Nürnberg, 1984). Table 29-1 summarizes typical ranges in phosphorus settling velocity for different systems.

Table 29-1: Recommended apparent settling velocity values for phosphorus (Panuska and Robertson, 1999)

Nutrient Dynamics	**Range in settling velocity values (m/year)**
Shallow water bodies with high net internal phosphorus flux	$\nu \leq 0$
Water bodies with moderate net internal phosphorus flux	$1 < \nu < 5$
Water bodies with minimal net internal phosphorus flux	$5 < \nu < 16$
Water bodies with high net internal phosphorus removal	$\nu > 16$

SWAT input variables that pertain to nutrient settling in ponds, wetlands and reservoirs are listed in Table 29-2. The model allows the user to define two settling rates for each nutrient and the time of the year during which each settling rate is used. A variation in settling rates is allowed so that impact of temperature and other seasonal factors may be accounted for in the modeling of nutrient settling. To use only one settling rate for the entire year, both variables for the nutrient may be set to the same value. Setting all variables to zero will cause the model to ignore settling of nutrients in the water body.

After nutrient losses in the water body are determined, the final concentration of nutrients in the water body is calculated by dividing the final mass of nutrient by the initial volume of water. The concentration of nutrients in outflow from the water body is equivalent to the final concentration of the nutrients in the water body for the day. The mass of nutrient in the outflow is calculated by multiplying the concentration of nutrient in the outflow by the volume of water leaving the water body on that day.

Table 29-2: SWAT input variables that control settling in ponds, wetlands and reservoirs.

Variable Name	Definition	Input File
IPND1	Beginning month of mid-year nutrient settling period for pond and wetland modeled in subbasin	.pnd
IPND2	Ending month of mid-year nutrient settling period for pond and wetland modeled in subbasin	.pnd
PSETL1	Phosphorus settling rate in pond during mid-year nutrient settling period ($IPND1 \leq month \leq IPND2$) (m/year)	.pnd
PSETL2	Phosphorus settling rate in pond during time outside mid-year nutrient settling period ($month < IPND1$ *or* $month > IPND2$) (m/year)	.pnd
NSETL1	Nitrogen settling rate in pond during mid-year nutrient settling period ($IPND1 \leq month \leq IPND2$) (m/year)	.pnd
NSETL2	Nitrogen settling rate in pond during time outside mid-year nutrient settling period ($month < IPND1$ *or* $month > IPND2$) (m/year)	.pnd
PSETLW1	Phosphorus settling rate in wetland during mid-year nutrient settling period ($IPND1 \leq month \leq IPND2$) (m/year)	.pnd
PSETLW2	Phosphorus settling rate in wetland during time outside mid-year nutrient settling period ($month < IPND1$ *or* $month > IPND2$) (m/year)	.pnd
NSETLW1	Nitrogen settling rate in wetland during mid-year nutrient settling period ($IPND1 \leq month \leq IPND2$) (m/year)	.pnd
NSETLW2	Nitrogen settling rate in wetland during time outside mid-year nutrient settling period ($month < IPND1$ *or* $month > IPND2$) (m/year)	.pnd
IRES1	Beginning month of mid-year nutrient settling period for reservoir	.lwq
IRES2	Ending month of mid-year nutrient settling period for reservoir	.lwq
PSETLR1	Phosphorus settling rate in reservoir during mid-year nutrient settling period ($IRES1 \leq month \leq IRES2$) (m/year)	.lwq
PSETLR2	Phosphorus settling rate in reservoir during time outside mid-year nutrient settling period ($month < IRES1$ *or* $month > IRES2$) (m/year)	.lwq
NSETLR1	Nitrogen settling rate in reservoir during mid-year nutrient settling period ($IRES1 \leq month \leq IRES2$) (m/year)	.lwq
NSETLR2	Nitrogen settling rate in reservoir during time outside mid-year nutrient settling period ($month < IRES1$ *or* $month > IRES2$) (m/year)	.lwq

29.2 TOTAL BALANCE

Assuming that the volume of the water body remains constant over time, the processes described above (inflow, settling, outflow) can be combined into the following mass balance equation for a well-mixed water body:

$$V \cdot \frac{dc}{dt} = W(t) - Q \cdot c - \nu \cdot c \cdot A_s \qquad 29.2.1$$

where V is the volume of the system (m^3 H_2O), c is the concentration of nutrient in the system (kg/m^3 H_2O), dt is the length of the time step (1 day), $W(t)$ is the amount of nutrient entering the water body during the day (kg/day), Q is the rate of water flow exiting the water body (m^3 H_2O/day), ν is the apparent settling velocity (m/day), and A_s is the area of the sediment-water interface (m^2).

29.3 EUTROPHICATION

Under favorable conditions of light and temperature, excess amounts of nutrients in water can increase the growth of algae and other plants. The result of this growth is an increase in the rate of eutrophication, which is a natural ecological process of change from a nutrient-poor to a nutrient-rich environment. Eutrophication is defined as the process by which a body of water becomes enriched in dissolved nutrients (as phosphates) that stimulate the growth of aquatic plant life, usually resulting in the depletion of dissolved oxygen (Merriam-Webster, Inc., 1996).

Nutrient enrichment of moving waters and lakes is a normal result of soil weathering and erosion processes. The gradual evolution of Ice Age lakes into marshes and, eventually, organic soils is a result of eutrophication. However, this process can be accelerated by the discharge of wastes containing high levels of nutrients into lakes or rivers. One example of this is Lake Erie, which is estimated to have aged the equivalent of 150 natural years in a 15-year span of accelerated eutrophication.

Excessive plant growth caused by accelerated eutrophication can lead to stagnation of the water. The stagnation is caused by an increased biological oxygen demand created by decaying plant remains. The result of this increased oxygen demand is a tendency toward anaerobic conditions and the inability of the water body to support fish and other aerobic organisms.

Nitrogen, carbon and phosphorus are essential to the growth of aquatic biota. Due to the difficulty of controlling the exchange of nitrogen and carbon between the atmosphere and water and fixation of atmospheric nitrogen by some blue-green algae, attempts to mitigate eutrophication have focused on phosphorus inputs. In fresh-water systems, phosphorus is often the limiting element. By controlling phosphorus loading, accelerated eutrophication of lake waters can be reduced.

In systems where phosphorus is the primary, controllable limiting nutrient of water body eutrophication, the amount of phosphorus present in the water body can be used to estimate the amount of eutrophication present in the water body.

29.3.1 PHOSPHORUS/CHLOROPHYLL *a* CORRELATIONS

A number of empirically derived equations have been developed to calculate chlorophyll *a* level as a function of total phosphorus concentration. SWAT uses an equation developed by Rast and Lee (1978) to calculate the chlorophyll *a* concentration in the water body.

$$Chla = 0.551 \cdot p^{0.76} \qquad 29.3.1$$

where $Chla$ is the chlorophyll *a* concentration (μg/L) and p is the total phosphorus concentration (μg/L).

The equation has been modified to include a user-defined coefficient:

$$Chla = Chla_{co} \cdot 0.551 \cdot p^{0.76} \qquad 29.3.2$$

The user-defined coefficient, $Chla_{co}$, is included to allow the user to adjust the predicted chlorophyll *a* concentration for limitations of nutrients other than phosphorus. When $Chla_{co}$ is set to 1.00, equation 29.3.2 is equivalent to equation 29.3.1. For most water bodies, the original equation will be adequate..

29.3.2 CHLOROPHYLL *a*/SECCHI-DISK DEPTH CORRELATION

The secchi-disk depth is another measure of the trophic status of a water body. The secchi-disk depth quantifies the clarity of the water, an attribute easily perceived by the general public. The secchi-disk depth can be calculated from chlorophyll levels using the equation (Chapra, 1997):

$$SD = 6.35 \cdot Chla^{-0.473} \qquad 29.3.3$$

where SD is the secchi-disk depth (m) and $Chla$ is the chlorophyll *a* concentration (μg/L).

For incorporation into SWAT, equation 29.3.3 was modified to include a user-defined coefficient:

$$SD = SD_{co} \cdot 6.35 \cdot Chla^{-0.473} \qquad 29.3.4$$

The user-defined coefficient, SD_{co}, is included to allow the user to adjust the predicted secchi-disk depth for impacts of suspended sediment and other particulate matter on water clarity that are ignored by the original equation. When SD_{co} is set to 1.00, equation 29.3.4 is equivalent to equation 29.3.3. For most water bodies, the original equation will be adequate.

While evaluation of water quality by secchi-disk depth measurements is subjective, some general correlations between secchi-disk depth and public perception of water quality have been made. One such correlation made for Annebessacook Lake in Maine (EPA, 1980) is given in Table 29-3.

Table 29-3: Relationship between secchi-disk depth and public perception of water quality.

Secchi-disk depth (m)	Public perception of water quality
0.0 – 0.9	gross pollution; water body totally unsuitable for recreation
1.0 – 1.9	algae blooms still evident; quality unacceptable for most uses
2.0 – 2.9	some complaints of declining water quality; some impairment of water use
3.0 – 3.9	satisfactory quality; no impairment of water use
4.0 – 4.9	excellent water quality; a positive factor encouraging use of lake
5.0 +	exceptional quality

Table 29-4: SWAT input variables that impact eutrophication calculations in ponds, wetlands and reservoirs.

Variable Name	Definition	Input File
CHLA	$Chla_{co}$ variable for calculation of chlorophyll *a* concentration in a pond	.pnd
CHLAW	$Chla_{co}$ variable for calculation of chlorophyll *a* concentration in a wetland	.pnd
CHLAR	$Chla_{co}$ variable for calculation of chlorophyll *a* concentration in a reservoir	.lwq
SECCI	SD_{co} variable for calculation of secchi-disk depth in a pond	.pnd
SECCIW	SD_{co} variable for calculation of secchi-disk depth in a wetland	.pnd
SECCIR	SD_{co} variable for calculation of secchi-disk depth in a reservoir	.lwq

29.4 NOMENCLATURE

A_s	Area of sediment-water interface (m^2)
$Chla$	Chlorophyll *a* concentration (μg/L)
$Chla_{co}$	User-defined coefficient to adjust predicted chlorophyll *a* concentration
M_{flowin}	Mass of nutrient entering water body on the given day (kg)
$M_{initial}$	Initial mass of nutrient in water body for the given day (kg)
$M_{settling}$	Mass of nutrient lost via settling on a given day (kg)
M_{stored}	Mass of nutrient in water body at end of previous day (kg)
Q	Volumetric flow rate for water exiting water body (m^3 H_2O/day)
SD	Secchi-disk depth (m)
SD_{co}	User-defined coefficient to adjust predicted secchi-disk depth
V	Volume of water in water body (assumed constant) (m^3 H_2O)
V_{flowin}	Volume of water entering water body on given day (m^3 H_2O)
$V_{initial}$	Initial volume of water in water body on given day (m^3 H_2O)
V_{stored}	Volume of water in water body at end of previous day (m^3 H_2O)
$W(t)$	Rate of nutrient loading (kg/day)
c	Concentration of nutrient in the water (kg/m^3 H_2O)
dt	Length of time step (1 day)
p	Total phosphorus concentration (μg P/L)
ν	Apparent settling velocity (m/day)

29.5 REFERENCES

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CHAPTER 30

EQUATIONS: PESTICIDES IN WATER BODIES

SWAT incorporates a simple mass balance developed by Chapra (1997) to model the transformation and transport of pesticides in water bodies. The model assumes a well-mixed layer of water overlying a sediment layer. Figure 30-1 illustrates the mechanisms affecting the pesticide mass balance in water bodies.

SWAT defines four different types of water bodies: ponds, wetlands, reservoirs and depressional/impounded areas (potholes). Pesticide processes are modeled only in reservoirs.

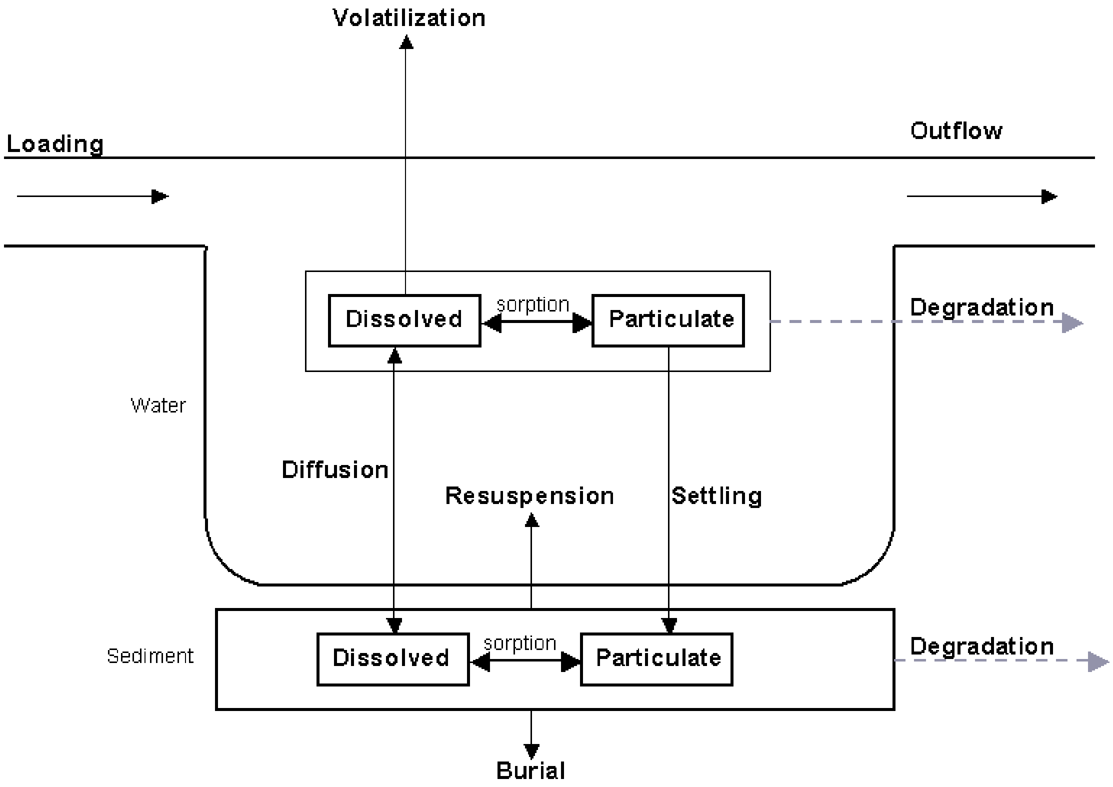

Figure 30-1: Pesticide mass balance for well-mixed water body with sediment layer (After Chapra, 1997).

