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.

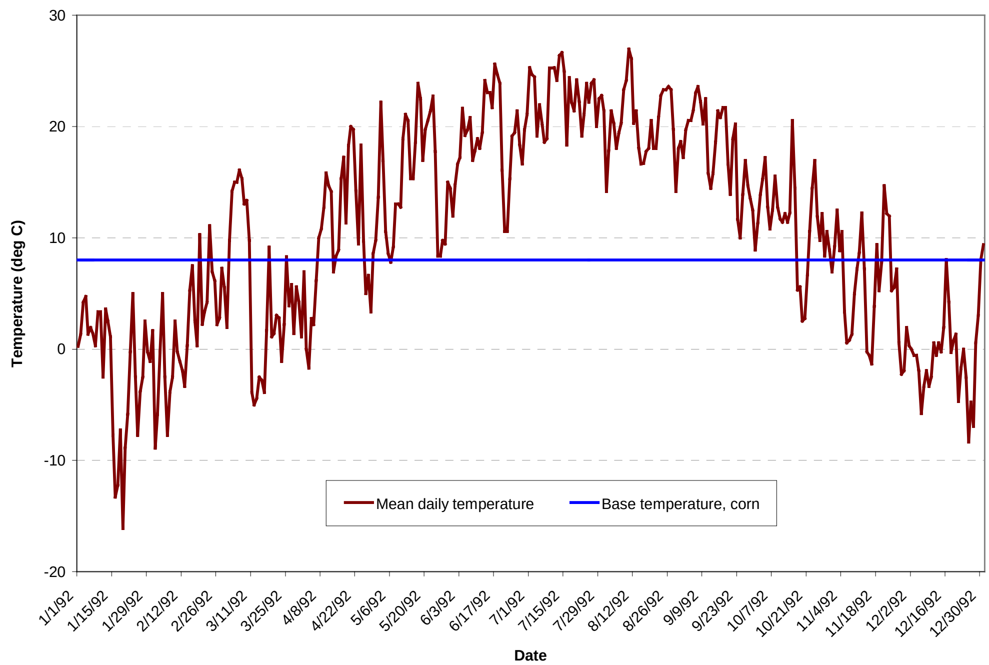

Figure 17-1: Mean daily temperature recorded for Greenfield, Indiana

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.

$$t_{dorm} = 1.0 \qquad \text{if } \phi > 40\text{ º N or S} \qquad 17.2.2$$

$$t_{dorm} = \frac{\phi - 20}{20} \qquad \text{if } 20\text{ º N or S} \leq \phi \leq 40\text{ º N or S} \qquad 17.2.3$$

$$t_{dorm} = 0.0 \qquad \text{if } \phi < 20\text{ º N or S} \qquad 17.2.4$$

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)

17.5 REFERENCES

Barnard, J.D. 1948. Heat units as a measure of canning crop maturity. The Canner 106:28.

Boswell, V.G. 1929. Factors influencing yield and quality of peas—Biophysical and biochemical studies. Maryland Agr. Exp. Sta. Bul. 306.

Boswell, V.G. 1926. The influence of temperature upon the growth and yield of garden peas. Proc. Amer. Soc. Hort. Sci. 23:162-168.

Cross, H.Z. and M.S. Zuber. 1972. Prediction of flowering dates in maize based on different methods of estimating thermal units. Agronomy Journal 64:351-355.

Magoon, C.A. and C.W. Culpepper. 1932. Response of sweet corn to varying temperatures from time of planting to canning maturity. U.S.D.A. tech. Bull. 312.

Phillips, E.E. 1950. Heat summation theory as applied to canning crops. The Canner 27:13-15.

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.

