

# AGRICULTURAL POLICY / ENVIRONMENTAL EXTENDER MODEL



THEORETICAL  
DOCUMENTATION  
VERSION 1501

JANUARY 2023

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# AGRICULTURAL POLICY/ENVIRONMENTAL EXTENDER MODEL

## THEORETICAL DOCUMENTATION

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VERSION 1501

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# CHAPTER 1

## INTRODUCTION

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The Agricultural Policy/Environmental eXtender (APEX) model was developed for use in whole farm/small watershed management. The model was constructed to evaluate various land management strategies considering sustainability, erosion (wind, sheet, and channel), economics, water supply and quality, soil quality, plant competition, weather and pests. Management capabilities include irrigation, drainage, furrow diking, buffer strips, terraces, waterways, fertilization, manure management, lagoons, reservoirs, crop rotation and selection, pesticide application, grazing, and tillage. Besides these farm management functions, APEX can be used in evaluating the effects of global climate/CO<sub>2</sub> changes; designing environmentally safe, economic landfill sites; designing biomass production systems for energy; and other spin off applications. The model operates on a daily time step (some processes are simulated with hourly or less time steps) and is capable of simulating hundreds of years if necessary. Farms may be subdivided into fields, soil types, land scape positions, or any other desirable configuration.

The individual field simulation component of APEX is taken from the Environmental Policy Integrated Climate (EPIC) model, which was developed in the early 1980's to assess the effect of erosion on productivity (Williams, et al., 1984). Various components from CREAMS (Knisel, 1980) and SWRRB (Williams, et al., 1985) were used in developing EPIC/APEX and the GLEAMS (Leonard, et al., 1987) pesticide component was added later. Since the 1985 National RCA application (Putman, et al., 1988), the model has been expanded and refined to allow simulation of many processes important in agricultural management (Sharpley and Williams, 1990; Williams, 1995). The drainage area considered by EPIC is generally a field-size area, up to about 100 ha, where weather, soils, and management systems are assumed to be homogeneous. The major components in APEX are weather simulation, hydrology,

erosion-sedimentation, nutrient cycling, pesticide fate, crop growth, soil temperature, tillage, economics, and plant environment control. Although APEX operates on a daily time step, the optional Green and Ampt infiltration equation simulates rainfall excess rates at shorter time intervals (0.1 h). The model offers options for simulating several other processes—five PET equations, six erosion/sediment yield equations, two peak runoff rate equations, etc. APEX can be used to compare management systems and their effects on nitrogen, phosphorus, carbon, pesticides and sediment in a single field or multiple fields in a watershed. The management components that can be changed are crop rotations, tillage operations, irrigation scheduling, drainage, furrow diking, liming, grazing, tree pruning, thinning, and harvest, manure handling, and nutrient and pesticide application rates and timing.

The APEX model was developed to extend the EPIC model capabilities to whole farms and small watersheds. In addition to the EPIC functions, APEX has components for routing water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet. APEX also has groundwater and reservoir components. A watershed can be subdivided as much as necessary to assure that each subarea is relatively homogeneous in terms of soil, land use, management, and weather. The routing mechanisms provide for evaluation of interactions between subareas involving surface runoff, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow. Water quality in terms of nitrogen (ammonium, nitrate, and organic), phosphorus (soluble and adsorbed/mineral and organic), and pesticides concentrations may be estimated for each subarea and at the watershed outlet. Commercial fertilizer or manure may be applied at any rate and depth on specified dates or automatically. The GLEAMS pesticide model is used to estimate pesticide fate considering runoff, leaching, sediment transport, and decay. Because of routing and subdividing there is no limit on watershed size. The major uses of APEX have been dairy manure management to maintain water quality in Erath and Hopkins Counties, TX, (Flowers, et al., 1996) and a national study to assess the effectiveness of filter strips in controlling sediment and other pollutants (Arnold, et al., 1998). APEX has its own databases for weather simulation, soils, crops, tillage, fertilizer, and pesticides. Convenient interfaces are supplied for assembling inputs and interpreting outputs.

The current version of APEX as of January 2023 supported by the model developers at Texas A&M AgriLife Blackland Research Center at Temple, TX, is APEX1501. Thus, the APEX0806 or older versions are obsolete and not supported.

The purpose here is to fully describe the APEX model beginning with the subarea component followed by routing, reservoir, groundwater, grazing, manure management, and feedlot dust emission and distribution components. The components are fully described because the model has been revised and expanded beyond the latest report (Williams, et al., 2000).