30.1 PESTICIDE IN THE WATER

Pesticide in a well-mixed water body is increased through addition of mass in inflow, resuspension and diffusion from the sediment layer. The amount of pesticide in a well-mixed water body is reduced through removal in outflow, degradation, volatilization, settling and diffusion into the underlying sediment.

30.1.1 SOLID-LIQUID PARTITIONING

Pesticides will partition into particulate and dissolved forms. The fraction of pesticide in each phase is a function of the pesticide's partition coefficient and the water body's suspended solid concentration:

$$F_d = \frac{1}{1 + K_d \cdot conc_{sed}} \qquad 30.1.1$$

$$F_p = \frac{K_d \cdot conc_{sed}}{1 + K_d \cdot conc_{sed}} = 1 - F_d \qquad 30.1.2$$

where F_d is the fraction of total pesticide in the dissolved phase, F_p is the fraction of total pesticide in the particulate phase, K_d is the pesticide partition coefficient (m^3/g), and $conc_{sed}$ is the concentration of suspended solids in the water (g/m^3).

The pesticide partition coefficient can be estimated from the octanol-water partition coefficient (Chapra, 1997):

$$K_d = 3.085 \times 10^{-8} \cdot K_{ow} \qquad 30.1.3$$

where K_d is the pesticide partition coefficient (m^3/g) and K_{ow} is the pesticide's octanol-water partition coefficient ($\text{mg}\,\text{m}_{\text{octanol}}^{-3}\left(\text{mg}\,\text{m}_{\text{water}}^{-3}\right)^{-1}$). Values for the octanol-water partition coefficient have been published for many chemicals. If a published value cannot be found, it can be estimated from solubility (Chapra, 1997):

$$\log\left(K_{ow}\right) = 5.00 - 0.670 \cdot \log\left(pst'_{sol}\right) \qquad 30.1.4$$

where pst'_{sol} is the pesticide solubility (μmoles/L). The solubility in these units is calculated:

$$pst'_{sol} = \frac{pst_{sol}}{MW} \cdot 10^3 \qquad 30.1.5$$

where pst'_{sol} is the pesticide solubility (μmoles/L), pst_{sol} is the pesticide solubility (mg/L) and MW is the molecular weight (g/mole).

30.1.2 DEGRADATION

Pesticides in both the particulate and dissolved forms are subject to degradation. The amount of pesticide that is removed from the water via degradation is:

$$pst_{deg,wtr} = k_{p,aq} \cdot pst_{lkwtr} \qquad 30.1.6$$

where $pst_{deg,wtr}$ is the amount of pesticide removed from the water via degradation (mg pst), $k_{p,aq}$ is the rate constant for degradation or removal of pesticide in the water (1/day), and pst_{lkwtr} is the amount of pesticide in the water at the beginning of the day (mg pst). The rate constant is related to the aqueous half-life:

$$k_{p,aq} = \frac{0.693}{t_{1/2,aq}} \qquad 30.1.7$$

where $k_{p,aq}$ is the rate constant for degradation or removal of pesticide in the water (1/day), and $t_{1/2,aq}$ is the aqueous half-life for the pesticide (days).

30.1.3 VOLATILIZATION

Pesticide in the dissolved phase is available for volatilization. The amount of pesticide removed from the water via volatilization is:

$$pst_{vol,wtr} = v_v \cdot SA \cdot \frac{F_d \cdot pst_{lkwtr}}{V} \qquad 30.1.8$$

where $pst_{vol,wtr}$ is the amount of pesticide removed via volatilization (mg pst), v_v is the volatilization mass-transfer coefficient (m/day), SA is the surface area of the water body (m^2), F_d is the fraction of total pesticide in the dissolved phase, pst_{lkwtr} is the amount of pesticide in the water (mg pst), and V is the volume of water in the water body (m^3 H_2O).

The volatilization mass-transfer coefficient can be calculated based on Whitman's two-film or two-resistance theory (Whitman, 1923; Lewis and Whitman, 1924 as described in Chapra, 1997). While the main body of the gas and liquid phases are assumed to be well-mixed and homogenous, the two-film theory assumes that a substance moving between the two phases encounters maximum resistance in two laminar boundary layers where transfer is a function of molecular diffusion. In this type of system the transfer coefficient or velocity is:

$$v_v = K_l \cdot \frac{H_e}{H_e + R \cdot T_K \cdot \left(K_l / K_g\right)} \qquad 30.1.9$$

where v_v is the volatilization mass-transfer coefficient (m/day), K_l is the mass-transfer velocity in the liquid laminar layer (m/day), K_g is the mass-transfer velocity in the gaseous laminar layer (m/day), H_e is Henry's constant (atm m^3 mole^{-1}), R is the universal gas constant (8.206×10^{-5} atm m^3 (K mole)$^{-1}$), and T_K is the temperature (K).

For lakes, the transfer coefficients are estimated using a stagnant film approach:

$$K_l = \frac{D_l}{z_l} \qquad K_g = \frac{D_g}{z_g} \qquad 30.1.10$$

where K_l is the mass-transfer velocity in the liquid laminar layer (m/day), K_g is the mass-transfer velocity in the gaseous laminar layer (m/day), D_l is the liquid molecular diffusion coefficient (m^2/day), D_g is the gas molecular diffusion coefficient (m^2/day), z_l is the thickness of the liquid film (m), and z_g is the thickness of the gas film (m).

Alternatively, the transfer coefficients can be estimated with the equations:

$$K_l = K_{l,\mathrm{O_2}} \cdot \left(\frac{32}{MW} \right)^{0.25} \qquad 30.1.11$$

$$K_g = 168 \cdot \mu_w \cdot \left(\frac{18}{MW} \right)^{0.25} \qquad 30.1.12$$

where K_l is the mass-transfer velocity in the liquid laminar layer (m/day), K_g is the mass-transfer velocity in the gaseous laminar layer (m/day), $K_{l,\mathrm{O_2}}$ is the oxygen transfer coefficient (m/day), MW is the molecular weight of the compound, and μ_w is the wind speed (m/s). Chapra (1997) lists several different equations that can be used to calculate $K_{l,\mathrm{O_2}}$.

30.1.4 SETTLING

Pesticide in the particulate phase may be removed from the water layer by settling. Settling transfers pesticide from the water to the sediment layer. The amount of pesticide that is removed from the water via settling is:

$$pst_{stl,wtr} = v_s \cdot SA \cdot \frac{F_p \cdot pst_{lkwtr}}{V} \qquad 30.1.13$$

where $pst_{stl,wtr}$ is the amount of pesticide removed from the water due to settling (mg pst), v_s is the settling velocity (m/day), SA is the surface area of the water body (m^2), F_p is the fraction of total pesticide in the particulate phase, pst_{lkwtr} is the amount of pesticide in the water (mg pst), and V is the volume of water in the water body (m^3 H_2O).

30.1.5 OUTFLOW

Pesticide is removed from the water body in outflow. The amount of dissolved and particulate pesticide removed from the water body in outflow is:

$$pst_{sol,o} = Q \cdot \frac{F_d \cdot pst_{lkwtr}}{V} \quad 30.1.14$$

$$pst_{sorb,o} = Q \cdot \frac{F_p \cdot pst_{lkwtr}}{V} \quad 30.1.15$$

where $pst_{sol,o}$ is the amount of dissolved pesticide removed via outflow (mg pst), $pst_{sorb,o}$ is the amount of particulate pesticide removed via outflow (mg pst), Q is the rate of outflow from the water body (m^3 H_2O/day), F_d is the fraction of total pesticide in the dissolved phase, F_p is the fraction of total pesticide in the particulate phase, pst_{lkwtr} is the amount of pesticide in the water (mg pst), and V is the volume of water in the water body (m^3 H_2O).

Table 30-1: SWAT input variables that pesticide partitioning.

Variable Name	Definition	Input File
LKPST_KOC	K_d: Pesticide partition coefficient (m^3/g)	.lwq
LKPST_REA	$k_{p,aq}$: Rate constant for degradation or removal of pesticide in the water (1/day)	.lwq
LKPST_VOL	v_v: Volatilization mass-transfer coefficient (m/day)	.lwq
LKPST_STL	v_s: Pesticide settling velocity (m/day)	.lwq

30.2 PESTICIDE IN THE SEDIMENT

Pesticide in the sediment layer underlying a water body is increased through addition of mass by settling and diffusion from the water. The amount of pesticide in the sediment layer is reduced through removal by degradation, resuspension, diffusion into the overlying water, and burial.

30.2.1 SOLID-LIQUID PARTITIONING

As in the water layer, pesticides in the sediment layer will partition into particulate and dissolved forms. Calculation of the solid-liquid partitioning in the sediment layer requires a suspended solid concentration. The "concentration" of solid particles in the sediment layer is defined as:

$$conc^*_{sed} = \frac{M_{sed}}{V_{tot}} \quad 30.2.1$$

where $conc^*_{sed}$ is the "concentration" of solid particles in the sediment layer (g/m^3), M_{sed} is the mass of solid particles in the sediment layer (g) and V_{tot} is the total volume of the sediment layer (m^3).

Mass and volume are also used to define the porosity and density of the sediment layer. In the sediment layer, porosity is the fraction of the total volume in the liquid phase:

$$\phi = \frac{V_{wtr}}{V_{tot}} \qquad 30.2.2$$

where ϕ is the porosity, V_{wtr} is the volume of water in the sediment layer (m^3) and V_{tot} is the total volume of the sediment layer (m^3). The fraction of the volume in the solid phase can then be defined as:

$$1 - \phi = \frac{V_{sed}}{V_{tot}} \qquad 30.2.3$$

where ϕ is the porosity, V_{sed} is the volume of solids in the sediment layer (m^3) and V_{tot} is the total volume of the sediment layer (m^3).

The density of sediment particles is defined as:

$$\rho_s = \frac{M_{sed}}{V_{sed}} \qquad 30.2.4$$

where ρ_s is the particle density (g/m^3), M_{sed} is the mass of solid particles in the sediment layer (g), and V_{sed} is the volume of solids in the sediment layer (m^3).

Solving equation 30.2.3 for V_{tot} and equation 30.2.4 for M_{sed} and substituting into equation 30.2.1 yields:

$$conc^*_{sed} = (1 - \phi) \cdot \rho_s \qquad 30.2.5$$

where $conc^*_{sed}$ is the "concentration" of solid particles in the sediment layer (g/m^3), ϕ is the porosity, and ρ_s is the particle density (g/m^3).

Typical values of porosity and particle density for fine-grained sediments are ϕ = 0.8-0.95 and ρ_s = 2.4-2.7 × 10^6 g/m^3 (Chapra, 1997). Assuming ϕ = 0.8 and ρ_s = 2.6 × 10^6 g/m^3, the "concentration" of solid particles in the sediment layer is 5.2×10^5 g/m^3.

The fraction of pesticide in each phase is then calculated:

$$F_{d,sed} = \frac{1}{\phi + (1 - \phi) \cdot \rho_s \cdot K_d} \qquad 30.2.6$$

$$F_{p,sed} = 1 - F_{d,sed} \qquad 30.2.7$$

where $F_{d,sed}$ is the fraction of total sediment pesticide in the dissolved phase, $F_{p,sed}$ is the fraction of total sediment pesticide in the particulate phase, ϕ is the porosity, ρ_s is the particle density (g/m^3), and K_d is the pesticide partition coefficient (m^3/g). The pesticide partition coefficient used for the water layer is also used for the sediment layer.