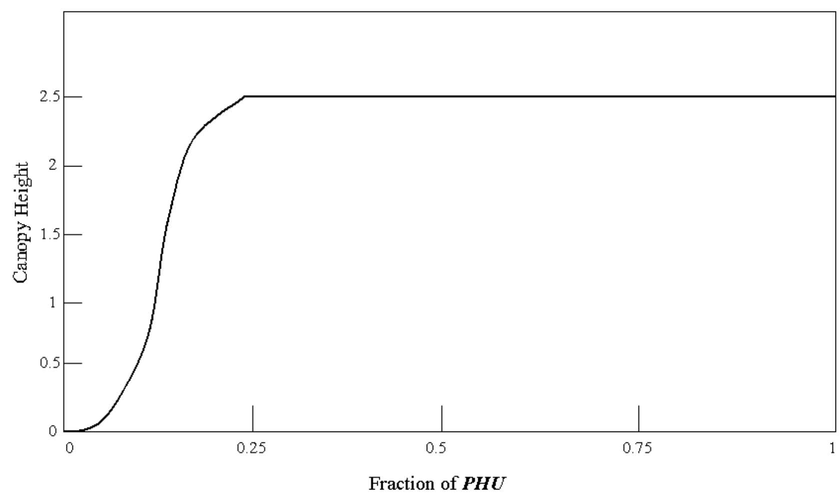

Figure 18-1: Seasonal change in plant canopy height during growing season.

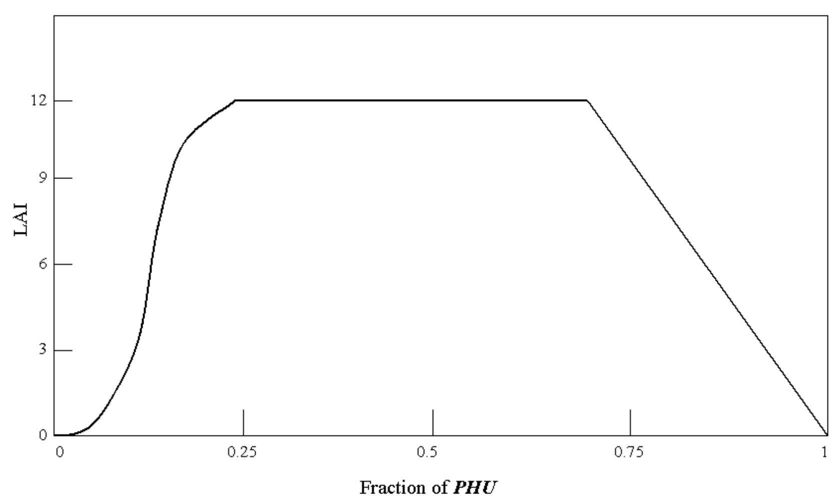

Figure 18-2: Seasonal change in plant leaf area index during growing season.

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:

$$\Delta LAI_i = \left(fr_{LAImx,i} - fr_{LAImx,i-1}\right) \cdot LAI_{mx} \cdot \left(1 - \exp\left(5 \cdot \left(LAI_{i-1} - LAI_{mx}\right)\right)\right) \qquad 18.1.14$$

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.