# CHAPTER 2

## THE SUBAREA COMPONENT

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### 2.1 WEATHER

The weather variables necessary for driving the APEX model are daily precipitation, maximum and minimum air temperature, and solar radiation. If the Penman methods are used to estimate potential evaporation, wind speed and relative humidity are also required. Of course, wind speed is also needed when wind induced erosion or dust emission and distribution are simulated. If daily precipitation, air temperature, and solar radiation data are available, they can be input directly into APEX. Rainfall and temperature data are available for many areas of the United States, but solar radiation, relative humidity, and wind data are scarce. Even rainfall and temperature data may not be adequate for the long-term APEX simulation (100 years+). Thus, APEX provides options for simulating various combinations of the five weather variables. The weather input options include:

1. All five variables generated. Precipitation may be simulated uniformly over the watershed or spatially distributed.
2. All variables input. Inputs may come from one weather station to represent the entire watershed or from several stations each representing certain subareas.
3. Some variables generated and others input. In this case precipitation must always be input.

For options 2 and 3 missing input data is generated. Descriptions of the models used for generating precipitation, temperature, radiation, relative humidity, and wind follow.

## PRECIPITATION

### POINT RAINFALL

The APEX precipitation model developed by Nicks (1974) is a first-order Markov chain model. Thus, input for the model must include monthly probabilities of receiving precipitation. On any given day, the input must include information as to whether the previous day was dry or wet. A random number (0-1) is generated and compared with the appropriate wet-dry probability. If the random number is less than or equal to the wet-dry probability, precipitation occurs on that day. Random numbers greater than the wet-dry probability give no precipitation. Since the wet-dry state of the first day is established, the process can be repeated for the next day and so on throughout the simulation period.

When a precipitation event occurs, the amount is generated from a skewed normal daily precipitation distribution

$$RF = XLV * RST(2, MO) + RST(1, MO) \quad (2.1.1)$$

$$XLV = (X1^3 - 1.) * 2. / RST(3, MO) \quad (2.1.1a)$$

$$X1 = (SND - R6) * R6 + 1. \quad (2.1.1b)$$

$$R6 = RST(3, MO) / 6. \quad (2.1.1c)$$

where RF is the storm rainfall volume in mm, MO is the month of the storm, RST subscripts 1, 2, and 3 are the monthly storm mean, standard deviation, and skew coefficient, and SND is the standard normal deviate.

If the standard deviation and skew coefficient are not available, the model simulates daily rainfall by using a modified exponential distribution.

$$RF = (RST(1, MO) / ECF) * (-\ln(\text{rnd}))^{\text{EXPK}} \quad (2.1.2)$$

where rnd is a uniform random number (0.0-1.0), ECF is the correction factor that preserves long-term mean rainfall, and EXPK is a parameter usually in the range of 1.0 to 2.0. The larger the EXPK value, the more extreme the rainfall events. A value of 1.3 gives satisfactory results at many locations in the United States. ECF is obtained by integrating Eq 2.1.2 over the limits 0.0-1.0 substituting 1.0 for ECF. The modified exponential is usually a satisfactory substitute and requires only the monthly mean daily rainfall as input.

Daily precipitation is partitioned between rainfall and snowfall. If the average of mean daily air temperature (TX) and surface layer soil temperature (STMP(1)) is 0 °C or below, the precipitation is snowfall, otherwise, it is rainfall.

If wet-dry probabilities are not available, the average monthly number of rainy days may be substituted. The probability of a wet day is calculated directly from the number of wet days:

$$PW=NWD/ND \quad (2.1.3)$$

where PW is the probability of a wet day, NWD is the number of rainy days, and ND is the number of days in a month. The probability of a wet day after a dry day can be estimated as a fraction of PW.

$$P(W|D)=b1*PW \quad (2.1.4)$$

where P(W|D) is the probability of a wet day following a dry day and b1 is a fraction usually in the range of 0.6 to 0.9. The probability of a wet day following a wet day can be calculated directly by using the equation

$$P(W|W)=1.0-b1+P(W|D) \quad (2.1.5)$$

where P(W|W) is the probability of a wet day after a wet day. When b1=1.0, wet days do not affect probability of rainfall--P(W|D)=P(W|W)=PW. Conversely, low b1 values give strong wet day effects-- b1=0.0, P(W|W)=1.0, P(W|D)=0. Thus, b1 controls the interval between rainfall events but has no effect on the number of wet days. For many locations, b1=0.75 gives satisfactory estimates of P(W|D). Although Eqs 2.1.4 and 2.1.5 may give slightly different probabilities than those estimated from rainfall records, they do guarantee correct simulation of the number of rainfall events.