30.2.2 DEGRADATION

Pesticides in both the particulate and dissolved forms are subject to degradation. The amount of pesticide that is removed from the sediment via degradation is:

$$pst_{deg,sed} = k_{p,sed} \cdot pst_{lksed} \qquad 30.2.8$$

where $pst_{deg,sed}$ is the amount of pesticide removed from the sediment via degradation (mg pst), $k_{p,sed}$ is the rate constant for degradation or removal of pesticide in the sediment (1/day), and pst_{lksed} is the amount of pesticide in the sediment (mg pst). The rate constant is related to the sediment half-life:

$$k_{p,sed} = \frac{0.693}{t_{1/2,sed}} \qquad 30.2.9$$

where $k_{p,sed}$ is the rate constant for degradation or removal of pesticide in the sediment (1/day), and $t_{1/2,sed}$ is the sediment half-life for the pesticide (days).

30.2.3 RESUSPENSION

Pesticide in the sediment layer is available for resuspension. The amount of pesticide that is removed from the sediment via resuspension is:

$$pst_{rsp,wtr} = v_r \cdot SA \cdot \frac{pst_{lksed}}{V_{tot}} \qquad 30.2.10$$

where $pst_{rsp,wtr}$ is the amount of pesticide removed via resuspension (mg pst), v_r is the resuspension velocity (m/day), SA is the surface area of the water body (m^2),

pst_{lksed} is the amount of pesticide in the sediment (mg pst), and V_{tot} is the volume of the sediment layer (m^3). The volume of the sediment layer is calculated:

$$V_{tot} = SA \cdot D_{sed} \qquad 30.2.11$$

where V_{tot} is the volume of the sediment layer (m^3), SA is the surface area of the water body (m^2), D_{sed} is the depth of the active sediment layer (m). Pesticide removed from the sediment layer by resuspension is added to the water layer.

30.2.4 DIFFUSION

Pesticide in the dissolved phase is available for diffusion. Diffusion transfers pesticide between the water and sediment layers. The direction of movement is controlled by the pesticide concentration. Pesticide will move from areas of high concentration to areas of low concentration. The amount of pesticide that is transferred between the water and sediment by diffusion is:

$$pst_{dif} = \left| v_d \cdot SA \cdot \left(\frac{F_{d,sed} \cdot pst_{lksed}}{V_{tot}} - \frac{F_d \cdot pst_{lkwtr}}{V} \right) \right| \qquad 30.2.12$$

where pst_{dif} is the amount of pesticide transferred between the water and sediment by diffusion (mg pst), v_d is the rate of diffusion or mixing velocity (m/day), SA is the surface area of the water body (m^2), $F_{d,sed}$ is the fraction of total sediment pesticide in the dissolved phase, pst_{lksed} is the amount of pesticide in the sediment (mg pst), V_{tot} is the volume of the sediment layer (m^3), F_d is the fraction of total water layer pesticide in the dissolved phase, pst_{lkwtr} is the amount of pesticide in the water (mg pst), and V is the volume of water in the water body (m^3 H_2O). If $\frac{F_{d,sed} \cdot pst_{lksed}}{V_{tot}} > \frac{F_d \cdot pst_{lkwtr}}{V}$, pst_{dif} is transferred from the sediment to the water layer. If $\frac{F_{d,sed} \cdot pst_{lksed}}{V_{tot}} < \frac{F_d \cdot pst_{lkwtr}}{V}$, pst_{dif} is transferred from the water to the sediment layer.

The diffusive mixing velocity, v_d, can be estimated from the empirically derived formula (Chapra, 1997):

$$v_d = \frac{69.35}{365} \cdot \phi \cdot MW^{-2/3} \qquad 30.2.13$$

where v_d is the rate of diffusion or mixing velocity (m/day), ϕ is the sediment porosity, and MW is the molecular weight of the pesticide compound.

30.2.5 BURIAL

Pesticide in the sediment layer may be lost by burial. The amount of pesticide that is removed from the sediment via burial is:

$$pst_{bur} = v_b \cdot SA \cdot \frac{pst_{lksed}}{V_{tot}} \qquad 30.2.14$$

where pst_{bur} is the amount of pesticide removed via burial (mg pst), v_b is the burial velocity (m/day), SA is the surface area of the water body (m^2), pst_{lksed} is the amount of pesticide in the sediment (mg pst), and V_{tot} is the volume of the sediment layer (m^3).

Table 30-2: SWAT input variables related to pesticide in the sediment.

Variable Name	Definition	Input File
LKPST_KOC	K_d: Pesticide partition coefficient (m^3/g)	.lwq
LKSPST_REA	$k_{p,sed}$: Rate constant for degradation or removal of pesticide in the sediment (1/day)	.lwq
LKPST_RSP	v_r: Resuspension velocity (m/day)	.lwq
LKSPST_ACT	D_{sed}: Depth of the active sediment layer (m)	.lwq
LKPST_MIX	v_d: Rate of diffusion or mixing velocity (m/day)	.lwq
LKSPST_BRY	v_b: Pesticide burial velocity (m/day)	.lwq

30.3 MASS BALANCE

The processes described above can be combined into mass balance equations for the well-mixed water body and the well-mixed sediment layer:

$$\Delta pst_{lkwtr} = pst_{in} - \left(pst_{sol,o} + pst_{sorb,o}\right) - pst_{deg,wtr} - pst_{vol,wtr} - pst_{stl,wtr} + pst_{rsp,wtr} \pm pst_{dif} \qquad 30.3.1$$

$$\Delta pst_{lksed} = pst_{deg,sed} + pst_{stl,wtr} - pst_{rsp,wtr} - pst_{bur} \pm pst_{dif} \qquad 30.3.2$$

where Δpst_{lkwtr} is the change in pesticide mass in the water layer (mg pst), Δpst_{lksed} is the change in pesticide mass in the sediment layer (mg pst), pst_{in} is the pesticide added to the water body via inflow (mg pst), $pst_{sol,o}$ is the amount of dissolved pesticide removed via outflow (mg pst), $pst_{sorb,o}$ is the amount of particulate pesticide removed via outflow (mg pst), $pst_{deg,wtr}$ is the amount of pesticide removed from the water via degradation (mg pst), $pst_{vol,wtr}$ is the amount of pesticide removed via volatilization (mg pst), $pst_{stl,wtr}$ is the amount of pesticide removed from the water due to settling (mg pst), $pst_{rsp,wtr}$ is the amount of pesticide removed via resuspension (mg pst), pst_{dif} is the amount of pesticide transferred between the water and sediment by diffusion (mg pst), $pst_{deg,sed}$ is the amount of pesticide removed from the sediment via degradation (mg pst), pst_{bur} is the amount of pesticide removed via burial (mg pst)

30.4 NOMENCLATURE

D_g	Gas molecular diffusion coefficient (m^2/day)
D_l	Liquid molecular diffusion coefficient (m^2/day)
D_{sed}	Depth of the active sediment layer (m)
F_d	Fraction of total pesticide in the dissolved phase
$F_{d,sed}$	Fraction of total sediment pesticide in the dissolved phase
F_p	Fraction of total pesticide in the particulate phase
$F_{p,sed}$	Fraction of total sediment pesticide in the particulate phase
H_e	Henry's constant (atm m^3 $mole^{-1}$)
K_d	Pesticide partition coefficient (m^3/g)
K_g	Mass-transfer velocity in the gaseous laminar layer (m/day)
K_l	Mass-transfer velocity in the liquid laminar layer (m/day)
K_{l,O_2}	Oxygen transfer coefficient (m/day)
M_{sed}	Mass of solid phase in the sediment layer (g)
MW	Molecular weight of the pesticide compound
Q	Rate of outflow from the water body (m^3 H_2O/day)
R	Universal gas constant (8.206×10^{-5} atm m^3 $(K\ mole)^{-1}$)
SA	Surface area of the water body (m^2)
V	Volume of water in the water body (m^3 H_2O)
V_{sed}	Volume of solids in the sediment layer (m^3)
V_{tot}	Total volume of the sediment layer (m^3)
V_{wtr}	Volume of water in the sediment layer (m^3)

$conc_{sed}$	Concentration of suspended solids in the water (g/m^3)
$conc_{sed}^{*}$	"Concentration" of solid particles in the sediment layer (g/m^3)
$k_{p,aq}$	Rate constant for degradation or removal of pesticide in the water (1/day)
$k_{p,sed}$	Rate constant for degradation or removal of pesticide in the sediment (1/day)
pst_{bur}	Amount of pesticide removed via burial (mg pst)
$pst_{deg,sed}$	Amount of pesticide removed from the sediment via degradation (mg pst)
$pst_{deg,wtr}$	Amount of pesticide removed from the water via degradation (mg pst)
pst_{dif}	Amount of pesticide transferred between the water and sediment by diffusion (mg pst)

pst_{in}	Pesticide added to the water body via inflow (mg pst)
pst_{lksed}	Amount of pesticide in the sediment (mg pst)
pst_{lkwtr}	Amount of pesticide in the water (mg pst)
$pst_{rsp,wtr}$	Amount of pesticide removed from sediment via resuspension (mg pst)
$pst_{sol,o}$	Amount of dissolved pesticide removed via outflow (mg pst)
$pst_{sorb,o}$	Amount of particulate pesticide removed via outflow (mg pst)
$pst_{stl,wtr}$	Amount of pesticide removed from the water due to settling (mg pst)
$pst_{vol,wtr}$	Amount of pesticide removed via volatilization (mg pst)
$t_{1/2,aq}$	Aqueous half-life for the pesticide (days)
$t_{1/2,sed}$	Sediment half-life for the pesticide (days)
v_b	Pesticide burial velocity (m/day)
v_d	Rate of diffusion or mixing velocity (m/day)
v_r	Resuspension velocity (m/day)
v_s	Settling velocity (m/day)
v_v	Volatilization mass-transfer coefficient (m/day)
z_g	Thickness of the gas film (m)
z_l	Thickness of the liquid film (m)

ϕ	Porosity
Δpst_{lkwtr}	Change in pesticide mass in the water layer (mg pst)
Δpst_{lksed}	Change in pesticide mass in the sediment layer (mg pst)
ρ_s	Particle density (g/m^3)
μ_w	Wind speed (m/s)

30.5 REFERENCES

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APPENDIX A

LIST OF VARIABLES

A	3 × 3 matrix of elements defined to ensure serial and cross correlation of generated temperature and radiation values $A = M_1 \cdot M_0^{-1}$
A_{ch}	Cross-sectional area of flow in the channel (m^2)
$A_{ch,bnkfull}$	Cross-sectional area of flow in the channel when filled to the top of the bank (m^2)
A_s	Area of sediment-water interface (m^2)
A_{surf}	Amplitude of the surface fluctuations in soil temperature (°C)
AGP	Algal growth potential (mg/L)
$Area$	Subbasin area (km^2 or ha)
AU	Astronomical unit (1 AU = 1.496 x 10^8 km)
AWC	Available water capacity (mm H_2O)
AWC_{ly}	Available water capacity for layer *ly* (mm H_2O)
B	3 × 3 matrix of elements defined to ensure serial and cross correlation of generated temperature and radiation values $B \cdot B^T = M_0 - M_1 \cdot M_0^{-1} \cdot M_1^T$
BFD	Number of baseflow days for the watershed
C	Runoff coefficient in peak runoff rate calculation
C_1	Coefficient in Muskingum flood routing equation
C_2	Coefficient in Muskingum flood routing equation
C_3	Coefficient in Muskingum flood routing equation
C_{CH}	Channel cover factor
C_{NH4}	Concentration of ammonium in the reach (mg N/L)
C_{NO3}	Concentration of nitrate in the reach (mg N/L)
$C_{solidphase}$	Concentration of the pesticide sorbed to the solid phase (mg chemical/kg solid material)
C_{solP}	Concentration of phosphorus in solution in the reach (mg P/L)
$C_{solution}$	Concentration of the pesticide in solution (mg chemical/L solution)
C_{USLE}	USLE cover and management factor
$C_{USLE,aa}$	Average annual C factor for the land cover
$C_{USLE,mn}$	Minimum value for the cover and management factor for the land cover
$CFRG$	Coarse fragment factor
$Chla$	Chlorophyll *a* concentration (μg/L)
$Chla_{co}$	User-defined coefficient to adjust predicted chlorophyll *a* concentration
CN	Curve number
CN_1	Moisture condition I curve number
CN_2	Moisture condition II curve number
CN_{2s}	Moisture condition II curve number adjusted for slope
CN_3	Moisture condition III curve number
CO_2	Concentration of carbon dioxide in the atmosphere (ppmv)
CO_{2amb}	Ambient atmospheric CO_2 concentration (330 ppmv)
CO_{2hi}	Elevated atmospheric CO_2 concentration (ppmv)
CV	Total aboveground biomass and residue present on current day (kg ha^{-1})
D_a	Oxygen deficit above the structure (mg O_2/L)
D_b	Oxygen deficit below the structure (mg O_2/L)
D_g	Gas molecular diffusion coefficient (m^2/day)
D_l	Liquid molecular diffusion coefficient (m^2/day)