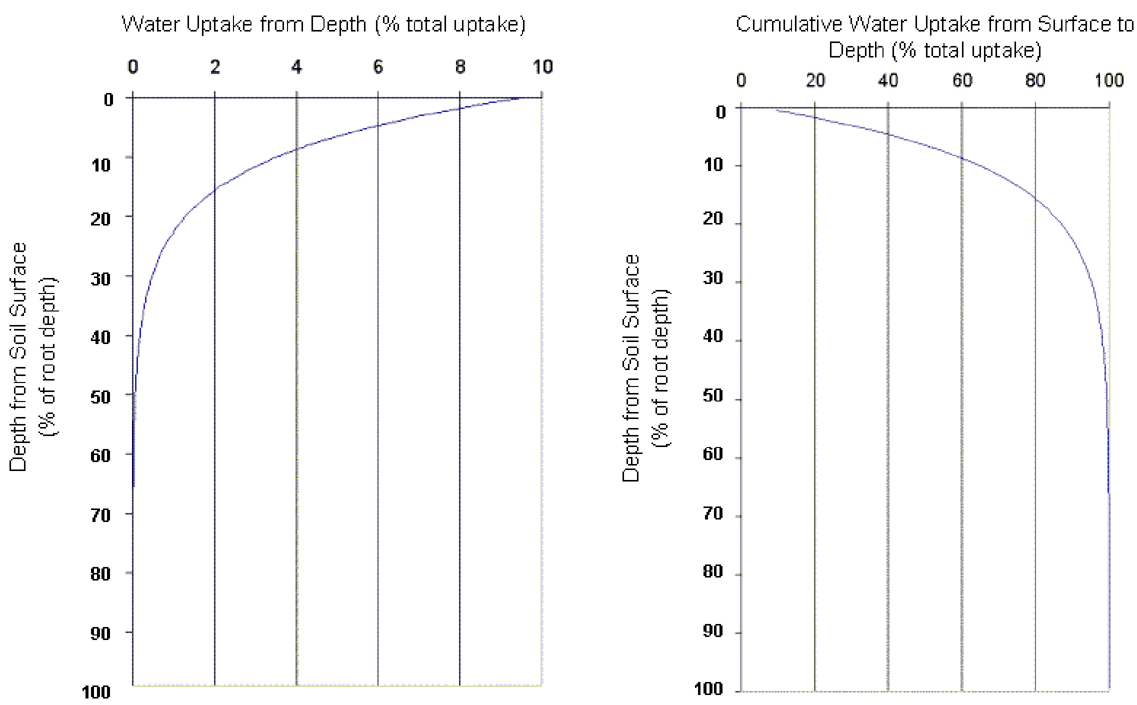

Figure 18-3: Depth distribution of water uptake

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.

$$fr_N = \left(fr_{N,1} - fr_{N,3}\right)\cdot\left[1 - \frac{fr_{PHU}}{fr_{PHU} + \exp(n_1 - n_2 \cdot fr_{PHU})}\right] + fr_{N,3} \qquad 18.3.1$$

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 ($fr_{N,3}$, $fr_{PHU,100\%}$):

$$n_1 = \ln\left[\frac{fr_{PHU,50\%}}{\left(1 - \dfrac{\left(fr_{N,2} - fr_{N,3}\right)}{\left(fr_{N,1} - fr_{N,3}\right)}\right)} - fr_{PHU,50\%}\right] + n_2 \cdot fr_{PHU,50\%} \qquad 18.3.2$$

$$n_2 = \frac{\left(\ln\left[\dfrac{fr_{PHU,50\%}}{\left(1 - \dfrac{\left(fr_{N,2} - fr_{N,3}\right)}{\left(fr_{N,1} - fr_{N,3}\right)}\right)} - fr_{PHU,50\%}\right] - \ln\left[\dfrac{fr_{PHU,100\%}}{\left(1 - \dfrac{\left(fr_{N,\sim 3} - fr_{N,3}\right)}{\left(fr_{N,1} - fr_{N,3}\right)}\right)} - fr_{PHU,100\%}\right]\right)}{fr_{PHU,100\%} - fr_{PHU,50\%}} \qquad 18.3.3$$

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 $\left(1-\frac{(fr_{N,\sim3}-fr_{N,3})}{(fr_{N,1}-fr_{N,3})}\right)$ does not equal 1. The model assumes $(fr_{N,\sim3}-fr_{N,3})=0.00001$.

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:

$$N_{up,z} = \frac{N_{up}}{[1-\exp(-\beta_n)]} \cdot \left[1-\exp\left(-\beta_n \cdot \frac{z}{z_{root}}\right)\right] \qquad 18.3.6$$

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.

$$N_{up,ly} = N_{up,zl} - N_{up,zu} \qquad 18.3.7$$

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.

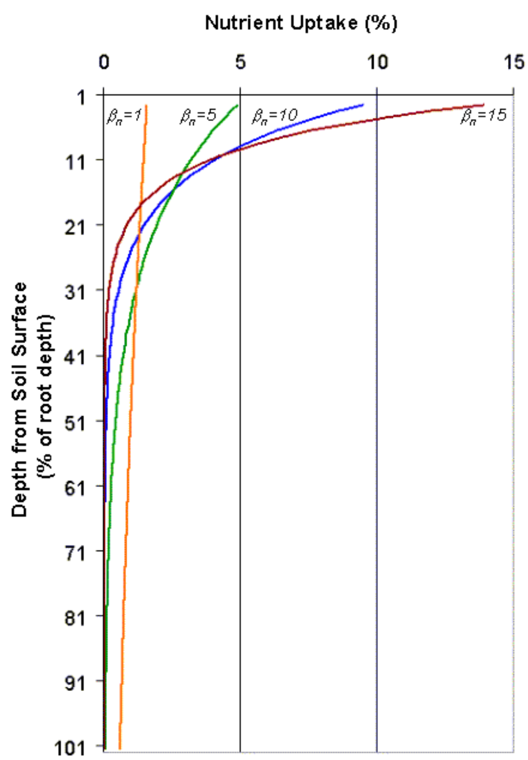

Figure 18-4: Depth distribution of nitrogen uptake

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 ($fr_{P,3}$, $fr_{PHU,100\%}$):