## SPATIALLY DISTRIBUTED RAINFALL

The spatial rainfall generator is provided for larger watershed applications or for areas with steep rainfall gradients (Jeong et al., 2014). To generate spatially distributed precipitation, a rectangular domain is formed outside the watershed such that the spatial domain covers the entire watershed with lateral and longitudinal distances three times the maximum lateral and longitudinal extents of the watershed (Figure 2.1).

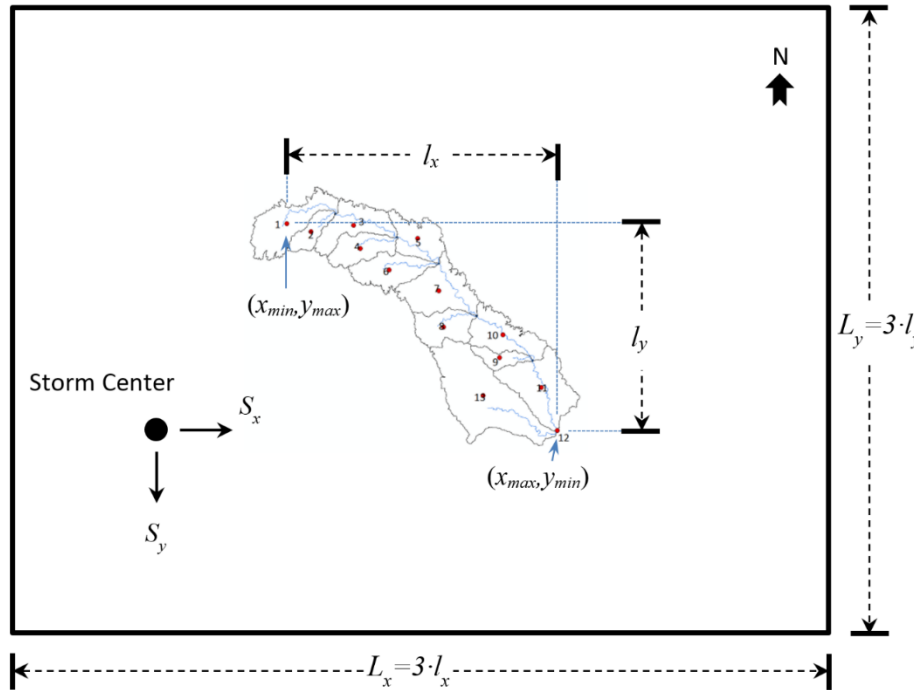
$$L_x = 3 * (x_{max} - x_{min}) \quad (2.1.6a)$$

$$L_y = 3 * (y_{max} - y_{min}) \quad (2.1.6b)$$

where  $L_x$  and  $L_y$  are the x and y scale of the box,  $x_{max}$  the maximum x coordinate of the subarea centroids,  $x_{min}$  is the minimum x coordinate of the subarea centroids. The y scale is computed similarly. For a watershed with east-west length orientation, the box extends east from  $x_{max}$  and west from  $x_{min}$  with a distance equal to the watershed width ( $l_x$ ), such that the total length equals to  $3*l_x$ . Similarly, in the north-south orientation, the box extends north from  $y_{max}$  and south from  $y_{min}$  a distance equal the watershed length ( $l_y$ ), such that the total length equals to  $3*l_y$ . These large dimensions assure that generated storm centers are completely random with respect to all subareas. With smaller dimensions, more storm centers will occur near the center of the watershed. The coordinates of the storm centers are generated using:

$$\begin{aligned}
 x_{storm} &= U \cdot L_x + 2 \cdot x_{min} - x_{max} \\
 y_{storm} &= U \cdot L_y + 2 \cdot y_{min} - y_{max}
 \end{aligned}
 \tag{2.1.7}$$

where  $x_{storm}$  and  $y_{storm}$  are the x- and y-coordinate of the storm center, respectively.  $U$  is a uniform random number (0.0 to 1.0).