D_m	Molecular diffusion coefficient for oxygen (m^2/day)
D_{sed}	Depth of the active sediment layer (m)
DA	HRU drainage area (km^2)
E	Depth rate evaporation (mm d^{-1})
E_0	Eccentricity correction factor of earth $(r_0/r)^2$
E_a	Actual amount of evapotranspiration on a given day (mm H_2O)
E_{can}	Amount of evaporation from free water in the canopy on a given day (mm H_2O)
E_{ch}	Evaporation from the reach for the day (m^3 H_2O)
E_o	Potential evapotranspiration (mm d^{-1})
E_o'	Potential evapotranspiration adjusted for evaporation of free water in the canopy (mm H_2O)
E_s	Maximum sublimation/soil evaporation on a given day (mm H_2O)
E_s'	Maximum sublimation/soil evaporation adjusted for plant water use on a given day (mm H_2O)
E_s''	Maximum soil water evaporation on a given day (mm H_2O)
$E_{soil,ly}$	Evaporative demand for layer *ly* (mm H_2O)
$E_{soil,ly}'$	Evaporative demand for layer *ly* adjusted for water content (mm H_2O)
$E_{soil,ly}''$	Amount of water removed from layer *ly* by evaporation (mm H_2O)
$E_{soil,z}$	Evaporative demand at depth *z* (mm H_2O)
E_{storm}	Total storm energy (0.0017 m-metric ton/m^2),
E_{sub}	Amount of sublimation on a given day (mm H_2O)
E_t	Transpiration rate (maximum) (mm d^{-1})
$E_{t,act}$	Actual amount of transpiration on a given day (mm H_2O)
EI_{USLE}	Rainfall erosion index (0.017 m-metric ton cm/(m^2 hr))
EL	Elevation (m)
EL_{band}	Mean elevation in the elevation band (m)
EL_{gage}	Elevation at the precipitation, temperature, or weather generator data recording gage (m)
F_d	Fraction of total pesticide in the dissolved phase
$F_{d,sed}$	Fraction of total sediment pesticide in the dissolved phase
F_{inf}	Cumulative infiltration at time *t* (mm H_2O)
F_p	Fraction of total pesticide in the particulate phase
$F_{p,sed}$	Fraction of total sediment pesticide in the particulate phase
FC	Water content of soil profile at field capacity (mm H_2O)
FC_{ly}	Water content of layer *ly* at field capacity (mm H_2O)
FL	Algal growth attenuation factor for light for the water column
FL_z	Algal growth attenuation factor for light at depth *z*
FN	Algal growth limitation factor for nitrogen
FP	Algal growth limitation factor for phosphorus
G	Heat flux density to the ground (MJ m^{-2} d^{-1})
H_0	Extraterrestrial daily irradiation (MJ m^{-2} d^{-1})
H_b	Net outgoing long-wave radiation (MJ m^{-2} d^{-1})
H_{day}	Solar radiation reaching ground on current day of simulation (MJ m^{-2} d^{-1})
H_e	Henry's constant (atm m^3 mole^{-1})
H_L	Long-wave radiation (MJ m^{-2} d^{-1})

H_{MX}	Maximum possible solar radiation (MJ m^{-2} d^{-1})
H_{net}	Net radiation on day (MJ m^{-2} d^{-1})
H_o	Saturated thickness normal to the hillslope at the outlet expressed as a fraction of the total thickness (mm/mm)
H_{phosyn}	Intercepted photosynthetically active radiation on a given day (MJ m^{-2})
H_R	Radiant energy (MJ m^{-2} d^{-1})
HI	Potential harvest index for a given day
HI_{act}	Actual harvest index
HI_{min}	Harvest index for the plant in drought conditions and represents the minimum harvest index allowed for the plant
HI_{opt}	Potential harvest index for the plant at maturity given ideal growing conditions
HI_{trg}	Target harvest index
HU	Number of heat units accumulated on a given day where base temperature is dependant on the plant species (heat units)
HU_0	Number of base zero heat units accumulated on a given day (heat units)
I_0	Extraterrestrial daily irradiance incident on a horizontal surface (MJ m^{-2} h^{-1})
I_{0n}	Extraterrestrial daily irradiance incident on a normal surface (MJ m^{-2} h^{-1})
I_{30}	Maximum 30 minute intensity (mm/hr)
I_a	Initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm H_2O)
I_{frac}	Fraction of daily solar radiation falling during specific hour on current day of simulation
I_{hr}	Solar radiation reaching ground during specific hour on current day of simulation (MJ m^{-2} h^{-1})
$I_{phosyn,hr}$	Photosynthetically-active solar radiation reaching ground during specific hour on current day of simulation (MJ m^{-2} h^{-1})
$I_{phosyn,z}$	Photosynthetically-active light intensity at a depth *z* below the water surface (MJ/m^2-hr)
I_{SC}	Solar constant (4.921 MJ m^{-2} h^{-1})
$\bar{I}_{phosyn,hr}$	Daylight average photosynthetically-active light intensity (MJ/m^2-hr)
J_i	Jet index used to calculate channel erodibility
K	Storage time constant for the reach (s)
$K_{0.1bnkfull}$	Storage time constant calculated for the reach segment with one-tenth of the bankfull flows (s)
K_1	Dimension coefficient in Penman-Monteith equation
$K_{bnkfull}$	Storage time constant calculated for the reach segment with bankfull flows (s)
K_{ch}	Effective hydraulic conductivity of the channel alluvium (mm/hr)
K_{CH}	Channel erodibility factor
K_d	Pesticide partition coefficient (m^3/g)
K_e	Effective hydraulic conductivity (mm/hr)
K_g	Mass-transfer velocity in the gaseous laminar layer (m/day)
K_l	Mass-transfer velocity in the liquid laminar layer (m/day)
K_L	Half-saturation coefficient for light (MJ/m^2-hr)
K_{l,O_2}	Oxygen transfer coefficient (m/day)
K_N	Michaelis-Menton half-saturation constant for nitrogen (mg N/L)

K_{oc}	Soil adsorption coefficient normalized for soil organic carbon content (ml/g or (mg/kg)/(mg/L) or L/kg)
K_p	Soil adsorption coefficient ((mg/kg)/(mg/L))
K_P	Michaelis-Menton half-saturation constant for phosphorus (mg P/L)
K_{sat}	Saturated hydraulic conductivity (mm/hr)
K_{USLE}	USLE soil erodibility factor (0.013 metric ton m^2 hr/(m^3-metric ton cm))
L	Channel length from the most distant point to the subbasin outlet (km)
L_c	Average flow channel length for the subbasin (km)
L_{cen}	Distance along the channel to the subbasin centroid (km)
L_{ch}	Length of main channel (km)
L_{gw}	Distance from the ridge or subbasin divide for the groundwater system to the main channel (m)
L_{hill}	Hillslope length (m)
L_{slp}	Subbasin slope length (m)
LAI	Leaf area index of the canopy
LAI_{evap}	Leaf area index at which no evaporation occurs from the water surface
LAI_{mx}	Maximum leaf area index for the plant
LS_{USLE}	USLE topographic factor
M	Particle-size parameter for estimation of USLE K factor
M_0	3×3 matrix of correlation coefficients between maximum temperature, minimum temperature and solar radiation on same day
M_1	3×3 matrix of correlation coefficients between maximum temperature, minimum temperature and solar radiation on consecutive days
M_{flowin}	Mass of nutrient entering water body on the given day (kg)
$M_{initial}$	Initial mass of nutrient in water body for the given day (kg)
M_S	Mass of the solids (Mg)
M_{sed}	Mass of solid phase in the sediment layer (g)
$M_{settling}$	Mass of nutrient lost via settling on a given day (kg)
M_{stored}	Mass of nutrient in water body at end of previous day (kg)
MW	Molecular weight of the pesticide compound
N	Time lapsed since the start of the recession (days)
$N_{actualup,ly}$	Actual nitrogen uptake for layer *ly* (kg N/ha)
$N_{dec,ly}$	Nitrogen decomposed from the fresh organic N pool (kg N/ha)
N_{demand}	Nitrogen uptake demand not met by overlying soil layers (kg N/ha)
$N_{denit,ly}$	Amount of nitrogen lost to denitrification (kg N/ha)
N_{evap}	Amount of nitrate moving from the first soil layer to the soil surface zone (kg N/ha)
N_{fix}	Amount of nitrogen added to the plant biomass by fixation (kg N/ha)
$N_{mina,ly}$	Nitrogen mineralized from the humus active organic N pool (kg N/ha)
$N_{minf,ly}$	Nitrogen mineralized from the fresh organic N pool (kg N/ha)
$N_{nit,ly}$	Amount of nitrogen converted from NH_4^+ to NO_3^- in layer *ly* (kg N/ha)
$N_{nit\vert vol,ly}$	Amount of ammonium converted via nitrification and volatilization in layer *ly* (kg N/ha)
N_{rain}	Nitrate added by rainfall (kg N/ha)
$N_{trns,ly}$	Amount of nitrogen transferred between the active and stable organic pools (kg N/ha)

N_{up}	Potential nitrogen uptake (kg N/ha)
$N_{up,ly}$	Potential nitrogen uptake for layer *ly* (kg N/ha)
$N_{up,z}$	Potential nitrogen uptake from the soil surface to depth *z* (kg N/ha)
$N_{up,zl}$	Potential nitrogen uptake from the soil surface to the lower boundary of the soil layer (kg N/ha)
$N_{up,zu}$	Potential nitrogen uptake from the soil surface to the upper boundary of the soil layer (kg N/ha)
$N_{vol,ly}$	Amount of nitrogen converted from NH_4^+ to NH_3 in layer *ly* (kg N/ha)
ND_{targ}	Number of days required for the reservoir to reach target storage
$NH4$	Ammonium content of the soil profile (kg NH_4-N/ha)
$NH4_{fert}$	Amount of ammonium added to the soil in the fertilizer (kg N/ha)
$NH4_{ly}$	Ammonium content of layer *ly* (kg NH_4-N/ha)
$NH4_{str}$	Ammonium concentration in the stream (mg N/L)
$NO2_{str}$	Nitrite concentration in the stream (mg N/L)
$NO3$	Nitrate content of the soil profile (kg NO_3-N/ha)
$NO3_{conc,z}$	Concentration of nitrate in the soil at depth *z* (mg/kg or ppm)
$NO3_{fert}$	Amount of nitrate added to the soil in the fertilizer (kg N/ha)
$NO3'_{lat}$	Amount of lateral flow nitrate generated in HRU on a given day (kg N/ha)
$NO3_{lat,ly}$	Nitrate removed in lateral flow from a layer (kg N/ha)
$NO3_{latstor,i-1}$	Lateral flow nitrate stored or lagged from the previous day (kg N/ha)
$NO3_{ly}$	Nitrate content of soil layer *ly* (kg NO_3-N/ha)
$NO3_{perc,ly}$	Nitrate moved to the underlying layer by percolation (kg N/ha)
$NO3_{str}$	Nitrate concentration in the stream (mg N/L)
$NO3_{surf}$	Nitrate removed in surface runoff (kg N/ha)
$NO3'_{surf}$	Amount of surface runoff nitrate generated in HRU on a given day (kg N/ha)
$NO3_{surstor,i-1}$	Surface runoff nitrate stored or lagged from the previous day (kg N/ha)
OM	Percent organic matter (%)
Ox_{sat}	Saturation oxygen concentration (mg O_2/L)
Ox_{str}	Dissolved oxygen concentration in the stream (mg O_2/L)
Ox_{surf}	Dissolved oxygen concentration in surface runoff (mg O_2/L)
P	Atmospheric pressure (kPa)
$P_{actualup,ly}$	Actual phosphorus uptake for layer *ly* (kg P/ha)
$P_{act\|sta,ly}$	Amount of phosphorus transferred between the active and stable mineral pools (kg P/ha)
P_{ch}	Wetted perimeter for a given depth of flow (m)
$P_{dec,ly}$	Phosphorus decomposed from the fresh organic P pool (kg P/ha)
P_{demand}	Phosphorus uptake demand not met by overlying soil layers (kg P/ha)
$P_i(D/D)$	Probability of a dry day on day *i* given a dry day on day $i - 1$
$P_i(D/W)$	Probability of a dry day on day *i* given a wet day on day $i - 1$
$P_i(W/D)$	Probability of a wet day on day *i* given a dry day on day $i - 1$
$P_i(W/W)$	Probability of a wet day on day *i* given a wet day on day $i - 1$
$P_{mina,ly}$	Phosphorus mineralized from the humus active organic P pool (kg P/ha)
$P_{minf,ly}$	Phosphorus mineralized from the fresh organic P pool (kg P/ha),
P_{perc}	Amount of phosphorus moving from the top 10 mm into the first soil layer (kg P/ha)