$$p_1 = \ln\left[\frac{fr_{PHU,50\%}}{\left(1-\frac{(fr_{P,2}-fr_{P,3})}{(fr_{P,1}-fr_{P,3})}\right)} - fr_{PHU,50\%}\right] + p_2 \cdot fr_{PHU,50\%} \qquad 18.3.20$$

$$p_2 = \frac{\left(\ln\left[\frac{fr_{PHU,50\%}}{\left(1-\frac{(fr_{P,2}-fr_{P,3})}{(fr_{P,1}-fr_{P,3})}\right)} - fr_{PHU,50\%}\right] - \ln\left[\frac{fr_{PHU,100\%}}{\left(1-\frac{(fr_{P,\sim 3}-fr_{P,3})}{(fr_{P,1}-fr_{P,3})}\right)} - fr_{PHU,100\%}\right]\right)}{fr_{PHU,100\%} - fr_{PHU,50\%}} \qquad 18.3.21$$

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, $fr_{P,\sim 3}$ 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 ($fr_{N,\sim 3}$) is used in equation 18.3.21 to ensure that the denominator term $\left(1-\frac{(fr_{P,\sim 3}-fr_{P,3})}{(fr_{P,1}-fr_{P,3})}\right)$ does not equal 1. The model assumes $(fr_{P,\sim 3} - fr_{P,3}) = 0.00001$.

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:

$$P_{up} = 1.5 \cdot \left(bio_{P,opt} - bio_P \right) \quad 18.3.23$$

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:

$$P_{up,z} = \frac{P_{up}}{\left[1 - \exp\left(-\beta_p\right)\right]} \cdot \left[1 - \exp\left(-\beta_p \cdot \frac{z}{z_{root}}\right)\right] \quad 18.3.24$$

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.

$$P_{up,ly} = P_{up,zl} - P_{up,zu} \quad 18.3.25$$

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:

$$bio_{ag} = (1 - fr_{root}) \cdot bio \qquad 18.4.4$$

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}).

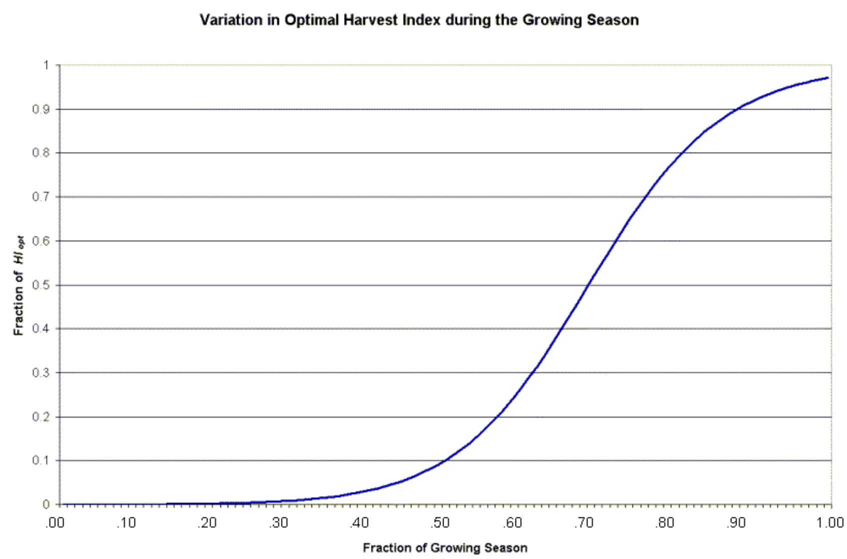

Figure 18-5: Variation in optimal harvest index (HI_i/HI_{opt}) with fraction of growing season (fr_{PHU})

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 1^{st} point on the optimal leaf area development curve
$fr_{LAI,2}$ Fraction of the maximum plant leaf area index corresponding to the 2^{nd} 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 ($kg/ha \cdot (MJ/m^2)^{-1} \cdot kPa^{-1}$ or $(10^{-1}\ g/MJ) \cdot kPa^{-1}$)
ℓ_1 First shape coefficient for optimal leaf area development curve
ℓ_2 Second shape coefficient for optimal leaf area development curve

18.6 REFERENCES

Jones, C.A. 1985. C-4 grasses and cereals. John Wiley & Sons, Inc., New York. 419 pp.