**Figure 2.1 Spatial boundaries of the storm domain set for the Cowhouse watershed in Texas (Jeong et al., 2014).  $l_x$  and  $l_y$  are the longitudinal and lateral lengths of the modeling domain in the x and y directions in which the stationary storm centroid is randomly selected.**

The storm center rainfall is simulated using Eqs 2.1.1 or 2.1.2. Monthly weather generator parameters for up to 10 stations may be input along with the subareas in the watershed they influence. The fractional area of influence of each station is required as input. These fractions are used to form a cumulative probability distribution. A storm is generated based on the cumulative distribution using the fractional areas and a set of 14 weather parameters including monthly mean and standard deviation of daily maximum temperature, daily minimum temperature, daily rainfall, monthly skew coefficient for daily precipitation, monthly probability of wet day after dry day, monthly probability of wet day after wet day, average number days of rain per month, monthly maximum 0.5h rainfall, average daily solar radiation for the month, average daily relative humidity for the month, and average daily wind speed in month.

The spatial distribution of rainfall is estimated based on the storm duration and intensity, rainfall slope and distance to the storm centroid following the stochastic approach suggested by Nicks and Igo (1980):

$$P_{i,j} = \alpha \cdot P_i \cdot N_{sub} \cdot \left( 1 - \tau_s^{-0.1478} \cdot \frac{d_s}{d_s + e^{2.291+0.00117 \cdot d_s}} \right) \cdot \frac{w_j}{\sum_j w_j} \quad (2.1.7)$$

$$w_j = (1 + s_x \cdot x_j) \cdot (1 + s_y \cdot y_j) \quad (2.1.7a)$$

In these equations,  $i$  is the time index (Julian day),  $j$  is the subarea number,  $P_{i,j}$  is the generated rainfall for subarea  $j$  on  $i$ th day,  $P_i$  is the storm center rainfall in mm generated by WXGEN,  $N_{sub}$  is the number of subareas in the watershed,  $x_j$  and  $y_j$  are the x and y -coordinates of the subarea centroids,  $w_j$  is the subarea rainfall weighting factor that accounts for rainfall duration, distance between subarea centroid and storm center and rainfall gradient,  $d_s$  is the distance between the subarea centroid and the storm center in km,  $\tau_s$  is the storm duration in h,  $\alpha$  is a random deviate drawn from a triangular distribution ranging between 0.8 and 1.2,  $s_x$  is a linear coefficient of change in rainfall from east to west in  $\text{km}^{-1}$ , and  $s_y$  is a linear coefficient of change in rainfall from south to north in  $\text{km}^{-1}$ . The exponential coefficient for storm duration (-0.1478) is adapted from Nicks (1974). The linear coefficients are estimated using:

$$s_x = -\frac{\bar{P}_{east} - \bar{P}_{west}}{\bar{P}_{east} \cdot l_x} \quad (2.1.8)$$

$$s_y = -\frac{\bar{P}_{south} - \bar{P}_{north}}{\bar{P}_{south} \cdot l_y}$$

where  $\bar{P}_{east}$  is the average annual precipitation on the East side of watershed,  $\bar{P}_{west}$  is the average annual precipitation on the West side of watershed, and  $l_x$  is the distance in km between the east and west side of the watershed. The coefficients for the north-south direction are defined similarly. In Eq 2.1.7, a storm is generated using WXGEN and monthly weather statistics available at the nearest station at a randomly selected location within the domain as described in Figure 2.1. Subareas near the storm origin are affected by the storm, with higher probability of rainfall than those subareas located further from the storm centroid, based on (1) the distance between the storm center and the centroid of subareas ( $P_{i,j}$  is a function of  $d_s$ ), (2) storm duration ( $P_{i,j}$  is a function of  $\tau_s$ ), and (3) rainfall gradients ( $P_{i,j}$  is a function of  $w_j$ ). For instance, if a storm  $P_i$  is generated by WXGEN for day  $i$  near weather station 1, the subareas near station 1 will have a higher chance of more rainfall than subareas far from station 1 based on the negative terms in Eq 2.1.7. The longer the storm duration ( $\tau_s$ ) is the lesser the distant effect is to decrease the rainfall. The distance of influence varies with the linear coefficients of rainfall gradients.  $N_{sub}$  and  $\sum w_j$  in Eq 2.1.7 are used to normalize  $w_j$  factors to preserve long-term mean rainfall.

## AIR TEMPERATURE AND SOLAR RADIATION

The model developed by Richardson (1981) was selected for use in APEX because it simulates temperature and radiation, which are mutually correlated with rainfall. The residuals of daily maximum and minimum air temperature and solar radiation are generated from a multivariate normal distribution.