$P_{solution,fert}$	Amount of phosphorus in the solution pool added to the soil in the fertilizer (kg P/ha)
$P_{solution,ly}$	Phosphorus content of soil solution in layer ly (kg P/ha)
$P_{sol\vert act,ly}$	Amount of phosphorus transferred between the soluble and active mineral pool (kg P/ha)
$P_{stor,i\text{-}1}$	Solution P loading stored or lagged from the previous day (kg P/ha)
P_{surf}	Amount of soluble phosphorus lost in surface runoff (kg P/ha)
P'_{surf}	Amount of solution P loading generated in HRU on a given day (kg P/ha)
P_{up}	Potential phosphorus uptake (kg P/ha)
$P_{up,ly}$	Potential phosphorus uptake for layer ly (kg P/ha)
$P_{up,z}$	Potential phosphorus uptake from the soil surface to depth z (kg P/ha)
$P_{up,zl}$	Potential phosphorus uptake from the soil surface to the lower boundary of the soil layer (kg P/ha)
$P_{up,zu}$	Potential phosphorus uptake from the soil surface to the upper boundary of the soil layer (kg P/ha)
P_{USLE}	USLE support practice factor
PHU	Potential heat units or total heat units required for plant maturity where base temperature is dependant on the plant species (heat units)
PHU_0	Total base zero heat units or potential base zero heat units (heat units)
Q	Volumetric flow rate for water exiting water body (m^3 H_2O/day)
Q_{gw}	Groundwater flow, or base flow, into the main channel (mm H_2O)
$Q_{gw,0}$	Groundwater flow at the start of the recession (mm H_2O)
$Q_{gw,N}$	Groundwater flow on day N (mm H_2O)
Q_{lat}	Lateral flow; water discharged from the hillslope outlet (mm H_2O/day)
$Q_{latstor,i\text{-}1}$	Lateral flow stored or lagged from the previous day (mm H_2O)
Q_{stor}	Surface runoff stored or lagged (mm H_2O)
Q_{surf}	Surface runoff on a given day (mm H_2O)
R	Universal gas constant (8.206×10^{-5} atm m^3 (K mole)$^{-1}$)
$R_{0.5sm}$	Smoothed maximum half-hour rainfall for a given month (mm H_2O)
$R_{0.5x}$	Extreme maximum half-hour rainfall for the specified month (mm H_2O)
$R_{\Delta t}$	Amount of rain falling during the time step (mm H_2O)
R_{band}	Precipitation falling in the elevation band (mm H_2O)
R_{ch}	Hydraulic radius for a given depth of flow (m)
R_{day}	Amount of rainfall on a given day (mm H_2O)
R'_{day}	Amount of precipitation on a given day before canopy interception is removed (mm H_2O)
R_h	Average relative humidity for the day
R_{hDmon}	Average relative humidity of the month on dry days
R_{hLmon}	Smallest relative humidity value that can be generated on a given day in the month
R_{hmon}	Average relative humidity for the month
R_{hUmon}	Largest relative humidity value that can be generated on a given day in the month
R_{hWmon}	Average relative humidity for the month on wet days
R_{INT}	Amount of free water held in the canopy on a given day (mm H_2O)
R_{NO3}	Concentration of nitrogen in the rain (mg N/L)

R_{tc}	Amount of rain falling during the time of concentration (mm H_2O)
RUE	Radiation-use efficiency of the plant (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ)
RUE_{amb}	Radiation-use efficiency of the plant at ambient atmospheric CO_2 concentration (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ)
RUE_{hi}	Radiation-use efficiency of the plant at the elevated atmospheric CO_2 concentration, CO_{2hi}, (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ)
$RUE_{vpd=1}$	Radiation-use efficiency for the plant at a vapor pressure deficit of 1 kPa (kg/ha·(MJ/m^2)$^{-1}$ or 10^{-1} g/MJ)
S	Retention parameter in SCS curve number equation (mm)
S_3	Retention parameter for the moisture condition III curve number
S_{frz}	Retention parameter adjusted for frozen conditions (mm)
S_{max}	Maximum value the retention parameter can achieve on any given day (mm)
SA	Surface area of the water body (m^2)
SA_{em}	Surface area of the reservoir/pond when filled to the emergency spillway (ha)
SA_{mx}	Surface area of the wetland when filled to the maximum water level (ha)
SA_{nor}	Surface area of the wetland when filled to the normal water level (ha)
SA_{pr}	Surface area of the reservoir/pond when filled to the principal spillway (ha)
SAT	Amount of water in the soil profile when completely saturated (mm H_2O),
SAT_{ly}	Amount of water in the soil layer when completely saturated (mm H_2O)
SC	Storage coefficient for variable storage flow routing
SD	Secchi-disk depth (m)
SD_{co}	User-defined coefficient to adjust predicted secchi-disk depth
SED	Solid build up (kg/curb km)
SED_{mx}	Maximum accumulation of solids possible for the urban land type (kg/curb km)
SND_{day}	Standard normal deviate for the day
SNO	Water content of snow cover on current day (mm H_2O)
SNO_{100}	Amount of snow above which there is 100% cover (mm H_2O)
SNO_{mlt}	Amount of snow melt on a given day (mm H_2O)
SW	Amount of water in soil profile (mm H_2O)
SW_{ly}	Soil water content of layer *ly* (mm H_2O)
$SW_{ly,excess}$	Drainable volume of water stored layer (mm H_2O)
T_{bare}	Temperature of soil surface with no cover (°C)
T_{base}	Plant's base or minimum temperature for growth (°C)
T_{DL}	Daylength (h)
$T_{DL,mn}$	Minimum daylength for the watershed during the year (hrs)
$T_{DL,thr}$	Threshold daylength to initiate dormancy (hrs)
T_{hr}	Air temperature during hour (°C)
T_K	Mean air temperature in Kelvin (273.15 + °C)
T_{mlt}	Threshold temperature for snow melt (°C)
T_{mn}	Minimum air temperature for day (°C)
$T_{mn,band}$	Minimum daily temperature in the elevation band (°C)
T_{mx}	Maximum air temperature for day (°C)
$T_{mx,band}$	Maximum daily temperature in the elevation band (°C)
T_{opt}	Plant's optimal temperature for growth (°C)
$T_{s\text{-}r}$	Rain/snow boundary temperature (°C)

T_{snow}	Snow pack temperature on a given day (°C)
T_{soil}	Soil temperature (°C)
$T_{soil,ly}$	Temperature of layer *ly* (°C)
T_{SR}	Time of sunrise in solar day (h)
T_{SS}	Time of sunset in solar day (h)
T_{ssurf}	Soil surface temperature (°C)
$T_{wat,K}$	Water temperature in Kelvin (273.15+°C)
T_{water}	Average daily water temperature (°C)
$\overline{T}_{AA}$	Average annual soil temperature (°C)
$\overline{T}_{AAair}$	Average annual air temperature (°C)
$\overline{T}_{av}$	Mean air temperature for day (°C)
$\overline{T}_{av,band}$	Mean daily temperature in the elevation band (°C)
$\overline{T}_{water}$	Average water temperature (°C)
TN	Total Kjeldahl nitrogen load (moles)
TP	Total phosphorus load (moles)
TT	Travel time (s)
TT_{lag}	Lateral flow travel time (days)
TT_{perc}	Travel time for percolation (hrs)
V	Volume of water in water body (m^3 H_2O)
V_A	Volume of air (m^3)
V_{bnk}	Volume of water added to the reach via return flow from bank storage (m^3 H_2O)
V_{ch}	Volume of water stored in the channel (m^3)
V_{em}	Volume of water held in the reservoir when filled to the emergency spillway (m^3 H_2O)
V_{evap}	Volume of water removed from the water body by evaporation during the day (m^3 H_2O)
V_{flowin}	Volume of water entering water body on given day (m^3 H_2O)
$V_{flowout}$	Volume of water flowing out of the water body during the day (m^3 H_2O)
$V'_{flowout}$	Initial estimate of the volume of water flowing out of the water body during the day (m^3 H_2O)
V_{in}	Volume of inflow during the time step (m^3 H_2O)
$V_{initial}$	Initial volume of water in water body on given day (m^3 H_2O)
V_{mx}	Volume of water held in the wetland when filled to the maximum water level (m^3 H_2O)
V_{nor}	Volume of water held in the wetland when filled to the normal water level (m^3 H_2O)
V_{out}	Volume of outflow during the time step (m^3 H_2O)
V_{pcp}	Volume of precipitation falling on the water body during the day (m^3 H_2O)
$V_{pot,mx}$	Maximum amount of water that can be stored in the pothole (m^3 H_2O)
V_{pr}	Volume of water held in the reservoir when filled to the principal spillway (m^3 H_2O)
V_S	Volume of solids (m^3)
V_{sed}	Volume of solids in the sediment layer (m^3)
V_{seep}	Volume of water lost from the water body by seepage (m^3 H_2O)

V_{stored}	Volume of water stored in water body or channel (m^3 H$_2$O)
V_T	Total soil volume (m^3)
V_{targ}	Target reservoir volume for a given day (m^3 H$_2$O)
V_{tot}	Total volume of the sediment layer (m^3)
V_W	Volume of water (m^3)
V_{wtr}	Volume of water in the sediment layer (m^3)
W	Width of channel at water level (m)
$W(t)$	Rate of nutrient loading (kg/day)
$W_{bnkfull}$	Top width of the channel when filled with water (m)
W_{btm}	Bottom width of the channel (m)
$W_{btm,fld}$	Bottom width of the flood plain (m)
WP	Water content at wilting point (mm H$_2$O)
WP_{ly}	Water content of layer ly at wilting point (mm H$_2$O)
X	Weighting factor in Muskingum routing
Y	Total constituent load (kg)
Y_{sed}	Cumulative amount of solids washed off at time t (kg/curb km)

a	Constant in equation used to calculate the cloud cover adjustment factor
a_1	Constant in equation used to calculate net emissivity
a_r	Unit channel regression intercept (m^3)
a_x	Regression intercept for a channel of length L and width W (m^3)
aa	Exponent between 0 and 1 that varies with atmospheric stability and surface roughness that is used in calculating wind speed at different heights
$adj_{0.5\alpha}$	Peak rate adjustment factor
adj_{hmd}	Change in relative humidity expressed as a fraction
adj_{pcp}	% change in rainfall
adj_{rad}	Change in radiation (MJ m^{-2} d^{-1})
adj_{tmp}	Change in temperature (°C)
$algae$	Algal biomass concentration (mg alg/L)
ap_{ef}	Pesticide application efficiency
aq_{dp}	Amount of water stored in the deep aquifer (mm H$_2$O)
aq_{sh}	Amount of water stored in the shallow aquifer (mm H$_2$O)
$aq_{shthr,q}$	Threshold water level in shallow aquifer for base flow (mm H$_2$O)
$area_{hru}$	HRU area (ha or km^2)
b	Constant in equation used to calculate the cloud cover adjustment factor
b_1	Constant in equation used to calculate net emissivity
b_H	Scaling factor that controls the degree of deviation in relative humidity caused by the presence or absence of precipitation
b_{mlt}	Melt factor for the day (mm H$_2$O/day-°C)
b_{mlt6}	Melt factor for June 21 (mm H$_2$O/day-°C)
b_{mlt12}	Melt factor for December 21 (mm H$_2$O/day-°C)
b_r	Unit channel regression slope
b_R	Scaling factor that controls the degree of deviation in solar radiation caused by the presence or absence of precipitation
b_T	Scaling factor that controls the degree of deviation in temperature caused by the presence or absence of precipitation

b_x	Regression slope for a channel of length L and width W
$bact_{lpsol,fert}$	Amount of less persistent bacteria in the solution pool added to the soil in the fertilizer (# bact/ha)
$bact_{lpsorb,fert}$	Amount of less persistent bacteria in the sorbed pool added to the soil in fertilizer (# bact/ha)
$bact_{psol,fert}$	Amount of persistent bacteria in the solution pool added to the soil in the fertilizer (# bact/ha)
$bact_{psorb,fert}$	Amount of persistent bacteria in the sorbed pool added to the soil in fertilizer (# bact/ha)
bcv	Weighting factor for impact of ground cover on soil surface temperature
bio	Total plant biomass on a given day (kg/ha)
bio_{ag}	Aboveground biomass on the day of harvest (kg ha^{-1})
bio_N	Actual mass of nitrogen stored in plant material (kg N/ha)
$bio_{N,opt}$	Optimal mass of nitrogen stored in plant material for the growth stage (kg N/ha)
bio_P	Actual mass of phosphorus stored in plant material (kg P/ha)
$bio_{P,opt}$	Optimal mass of phosphorus stored in plant material for the current growth stage (kg P/ha)
bio_{trg}	Target biomass specified by the user (kg/ha)
bnk	Total amount of water in bank storage (m^3 H_2O)
bnk_{in}	Amount of water entering bank storage (m^3 H_2O)
$bnk_{revap,mx}$	Maximum amount of water moving into the unsaturated zone in response to water deficiencies (m^3 H_2O)
c	Concentration of nutrient in the water (kg/m^3 H_2O)
c_k	Celerity corresponding to the flow for a specified depth (m/s)
c_p	Specific heat of moist air at constant pressure (1.013×10^{-3} MJ kg^{-1} °C^{-1})
c_{perm}	Profile-permeability class
$c_{soilstr}$	Soil-structure code used in soil classification
c_{sp}	Coefficient in sediment transport equation
can_{day}	Maximum amount of water that can be trapped in the canopy on a given day (mm H_2O)
can_{mx}	Maximum amount of water that can be trapped in the canopy when the canopy is fully developed (mm H_2O)
$cbod$	Carbonaceous biological oxygen demand concentration (mg CBOD/L)
$cbod_{surq}$	CBOD concentration in surface runoff (mg CBOD/L)
$chla$	Chlorophyll *a* concentration (μg chla/L)
$coef_1$	Weighting coefficient for storage time constant calculation
$coef_2$	Weighting coefficient for storage time constant calculation
$coef_a$	Empirical water quality factor
$coef_b$	Empirical dam aeration coefficient
$coef_{crk}$	Adjustment coefficient for crack flow
$coef_{ev}$	Evaporation coefficient
$conc_N$	Concentration of nitrogen in a layer (mg/kg or ppm)
$conc_{NO3,mobile}$	Concentration of nitrate in the mobile water for a given layer (kg N/mm H_2O)
$conc_{orgN}$	Concentration of organic nitrogen in the soil surface top 10 mm (g N/ metric ton soil)