McCree, K.J. 1972. The action spectrum, absorption and quantum yield of photosynthesis in crop plants. Agric. Met. 9:191-216.

Monsi, M. and T. Saeki. 1953. Uber den Lictfaktor in den Pflanzengesellschaften und sein Bedeutung fur die Stoffproduktion. Japan J. Bot. 14:22-52.

Monteith, J.L. 1972. Solar radiation and productivity in tropical ecosystems. J. Appl. Ecol. 9:747-766.

Monteith, J.L. 1977. Climate and the efficiency of crop production in Britian. Phil. Trans. Res. Soc. London Ser. B 281:277-329.

Ross, J. 1975. Radiative transfer in plant communities. p. 13-55 *In* J.L. Monteith (ed.) Vegetation and the atmosphere, Vol. 1. Academic Press, London.

Stanhill, G. and M. Fuchs. 1977. The relative flux density of photosynthetically active radiation. J. Appl. Ecol. 14:317-322.

Stockle, C.O. and J.R. Kiniry. 1990. Variability in crop radiation-use efficiency associated with vapor-pressure deficit. Field Crops Res. 25:171-181.

Stockle, C.O., J.R. Williams, N.J. Rosenburg, and C.A. Jones. 1992. A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part 1—Modification of the EPIC model for climate change analysis. Agricultural Systems 38:225-238.

Szeicz, G. 1974. Solar radiation for plant growth. J. Appl. Ecol. 11:617-636.

Watson, D.J. 1947. Comparative physiological studies on the growth of field crops. 1. Variation in net assimilation rate and leaf area index between species and varieties and within and between years. Ann. Bot. N.S. 11:41-76.

Williams, J. R., C.A. Jones, and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27:129-144.

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:

$$tstrs = 1 \qquad \text{when } \bar{T}_{av} \leq T_{base} \qquad 19.1.2$$

$$tstrs = 1 - \exp\left[\frac{-0.1054 \cdot \left(T_{opt} - \bar{T}_{av}\right)^2}{\left(\bar{T}_{av} - T_{base}\right)^2}\right] \quad \text{when } T_{base} < \bar{T}_{av} \leq T_{opt} \qquad 19.1.3$$

$$tstrs = 1 - \exp\left[\frac{-0.1054 \cdot \left(T_{opt} - \bar{T}_{av}\right)^2}{\left(2 \cdot T_{opt} - \bar{T}_{av} - T_{base}\right)^2}\right] \quad \text{when } T_{opt} < \bar{T}_{av} \leq 2 \cdot T_{opt} - T_{base} \qquad 19.1.4$$

$$tstrs = 1 \qquad \text{when } \bar{T}_{av} > 2 \cdot T_{opt} - T_{base} \qquad 19.1.5$$

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.

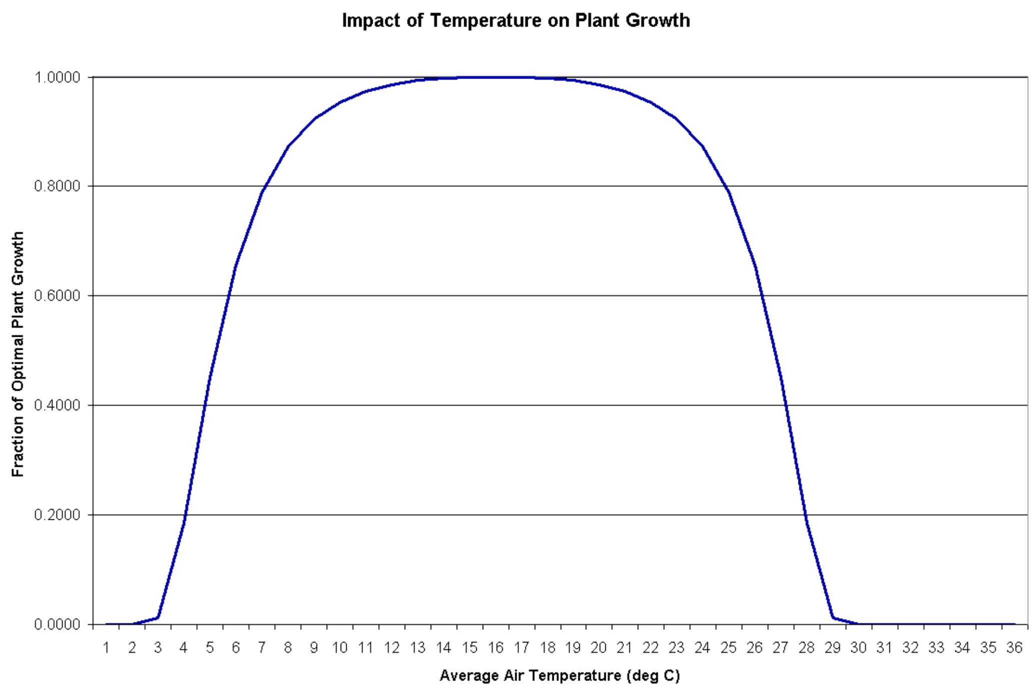

Figure 19-1: Impact of mean air temperature on plant growth for a plant with T_{base}= 0°C and T_{opt}=15°C

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:

$$nstrs = 1 - \frac{\varphi_n}{\varphi_n + \exp\left[3.535 - 0.02597 \cdot \varphi_n\right]} \qquad 19.1.6$$

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:

$$HI_{act} = (HI - HI_{min}) \cdot \frac{\gamma_{wu}}{\gamma_{wu} + \exp[6.13 - 0.883 \cdot \gamma_{wu}]} + HI_{min} \qquad 19.3.1$$

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 $rsd_{surf,i-1}$ 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*: Total 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*: Total 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:

$$NO3_{fert} = fert_{minN} \cdot (1 - fert_{NH4}) \cdot fert \qquad 20.7.1$$

$$NH4_{fert} = fert_{minN} \cdot fert_{NH4} \cdot fert \qquad 20.7.2$$

$$orgN_{frsh,fert} = 0.5 \cdot fert_{orgN} \cdot fert \qquad 20.7.3$$

$$orgN_{act,fert} = 0.5 \cdot fert_{orgN} \cdot fert \qquad 20.7.4$$

$$P_{solution,fert} = fert_{minP} \cdot fert \qquad 20.7.5$$

$$orgP_{frsh,fert} = 0.5 \cdot fert_{orgP} \cdot fert \qquad 20.7.6$$

$$orgP_{hum,fert} = 0.5 \cdot fert_{orgP} \cdot fert \qquad 20.7.7$$

$$bact_{lpsol,fert} = fert_{lpbact} \cdot k_{bact} \cdot fert \qquad 20.7.8$$

$$bact_{lpsorb,fert} = fert_{lpbact} \cdot (1 - k_{bact}) \cdot fert \qquad 20.7.9$$

$$bact_{psol,fert} = fert_{pbact} \cdot k_{bact} \cdot fert \qquad 20.7.10$$

$$bact_{psorb,fert} = fert_{pbact} \cdot (1 - k_{bact}) \cdot fert \qquad 20.7.11$$

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:

$$minN_{app} = yld_{est,N} - \left(NO3 + NH4\right) - bio_N \qquad 20.8.5$$

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:

$$pest' = ap_{ef} \cdot pest \quad 20.9.1$$

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:

$$gc = \frac{1.99532 - \text{erfc}[1.333 \cdot LAI - 2]}{2.1} \quad 20.9.2$$

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.

The complementary error function frequently occurs in solutions to advective-dispersive equations. Values for erfc(β) and erf(β) (erf is the error function for β), where β is the argument of the function, are graphed in Figure 20-1. 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.