$conc_{P}$	Concentration of phosphorus in a layer (mg/kg or ppm)
$conc_{pst,flow}$	Concentration of pesticide in the mobile water (kg pst/ha-mm H_2O)
$conc_{sed}$	Concentration of sediment in lateral and groundwater flow (mg/L)
$conc^{*}_{sed}$	"Concentration" of solid particles in the sediment layer (g/m^3)
$conc_{sed,ch,i}$	Initial sediment concentration in the reach (kg/L or ton/m^3)
$conc_{sed,ch,mx}$	Maximum concentration of sediment that can be transported by the water (kg/L or ton/m^3)
$conc_{sed,eq}$	Equilibrium concentration of suspended solids in the water body (Mg/m^3)
$conc_{sed,surq}$	Concentration of sediment in surface runoff (Mg sed/m^3 H_2O)
$conc_{sedP}$	Concentration of phosphorus attached to sediment in the top 10 mm (g P/ metric ton soil)
cov_1	Snow cover areal depletion curve shape coefficient
cov_2	Snow cover areal depletion curve shape coefficient
cov_{sol}	Soil cover index
crk	Total crack volume for the soil profile on a given day (mm)
crk_{ly}	Crack volume for the soil layer on a given day expressed as a depth (mm)
$crk_{ly,d-1}$	Crack volume for the soil layer on the previous day (mm)
$crk_{ly,i}$	Initial crack volume calculated for the soil layer on a given day expressed as a depth (mm)
crk_{max}	Potential crack volume for the soil profile expressed as a fraction of the total volume
$crk_{max,ly}$	Maximum crack volume possible for the soil layer (mm)
d	Zero plane displacement of the wind profile (cm)
d_{50}	Median particle size of the inflow sediment (µm)
d_n	Day number of year, 1 on January 1 and 365 on December 31
$days_{dry}$	Number of dry days in the month
$days_{tot}$	Total number of days in the month
$days_{wet}$	Number of wet days in the month
dd	Damping depth (mm)
dd_{max}	Maximum damping depth (mm)
$depth$	Depth of water in the channel (m)
$depth_{bnkfull}$	Depth of water in the channel when filled to the top of the bank (m)
$depth_{dcut}$	Amount of downcutting (m)
$depth_{fld}$	Depth of water in the flood plain (m)
$depth_{ly}$	Depth of the soil layer (mm)
df	Depth factor used in soil temperature calculations
div	Volume of water added or removed from the reach for the day through diversions (m^3 H_2O)
dt	Length of time step (1 day)
dur_{flw}	Duration of flow (hr)
e	Actual vapor pressure on a given day (kPa)
e_{mon}	Actual vapor pressure at the mean monthly temperature (kPa)
e^{o}	Saturation vapor pressure on a given day (kPa)
e^{o}_{mon}	Saturation vapor pressure at the mean monthly temperature (kPa)
$epco$	Plant uptake compensation factor
$esco$	Soil evaporation compensation coefficient

$expsa$	Exponent for impoundment surface area calculation
f	Coefficient
f_{cl-si}	Factor that gives low soil erodibility factors for soils with high clay to silt ratios
f_{cld}	Factor to adjust for cloud cover in net long-wave radiation calculation
f_{csand}	Factor that gives low soil erodibility factors for soils with high coarse-sand contents and high values for soils with little sand
f_{gr}	Growth stage factor in nitrogen fixation equation
f_{hisand}	Factor that reduces soil erodibility for soils with extremely high sand contents
f_{inf}	Infiltration rate (mm/hr)
f_{NH4}	Preference factor for ammonia nitrogen
f_{no3}	Soil nitrate factor in nitrogen fixation equation
f_{orgc}	Factor that reduces soil erodibility for soils with high organic carbon content
f_{sw}	Soil water factor in nitrogen fixation equation
$fert$	Amount of fertilizer applied (kg/ha)
$fert_{eff}$	Fertilizer application efficiency assigned by the user
$fert_{lpbact}$	Concentration of less persistent bacteria in the fertilizer (# bact/kg fert)
$fert_{minN}$	Fraction of mineral nitrogen in the fertilizer
$fert_{minP}$	Fraction of mineral P in the fertilizer
$fert_{NH4}$	Fraction of mineral N in the fertilizer that is ammonium
$fert_{orgN}$	Fraction of organic N in the fertilizer
$fert_{orgP}$	Fraction of organic P in the fertilizer
$fert_{pbact}$	Concentration of persistent bacteria in the fertilizer (# bact/kg fert)
fr_{actN}	Fraction of humic nitrogen in the active pool
fr_{av}	Fraction of the curb length available for sweeping (the availability factor)
fr_{bnd}	Fraction of subbasin area within the elevation band
fr_{DL}	Fraction of daylight hours
$fr_{g,mx}$	Fraction of the maximum stomatal conductance, $g_{\ell,mx}$, achieved at the vapor pressure deficit, vpd_{fr}
fr_{imp}	Fraction of the subbasin area draining into the impoundment
$fr_{LAI,1}$	Fraction of the maximum plant leaf area index corresponding to the 1st point on the optimal leaf area development curve
$fr_{LAI,2}$	Fraction of the maximum plant leaf area index corresponding to the 2nd point on the optimal leaf area development curve
fr_{LAImx}	Fraction of the plant's maximum leaf area index corresponding to a given fraction of potential heat units for the plant
fr_N	Optimal fraction of nitrogen in the plant biomass for current growth stage
$fr_{N,1}$	Normal fraction of nitrogen in the plant biomass at emergence
$fr_{N,2}$	Normal fraction of nitrogen in the plant biomass at 50% maturity
$fr_{N,3}$	Normal fraction of nitrogen in the plant biomass at maturity
$fr_{N,\sim 3}$	Normal fraction of nitrogen in the plant biomass near maturity
$fr_{N,yld}$	Fraction of nitrogen in the yield
fr_{NH4}	Fraction of algal nitrogen uptake from ammonium pool,
$fr_{nit,ly}$	Estimated fraction of nitrogen lost by nitrification
fr_P	Fraction of phosphorus in the plant biomass
$fr_{P,1}$	Normal fraction of phosphorus in the plant biomass at emergence
$fr_{P,2}$	Normal fraction of phosphorus in the plant biomass at 50% maturity

$fr_{P,3}$	Normal fraction of phosphorus in the plant biomass at maturity
$fr_{P,\sim 3}$	Normal fraction of phosphorus in the plant biomass near maturity
$fr_{P,yld}$	Fraction of phosphorus in the yield
fr_{phosyn}	Fraction of solar radiation that is photosynthetically active
fr_{PHU}	Fraction of potential heat units accumulated for the plant on a given day in the growing season
$fr_{PHU,1}$	Fraction of the growing season corresponding to the 1st point on the optimal leaf area development curve
$fr_{PHU,2}$	Fraction of the growing season corresponding to the 2nd point on the optimal leaf area development curve
$fr_{PHU,50\%}$	Fraction of potential heat units accumulated for the plant at 50% maturity ($fr_{PHU,50\%}$=0.5)
$fr_{PHU,100\%}$	Fraction of potential heat units accumulated for the plant at maturity ($fr_{PHU,100\%}$=1.0)
$fr_{PHU,sen}$	Fraction of growing season at which senescence becomes the dominant growth process
fr_{pot}	Fraction of the HRU area draining into the pothole
fr_{root}	Fraction of total biomass in the roots on a given day in the growing season
fr_{trns}	Fraction of transmission losses partitioned to the deep aquifer
$fr_{vol,ly}$	Estimated fraction of nitrogen lost by volatilization
fr_{wsh}	Wash-off fraction for the pesticide
$fr_{\Delta t}$	Fraction of the time step in which water is flowing in the channel
g	Exponent
g_{ℓ}	Leaf conductance (m s^{-1})
$g_{\ell,mx}$	Maximum conductance of a single leaf (m s^{-1})
g_{mon}	Skew coefficient for daily precipitation in the month
gc	Fraction of the ground surface covered by plants
h_c	Canopy height (cm)
$h_{c,mx}$	Plant’s maximum canopy height (m)
h_{fall}	Height through which water falls (m)
h_{wtbl}	Water table height (m)
$harv_{eff}$	Efficiency of the harvest operation
hr	Hour of day (1-24)
i	Rainfall intensity (mm/hr)
i_{mx}	Maximum rainfall intensity (mm/hr)
imp_{con}	Fraction of the HRU area that is impervious and hydraulically connected to the drainage system
imp_{dcon}	Fraction of the HRU area that is impervious but not hydraulically connected to the drainage system
imp_{tot}	Fraction of the HRU area that is impervious (both connected and disconnected)
irr	Amount of irrigation water added on a given day (m^3 H_2O)
k	Von Kármán constant
k_{bact}	Bacterial partition coefficient
$k_{d,perc}$	Phosphorus percolation coefficient (10 m^3/Mg)
$k_{d,surf}$	Phosphorus soil partitioning coefficient (m^3/Mg)
k_i	Decay constant for rainfall intensity (hr)

k_{ℓ}	Light extinction coefficient
$k_{\ell,0}$	Non-algal portion of the light extinction coefficient (m^{-1})
$k_{\ell,1}$	Linear algal self shading coefficient (m^{-1} $(\mu g\text{-chla/L})^{-1}$)
$k_{\ell,2}$	Nonlinear algal self shading coefficient (m^{-1} $(\mu g\text{-chla/L})^{-2/3}$)
$k_{p,aq}$	Rate constant for degradation or removal of pesticide in the water (1/day)
$k_{p,foliar}$	Rate constant for degradation or removal of the pesticide on foliage (1/day)
$k_{p,sed}$	Rate constant for degradation or removal of pesticide in the sediment (1/day)
$k_{p,soil}$	Rate constant for degradation or removal of the pesticide in soil (1/day)
k_r	Decay factor (m^{-1} km^{-1})
k_s	Sediment settling decay constant (1/day)
kk	Coefficient in urban wash off equation
m	Exponential term in USLE LS factor calculation
m_c	Percent clay content
m_s	Percent sand content
m_{silt}	Percent silt content (0.002-0.05 mm diameter particles)
m_{vfs}	Percent very fine sand content (0.05-0.10 mm diameter particles)
$minN_{app}$	Amount of mineral nitrogen applied (kg N/ha)
$minN_{app,mx}$	Maximum amount of mineral N allowed to be applied on any one day (kg N/ha)
$minN_{app,mxyr}$	Maximum amount of mineral N allowed to be applied during a year (kg N/ha)
$minP_{act,ly}$	Amount of phosphorus in the active mineral pool (mg/kg or kg P/ha)
$minP_{sta,ly}$	Amount of phosphorus in the stable mineral pool (mg/kg or kg P/ha)
mon	Month of the year
$mon_{fld,beg}$	Beginning month of the flood season
$mon_{fld,end}$	Ending month of the flood season
n	Manning's roughness coefficient for the subbasin or channel
n_1	First shape coefficient in plant nitrogen equation
n_2	Second shape coefficient in plant nitrogen equation
$nstrs$	Nitrogen stress for a given day
$orgC_{ly}$	Amount of organic carbon in the layer (%)
$orgC_{surq}$	Organic carbon in surface runoff (kg orgC),
$orgN_{act,fert}$	Amount of nitrogen in the active organic pool added to the soil in the fertilizer (kg N/ha)
$orgN_{act,ly}$	Nitrogen in the active organic pool (mg/kg or kg N/ha)
$orgN_{frsh,fert}$	Amount of nitrogen in the fresh organic pool added to the soil in the fertilizer (kg N/ha)
$orgN_{frsh,surf}$	Nitrogen in the fresh organic pool in the top 10mm (kg N/ha)
$orgN_{hum,ly}$	Humic organic nitrogen in the layer (mg/kg or kg N/ha)
$orgN_{sta,ly}$	Nitrogen in the stable organic pool (mg/kg or kg N/ha)
$orgN_{stor,i-1}$	Surface runoff organic N stored or lagged from the previous day (kg N/ha)
$orgN_{str}$	Organic nitrogen concentration in the stream (mg N/L)
$orgN_{surf}$	Amount of organic nitrogen transport to the main channel in surface runoff (kg N/ha)