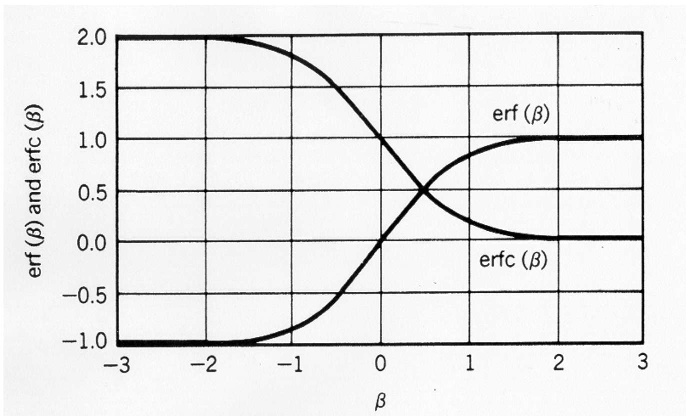

Figure 20-1: erf(β) and erfc(β) plotted versus β (from Domenico and Schwartz, 1990)

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:

$$trap_{ef,bact} = 1 - \frac{(12 + 4.5 \cdot width_{filtstrip})}{100} \qquad 20.10.1$$

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:

$$trap_{ef} = 0.367 \cdot (width_{filtstrip})^{0.2967} \qquad 20.10.2$$

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):

$$CN_c = \frac{CN_p \cdot \left(1 - imp_{tot} + \frac{imp_{dcon}}{2}\right) + 98 \cdot \left(\frac{imp_{dcon}}{2}\right)}{1 - imp_{con}} \quad \text{if } imp_{tot} \le 0.30 \qquad 22.2.1$$

$$CN_c = \frac{CN_p \cdot (1 - imp_{tot}) + 98 \cdot imp_{dcon}}{1 - imp_{con}} \quad \text{if } imp_{tot} > 0.30 \qquad 22.2.2$$

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.

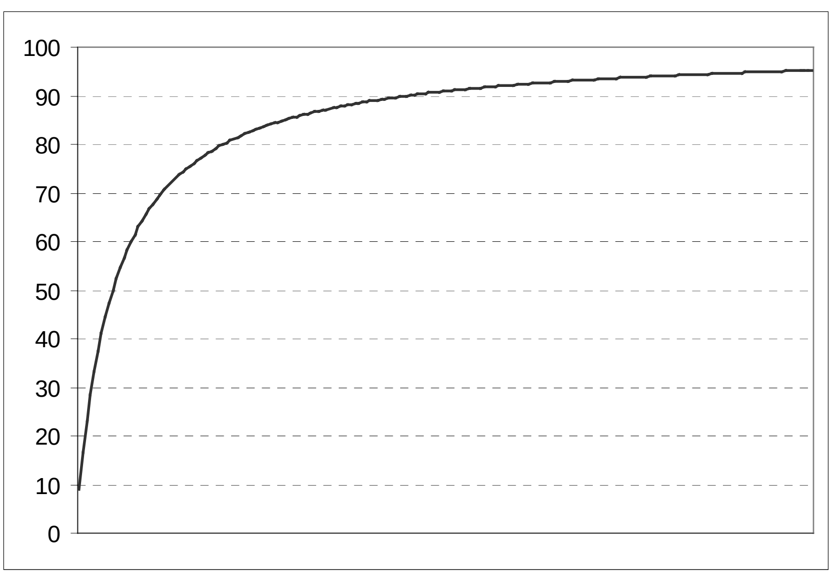

Figure 22-1: Build-up function for solids in urban areas.

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

Driver, N.E. and G.D. Tasker. 1988. Techniques for estimation of storm-runoff loads, volumes, and selected constituent concentrations in urban watersheds in the United States. U.S. Dept. of the Interior, U.S. Geological Survey: Books and Open-File Reports Section 88-191.

Huber, W.C. and R.E. Dickinson. 1988. Storm water management model, version 4: user’s manual. U.S. Environmental Protection Agency, Athens, GA.

Northern Virginia Planning District Commission. 1979. Guidebook for screening urban nonpoint pollution management strategies: a final report prepared for Metropolitan Washington Council of Governments. Northern Virginia Planning District Commission, Falls Church, VA.

Pitt, R. 1979. Demonstration of non-point pollution abatement through improved street cleaning practices. EPA-600/2-79-161 (NTIS PB80-108988), U.S. Environmental Protection Agency, Cincinnati, OH.

Soil Conservation Service Engineering Division. 1986. Urban hydrology for small watersheds. U.S. Department of Agriculture, Technical Release 55.

U.S. Environmental Protection Agency. 1983. Results of the nationwide urban runoff program; Volume 1 final report. NTIS PB84-185552, U.S. Environmental Protection Agency, Washington, D.C.