$orgN'_{surf}$	Amount of surface runoff organic N generated in HRU on a given day (kg N/ha)
$orgP_{act,ly}$	Amount of phosphorus in the active organic pool (kg P/ha)
$orgP_{frsh,fert}$	Amount of phosphorus in the fresh organic pool added to the soil in the fertilizer (kg P/ha)
$orgP_{frsh,ly}$	Phosphorus in the fresh organic pool in layer *ly* (kg P/ha)
$orgP_{hum,fert}$	Amount of phosphorus in the humus organic pool added to the soil in the fertilizer (kg P/ha)
$orgP_{hum,ly}$	Amount of phosphorus in humic organic pool in the layer (mg/kg or kg P/ha)
$orgP_{sta,ly}$	Amount of phosphorus in the stable organic pool (kg P/ha)
$orgP_{str}$	Organic phosphorus concentration in the stream (mg P/L)
p	Total phosphorus concentration (μg P/L)
p_1	First shape coefficient in plant phosphorus equation
p_2	Second shape coefficient in plant phosphorus equation
pai	Phosphorus availability index
$pest$	Actual amount of pesticide applied (kg pst/ha)
$pest'$	Effective amount of pesticide applied (kg pst/ha)
$pest_{fol}$	Amount of pesticide applied to foliage (kg pst/ha)
$pest_{surf}$	Amount of pesticide applied to the soil surface (kg pst/ha)
$plaps$	Precipitation lapse rate (mm H_2O/km)
prf	Peak rate adjustment factor
pst_{bur}	Amount of pesticide removed via burial (mg pst)
$pst_{deg,sed}$	Amount of pesticide removed from the sediment via degradation (mg pst)
$pst_{deg,wtr}$	Amount of pesticide removed from the water via degradation (mg pst)
pst_{dif}	Amount of pesticide transferred between the water and sediment by diffusion (mg pst)
pst_f	Amount of pesticide on the foliage (kg pst/ha)
$pst_{f,wsh}$	Amount of pesticide on foliage that is washed off the plant and onto the soil surface on a given day (kg pst/ha)
pst_{flow}	Amount of pesticide removed in the flow (kg pst/ha)
pst_{in}	Pesticide added to the water body via inflow (mg pst)
pst'_{lat}	Amount of lateral flow soluble pesticide generated in HRU on a given day (kg pst/ha)
$pst_{lat,ly}$	Pesticide removed in lateral flow from a layer (kg pst/ha)
$pst_{latstor,i-1}$	Lateral flow pesticide stored or lagged from the previous day (kg pst/ha)
pst_{lksed}	Amount of pesticide in the sediment (mg pst)
pst_{lkwtr}	Amount of pesticide in the water (mg pst)
$pst_{perc,ly}$	Pesticide moved to the underlying layer by percolation (kg pst/ha)
pst_{rchsed}	Amount of pesticide in the sediment (mg pst)
pst_{rchwtr}	Amount of pesticide in the water (mg pst)
$pst_{rsp,wtr}$	Amount of pesticide removed from sediment via resuspension (mg pst)
$pst_{s,ly}$	Amount of pesticide in the soil (kg pst/ha)
pst_{sed}	Amount of sorbed pesticide transported to the main channel in surface runoff (kg pst/ha)
pst'_{sed}	Sorbed pesticide loading generated in HRU on a given day (kg pst/ha)

$pst_{sedstor,i-1}$	Sorbed pesticide stored or lagged from the previous day (kg pst/ha)
pst_{sol}	Solubility of the pesticide in water (mg/L)
$pst_{sol,o}$	Amount of dissolved pesticide removed via outflow (mg pst)
$pst_{sorb,o}$	Amount of particulate pesticide removed via outflow (mg pst)
$pst_{stl,wtr}$	Amount of pesticide removed from the water due to settling (mg pst)
pst_{surf}	Pesticide removed in surface runoff (kg pst/ha)
pst'_{surf}	Amount of surface runoff soluble pesticide generated in HRU on a given day (kg pst/ha)
$pst_{surstor,i-1}$	Surface runoff soluble pesticide stored or lagged from the previous day (kg pst/ha)
$pst_{vol,wtr}$	Amount of pesticide removed via volatilization (mg pst)
$pstrs$	Phosphorus stress for a given day
q_0^*	Unit source area flow rate (mm hr^{-1})
q_{ch}	Average channel flow rate (m^3 s^{-1})
q_{ch}^*	Average channel flow rate (mm hr^{-1})
$q_{ch,pk}$	Peak flow rate (m^3/s)
q_{in}	Inflow rate (m^3/s)
q_{out}	Outflow rate (m^3/s)
q_{ov}	Average overland flow rate (m^3 s^{-1})
q_{peak}	Peak runoff rate (m^3/s or mm/hr)
$q_{peak,f}$	Peak rate after transmission losses (m^3/s)
$q_{peak,i}$	Peak rate before accounting for transmission losses (m^3/s)
q_{rel}	Average daily principal spillway release rate (m^3/s)
$q_{rel,mn}$	Minimum average daily outflow for the month (m^3/s)
$q_{rel,mx}$	Maximum average daily outflow for the month (m^3/s)
q_{tile}	Average daily tile flow rate (m^3/s)
r	Actual earth-sun distance (AU)
r_0	Mean earth-sun distance, 1 AU
r_1	First shape coefficient for radiation-use efficiency curve
r_2	Second shape coefficient for radiation-use efficiency curve
r_a	Diffusion resistance of the air layer (aerodynamic resistance) (s m^{-1})
r_c	Plant canopy resistance (s m^{-1})
r_g	Gaseous surface renewal rate (1/day)
r_l	Liquid surface renewal rate (1/day)
r_ℓ	Minimum effective resistance of a single leaf (s m^{-1})
$r_{\ell-ab}$	Minimum abaxial stomatal leaf resistance (s m^{-1})
$r_{\ell-ad}$	Minimum adaxial stomatal leaf resistance (s m^{-1})
$ratio_{WD}$	Channel width to depth ratio
$reff$	Removal efficiency of the sweeping equipment
$rexp$	Exponent for exponential precipitation distribution
rnd_1	Random number between 0.0 and 1.0
rnd_2	Random number between 0.0 and 1.0
$rock$	Percent rock in soil layer (%)
rsd_{ly}	Residue in layer *ly* (kg/ha)

rsd_{surf}	Material in the residue pool for the top 10mm of soil on day i (kg ha^{-1})
sed	Sediment yield on a given day (metric tons)
sed_{ch}	Amount of suspended sediment in the reach (metric tons)
sed_{deg}	Amount of sediment reentrained in the reach segment (metric tons)
sed_{dep}	Amount of sediment deposited in the reach segment (metric tons)
sed_{flowin}	Amount of sediment added to the water body with inflow (metric tons)
$sed_{flowout}$	Amount of sediment transported out of the water body (metric tons)
sed_{lat}	Sediment loading in lateral and groundwater flow (metric tons)
sed_{out}	Amount of sediment transported out of the reach (metric tons)
sed_{stl}	Amount of sediment removed from the water by settling (metric tons)
$sed_{stor,i-1}$	Sediment stored or lagged from the previous day (metric tons)
sed_{wb}	Sediment in the water body (metric tons)
$sedP_{stor,i-1}$	Sediment-attached P stored or lagged from the previous day (kg P/ha)
$sedP_{surf}$	Amount of phosphorus transported with sediment to the main channel in surface runoff (kg P/ha)
$sedP'_{surf}$	Amount of sediment-attached P loading generated in HRU on a given day (kg P/ha)
slp	Average slope of the subbasin (% or m/m)
slp_{ch}	Average channel slope along channel length (m m^{-1})
sno_{cov}	Fraction of the HRU area covered by snow
$spexp$	Exponent in sediment transport equation
$starg$	Target reservoir volume specified for a given month (m^3 H_2O)
$surlag$	Surface runoff lag coefficient
t	Number of hours before (+) or after (-) solar noon
$t_{1/2,aq}$	Aqueous half-life for the pesticide (days)
$t_{1/2,f}$	Half-life of the pesticide on foliage (days)
$t_{1/2,s}$	Half-life of the pesticide in the soil (days)
$t_{1/2,sed}$	Sediment half-life for the pesticide (days)
t_{half}	Length of time needed for solid build up to increase from 0 kg/curb km to ½ SED_{mx} (days)
t_{ch}	Time of concentration for channel flow (hr)
t_{conc}	Time of concentration for a subbasin (hr)
t_{dorm}	Dormancy threshold (hrs)
t_{drain}	Time required to drain the soil to field capacity (hrs)
t_i	Solar time at the midpoint of the hour i
t_{ov}	Time of concentration for overland flow (hr)
$tile_{lag}$	Drain tile lag time (hrs).
$tile_{wtr}$	Amount of water removed from the layer on a given day by tile drainage (mm H_2O)
$tlaps$	Temperature lapse rate (°C/km)
$tloss$	Channel transmission losses (m^3 H_2O)
$trap_{ef}$	Fraction of the constituent loading trapped by the filter strip
$trap_{ef,bact}$	Fraction of the bacteria loading trapped by the filter strip
$tstrs$	Temperature stress for a given day expressed as a fraction of optimal plant growth
u_z	Wind speed at height z_w (m s^{-1})
u_{z1}	Wind speed (m s^{-1}) at height z_1

u_{z2}	Wind speed (m s^{-1}) at height z_2
urb_{coef}	Wash off coefficient (mm^{-1})
v_b	Pesticide burial velocity (m/day)
v_c	Average channel velocity (m s^{-1})
$v_{ch,pk}$	Peak channel velocity (m/s)
v_d	Pesticide rate of diffusion or mixing velocity (m/day)
v_{lat}	Velocity of flow at the hillslope outlet ($mm \cdot h^{-1}$)
v_{ov}	Overland flow velocity (m s^{-1})
v_r	Pesticide resuspension velocity (m/day)
v_s	Pesticide settling velocity (m/day)
v_{surf}	Surface runoff flow rate (m^3/s)
v_v	Pesticide volatilization mass-transfer coefficient (m/day)
$vol_{Qsurf,f}$	Volume of runoff after transmission losses (m^3)
$vol_{Qsurf,i}$	Volume of runoff prior to transmission losses (m^3)
vol_{thr}	Threshold volume for a channel of length L and width W (m^3)
vpd	Vapor pressure deficit (kPa)
vpd_{fr}	Vapor pressure deficit corresponding to $fr_{g,mx}$ (kPa)
vpd_{thr}	Threshold vapor pressure deficit above which a plant will exhibit reduced leaf conductance or reduced radiation-use efficiency (kPa)
w_1	Shape coefficient in retention parameter adjustments for soil moisture content
w_2	Shape coefficient in retention parameter adjustments for soil moisture content
$w_{actualup}$	Total plant water uptake for the day (mm H_2O)
$w_{actualup,ly}$	Actual water uptake for layer ly (mm H_2O)
$w_{crk,btm}$	Amount of water flow past the lower boundary of the soil profile due to bypass flow (mm H_2O)
w_{deep}	Amount of water percolating from the shallow aquifer into the deep aquifer (mm H_2O)
$w_{deep,mx}$	Maximum amount of water moving into the deep aquifer on day i (mm H_2O)
w_{demand}	Water uptake demand not met by overlying soil layers (mm H_2O)
w_{inf}	Amount of water entering the soil profile on a given day (mm H_2O)
w_{mobile}	Amount of mobile water in the layer (mm H_2O)
$w_{perc,ly}$	Amount of water percolating to the underlying soil layer on a given day (mm H_2O)
$w_{pump,dp}$	Amount of water removed from the deep aquifer by pumping (mm H_2O)
$w_{pump,sh}$	Amount of water removed from the shallow aquifer by pumping (mm H_2O)
w_{rchrg}	Amount of water entering the aquifer via recharge (mm H_2O)
w_{revap}	Amount of water moving into the soil zone in response to water deficiencies (mm H_2O)
$w_{revap,mx}$	Maximum amount of water moving into the soil zone in response to water deficiencies on day i (mm H_2O)
w_{seep}	Total amount of water exiting the bottom of the soil profile (mm H_2O)
$w_{up,ly}$	Potential water uptake for layer ly (mm H_2O)
$w'_{up,ly}$	Adjusted potential water uptake for layer ly (mm H_2O)
$w''_{up,ly}$	Potential water uptake when the soil water content is less than 25% of plant available water (mm H_2O)

$w_{up,z}$	Potential water uptake from the soil surface to a specified depth, z, on a given day (mm H_2O)
$w_{up,zl}$	Potential water uptake for the profile to the lower boundary of the soil layer (mm H_2O)
$w_{up,zu}$	Potential water uptake for the profile to the upper boundary of the soil layer (mm H_2O)
$width_{filtstrip}$	Width of filter strip (m)
$wstrs$	Water stress for a given day expressed as a fraction of total water demand
yld	Crop yield (kg/ha)
yld_{act}	Actual yield (kg ha^{-1})
$yld_{est,N}$	Nitrogen yield estimate (kg N/ha)
$yld_{est,Nprev}$	Nitrogen yield estimate from the previous year (kg N/ha)
yld_N	Amount of nitrogen removed in the yield (kg N/ha)
yld_P	Amount of phosphorus removed in the yield (kg P/ha)
$yld_{yr,N}$	Nitrogen yield target for the current year (kg N/ha)
yr_{sim}	Year of simulation (1 - yr_{tot})
yr_{tot}	Total number of calendar years simulated
yrs	Number of years of rainfall data used to obtain values for monthly extreme half-hour rainfalls
z	Depth below soil surface (mm)
z_1	Height of wind speed measurement (cm)
z_2	Height of wind speed measurement (cm)
z_{ch}	Inverse of the channel side slope
z_{fld}	Inverse of the flood plain side slope
z_g	Thickness of the gas film (m)
z_l	Thickness of the liquid film (m)
$z_{l,ly}$	Depth from the surface to the bottom of the soil layer (mm)
$z_{mid,ly}$	Depth from the soil surface to the middle of the layer (mm)
z_{om}	Roughness length for momentum transfer (cm)
z_{ov}	Roughness length for vapor transfer (cm)
z_p	Height of the humidity (psychrometer) and temperature measurements (cm)
z_{root}	Depth of root development in the soil (mm)
$z_{root,mx}$	Maximum depth for root development in the soil (mm)
z_{tot}	Depth to bottom of soil profile (mm)
z_w	Height of the wind speed measurement (cm)
zd	Ratio of depth in soil to damping depth
α	Short-wave reflectance or albedo
α_0	Ratio of chlorophyll *a* to algal biomass (μg chla/mg alg)
$\alpha_{0.5}$	Maximum half-hour rainfall expressed as a fraction of daily rainfall
$\alpha_{0.5L}$	Smallest half-hour rainfall fraction that can be generated on a given day
$\alpha_{0.5mon}$	Average maximum half-hour rainfall fraction for the month
$\alpha_{0.5U}$	Largest half-hour rainfall fraction that can be generated on a given day
α_1	Fraction of algal biomass that is nitrogen (mg N/mg alg biomass),
α_2	Fraction of algal biomass that is phosphorus (mg P/mg alg biomass)
α_3	Rate of oxygen production per unit of algal photosynthesis (mg O_2/mg alg)

α_4	Rate of oxygen uptake per unit of algae respired (mg O_2/mg alg)
α_5	Rate of oxygen uptake per unit NH_4^+ oxidation (mg O_2/mg N)
α_6	Rate of oxygen uptake per unit NO_2 oxidation (mg O_2/mg N)
α_{bnk}	Bank flow recession constant or constant of proportionality
α_{gw}	Baseflow recession constant
α_{hill}	Slope of the hillslope segment (degrees)
α_{pet}	Coefficient in Priestley-Taylor equation
α_{plant}	Plant albedo (set at 0.23)
α_{soil}	Soil albedo
α_{tc}	Fraction of daily rainfall that occurs during the time of concentration
β_0	Coefficient for USGS regression equations for urban loadings
β_1	Coefficient for USGS regression equations for urban loadings
β_2	Coefficient for USGS regression equations for urban loadings
β_3	Coefficient for USGS regression equations for urban loadings
β_4	Coefficient for USGS regression equations for urban loadings
β_{deep}	Aquifer percolation coefficient
β_{eqP}	Slow equilibration rate constant (0.0006 d^{-1})
β_{min}	Rate coefficient for mineralization of the humus active organic nutrients
β_n	Nitrogen uptake distribution parameter
$\beta_{N,1}$	Rate constant for biological oxidation of ammonia nitrogen (day^{-1} or hr^{-1})
$\beta_{N,1,20}$	Rate constant for biological oxidation of ammonia nitrogen at 20°C (day^{-1} or hr^{-1})
$\beta_{N,2}$	Rate constant for biological oxidation of nitrite to nitrate (day^{-1} or hr^{-1})
$\beta_{N,2,20}$	Rate constant for biological oxidation of nitrite to nitrate at 20°C (day^{-1} or hr^{-1})
$\beta_{N,3}$	Rate constant for hydrolysis of organic nitrogen to ammonia nitrogen (day^{-1} or hr^{-1})
$\beta_{N,3,20}$	Local rate constant for hydrolysis of organic nitrogen to NH_4^+ at 20°C (day^{-1} or hr^{-1})
β_{NO3}	Nitrate percolation coefficient
β_p	Phosphorus uptake distribution parameter
$\beta_{P,4}$	Rate constant for mineralization of organic phosphorus (day^{-1} or hr^{-1})
$\beta_{P,4,20}$	Local rate constant for organic phosphorus mineralization at 20°C (day^{-1} or hr^{-1})
β_{pst}	Pesticide percolation coefficient
β_{rev}	Revap coefficient
β_{rsd}	Rate coefficient for mineralization of the residue fresh organic nutrients
β_{sa}	Coefficient for impoundment surface area equation
β_{trns}	Rate constant for nitrogen transfer between active and stable organic pools (1×10^{-5})
β_w	Water-use distribution parameter
$\chi_i(j)$	3×1 matrix for day i whose elements are residuals of maximum temperature (j = 1), minimum temperature (j = 2) and solar radiation (j = 3),
Δ	Slope of the saturation vapor pressure curve (kPa °C^{-1})
$\Delta algae$	Change in algal biomass concentration (mg alg/L)
Δbio	Potential increase in total plant biomass on a given day (kg/ha)
Δbio_{act}	Actual increase in total plant biomass on a given day (kg/ha)

$\Delta g_{\ell,dcl}$	Rate of decline in leaf conductance per unit increase in vapor pressure deficit (m s^{-1} kPa^{-1})
ΔLAI_i	Leaf area added on day *i* (potential)
$\Delta LAI_{act,i}$	Actual leaf area added on day *i*
$\Delta NH4_{str}$	Change in ammonium concentration (mg N/L)
$\Delta NO2_{str}$	Change in nitrite concentration (mg N/L)
$\Delta orgN_{str}$	Change in organic nitrogen concentration (mg N/L)
$\Delta orgP_{str}$	Change in organic phosphorus concentration (mg P/L)
ΔOx_{str}	Change in dissolved oxygen concentration (mg O_2/L)
Δpst_{lkwtr}	Change in pesticide mass in the water layer (mg pst)
Δpst_{lksed}	Change in pesticide mass in the sediment layer (mg pst)
Δpst_{rchwtr}	Change in pesticide mass in the water layer (mg pst)
Δpst_{rchsed}	Change in pesticide mass in the sediment layer (mg pst)
Δrsd	Biomass added to the residue pool on a given day (kg ha^{-1})
Δrue_{dcl}	Rate of decline in radiation-use efficiency per unit increase in vapor pressure deficit (kg/ha·(MJ/m^{2})$^{-1}$·kPa^{-1} or (10^{-1} g/MJ)·kPa^{-1})
$\Delta solP_{str}$	Change in solution phosphorus concentration (mg P/L)
Δt	Length of the time step (s)
δ	Solar declination (radians)
δ_{gw}	Delay time or drainage time for aquifer recharge (days)
$\delta_{ntr,ly}$	Residue decay rate constant
ε	Emissivity
ε'	Net emittance
ε_a	Atmospheric emittance
$\varepsilon_{C:N}$	Residue C:N ratio in the soil layer
$\varepsilon_{C:P}$	Residue C:P ratio in the soil layer
$\varepsilon_{C:sed}$	Carbon enrichment ratio
ε_i	3 × 1 matrix of independent random components
$\varepsilon_{N:sed}$	Nitrogen enrichment ratio
$\varepsilon_{P:sed}$	Phosphorus enrichment ratio
$\varepsilon_{pst:sed}$	Pesticide enrichment ratio
ε_{sr}	Radiation term for bare soil surface temperature calculation
ε_{vs}	Vegetative or soil emittance
ϕ	Latitude in radians
ϕ_d	Drainable porosity of the soil (mm/mm)
ϕ_{fc}	Porosity of the soil layer filled with water when the layer is at field capacity water content (mm/mm)
ϕ_{soil}	Porosity of the soil (mm/mm)
γ	Psychrometric constant (kPa °C^{-1})
$\gamma_{ntr,ly}$	Nutrient cycling residue composition factor for layer *ly*
γ_{reg}	Plant growth factor (0.0-1.0)
$\gamma_{sw,ly}$	Nutrient cycling water factor for layer *ly*
$\gamma_{tmp,ly}$	Nutrient cycling temperature factor for layer *ly*

γ_{wu}	Water deficiency factor
η	Evaporation coefficient (0.6)
$\eta_{midz,ly}$	Volatilization depth factor
$\eta_{nit,ly}$	Nitrification regulator
$\eta_{sw,ly}$	Nitrification soil water factor
$\eta_{tmp,ly}$	Nitrification/volatilization temperature factor
$\eta_{vol,ly}$	Volatilization regulator
φ	Scaling factor for impact of soil water on damping depth
φ_n	Scaling factor for nitrogen stress equation
φ_p	Scaling factor for phosphorus stress equation
κ_1	CBOD deoxygenation rate (day^{-1} or hr^{-1})
$\kappa_{1,20}$	CBOD deoxygenation rate at 20°C (day^{-1} or hr^{-1})
κ_2	Reaeration rate for Fickian diffusion (day^{-1} or hr^{-1})
$\kappa_{2,20}$	Reaeration rate at 20°C (day^{-1} or hr^{-1})
κ_3	Settling loss rate of CBOD (day^{-1} or hr^{-1})
$\kappa_{3,20}$	Settling loss rate of CBOD at 20°C (day^{-1} or hr^{-1})
κ_4	Sediment oxygen demand rate (mg $O_2/(m^2\cdot day)$)
$\kappa_{4,20}$	Sediment oxygen demand rate at 20°C (mg $O_2/(m^2\cdot day)$ or mg $O_2/(m^2\cdot hr)$)
λ	Latent heat of vaporization (MJ kg^{-1})
ℓ	Lag coefficient that controls influence of previous day's temperature on current day's temperature
ℓ_1	First shape coefficient for optimal leaf area development curve
ℓ_2	Second shape coefficient for optimal leaf area development curve
ℓ_{crk}	Lag factor for crack development during drying
ℓ_{sno}	Snow temperature lag factor
μ	Specific yield of the shallow aquifer (m/m)
μ_{10m}	Mean wind speed for the day at height of 10 meters (m s^{-1})
μ_a	Local specific growth rate of algae (day^{-1})
$\mu_{a,20}$	Local specific algal growth rate at 20°C (day^{-1} or hr^{-1})
μ_{max}	Maximum specific algal growth rate (day^{-1} or hr^{-1})
μ_{mon}	Mean daily rainfall (mm H_2O) for the month
μdew_{mon}	Average dew point temperature for the month (°C)
μDmx_{mon}	Average daily maximum temperature of the month on dry days (°C)
$\mu Drad_{mon}$	Average daily solar radiation of the month on dry days (MJ m^{-2})
μmn_{mon}	Average daily minimum temperature for the month (°C)
μmx_{mon}	Average daily maximum temperature for the month (°C)
μrad_{mon}	Average daily solar radiation for the month (MJ m^{-2})
μtmp_{mon}	Mean air temperature for the month (°C)
μ_w	Wind speed (m/s)
μWmx_{mon}	Average daily maximum temperature of the month on wet days (°C)
μwnd_{mon}	Average wind speed for the month (m s^{-1})
$\mu Wrad_{mon}$	Average daily solar radiation of the month on wet days (MJ m^{-2})
ν	Apparent settling velocity (m/day)

θ_e	Fraction of water volume that excludes anions
θ_v	Volumetric moisture content (mm/mm)
θ_z	Zenith angle (radians)
$\rho_0(j,k)$	Correlation coefficient between variables *j* and *k* on the same day where *j* and *k* may be set to 1 (maximum temperature), 2 (minimum temperature) or 3 (solar radiation)
$\rho_1(j,k)$	Correlation coefficient between variable *j* and *k* with variable *k* lagged one day with respect to variable *j*
ρ_a	Local respiration rate of algae (day^{-1})
$\rho_{a,20}$	Local algal respiration rate at 20°C (day^{-1} or hr^{-1})
ρ_{air}	Air density (kg m^{-3})
ρ_b	Soil bulk density (Mg m^{-3})
ρ_s	Particle density (Mg m^{-3})
ρ_w	Density of water (1 Mg m^{-3})
σ	Stefan-Boltzmann constant (4.903×10^{-9} MJ m^{-2} K^{-4} d^{-1})
σ_1	Local settling rate for algae (m/day)
$\sigma_{1,20}$	Local algal settling rate at 20°C (m/day or m/hr)
σ_2	Benthos (sediment) source rate for soluble P (mg P/m^2-day or mg P/m^2-hr)
$\sigma_{2,20}$	Benthos (sediment) source rate for soluble phosphorus at 20°C (mg P/m^2-day or mg P/m^2-hr)
σ_3	Benthos (sediment) source rate for ammonium (mg N/m^2-day or mg N/m^2-hr)
$\sigma_{3,20}$	Benthos (sediment) source rate for ammonium nitrogen at 20°C (mg N/m^2-day or mg N/m^2-hr)
σ_4	Rate coefficient of organic nitrogen settling (day^{-1} or hr^{-1})
$\sigma_{4,20}$	Local settling rate for organic nitrogen at 20°C (day^{-1} or hr^{-1})
σ_5	Rate coefficient for organic phosphorus settling (day^{-1} or hr^{-1})
$\sigma_{5,20}$	Local settling rate for organic phosphorus at 20°C (day^{-1} or hr^{-1})
σ_{mon}	Standard deviation of daily rainfall (mm H_2O) for the month
σmn_{mon}	Standard deviation for daily minimum temperature during the month (°C)
σmx_{mon}	Standard deviation for daily maximum temperature during the month (°C)
σrad_{mon}	Standard deviation for daily solar radiation during the month (MJ m^{-2})
ω	Angular velocity of the earth's rotation (0.2618 radians h^{-1})
ω_{tmp}	Angular frequency in soil temperature variation
Ψ_{wf}	Wetting front matric potential (mm)

APPENDIX B

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