The multivariate generation model used implies that the residuals of maximum temperature, minimum temperature, and solar radiation are normally distributed and that the serial correlation of each

variable may be described by a first-order linear autoregressive model. Details of the multivariate generation model were described by Richardson (1981). The dependence structure of daily maximum temperature, minimum temperature, and solar radiation was described by Richardson (1982).

The temperature model requires monthly means of maximum and minimum temperatures and their standard deviations as inputs. If the standard deviations are not available, the long-term observed extreme monthly minimums and maximums may be substituted. The model estimates standard deviation as 0.25 of the difference between the extreme and the mean for each month.

The solar radiation model uses the extreme approach exclusively. Thus, only the monthly means of daily solar radiation are required as inputs. The equation for estimating standard deviation is

$$SDRA=0.25*(RAMX-RA) \quad (2.1.9)$$

where SDRA is the standard deviation of daily solar radiation in MJ m<sup>-2</sup>, RAMX is the maximum daily solar radiation at midmonth, and RA is the mean daily solar radiation for month.

Maximum temperature and solar radiation tend to be lower on rainy days. Thus, it is necessary to adjust the mean maximum temperature and solar radiation downward for simulating rainy day conditions. For TMX this is accomplished by assuming that wet day values are less than dry day values by some fraction of TMX-TMN:

$$TWMX=TDMX-b_2*(TMX-TMN) \quad (2.1.10)$$

where TWMX is the daily mean maximum temperature for wet days in °C, TDMX is the daily mean maximum temperature for dry days in °C, b<sub>2</sub> is a scaling factor ranging from 0.0 to 1.0, TMX is the daily mean maximum temperature, and TMN is the daily mean minimum temperature. Choosing b<sub>2</sub>=1.0 provides highest deviations on wet days and b<sub>2</sub>=0.0 ignores the wet day effect. Observed data indicate that b<sub>2</sub> usually lies between 0.5 and 1.0.

Since Eq 2.1.10 gives lower mean maximum temperature values for wet days, a companion equation is necessary to slightly increase mean maximum temperature for dry days. The development is taken directly from the continuity equation

$$TMX*ND=TWMX*NWD+TDMX*NDD \quad (2.1.11)$$

where ND is the number of days in a month, NWD is the number of wet days, and NDD is the number of dry days. The desired equation is obtained by substituting Eq 2.1.10 into Eq 2.1.11 and solving for TDMX

$$TDMX=TMX+b_2*(TMX-TMN)*NWD/ND \quad (2.1.12)$$

Use of the continuity equation guarantees that the long-term simulated value for mean maximum temperature agrees with the input value of TMX.

The method of adjusting solar radiation for wet and dry days is similar to that of adjusting maximum temperature. The radiation on wet days is a fraction of the dry day radiation

$$RAW=b_3*RAD \quad (2.1.13)$$

where RAW is the daily mean solar radiation on wet days in MJ m<sup>-2</sup>, b<sub>3</sub> is a scaling factor ranging from 0.0 to 1.0, and RAD is the daily mean solar radiation on dry days. A b<sub>3</sub> value of 0.5 gives satisfactory results for many locations. The dry day equation is developed by replacing temperature with radiation in Eq 2.1.11 and substituting Eq 2.1.13 for RAW. Then,

$$RAD=RA*ND/(b_3*NWD+NDD) \quad (2.1.14)$$

where RA is the daily mean solar radiation in MJ m<sup>-2</sup>. The maximum possible solar radiation is computed with the equations

$$RAMX=30.*DD*(H*YLS*\sin(SD)+YLC*\cos(SD)*\sin(H)) \quad (2.1.15)$$

$$DD=1.+0.0335*\sin((IDA+88.2)/58.13) \quad (2.1.15a)$$

$$SD=.4102*\sin((IDA-80.25)/58.13) \quad (2.1.15b)$$

$$CH=-\tan(YLAT/57.296)*\tan(SD) \quad (2.1.15c)$$

$$H=\arccos(CH); \quad -1.0<CH<1.0 \quad (2.1.15d)$$

$$H=0.0; \quad CH>1.0 \quad (2.1.15e)$$

$$H=3.1416; \quad CH<-1.0 \quad (2.1.15f)$$

$$YLS=\sin(YLAT/57.296) \quad (2.1.15g)$$

$$YLC=\cos(YLAT/57.296) \quad (2.1.15h)$$

where YLAT is the latitude of the site in degrees, SD is the sun's declination angle (radians), and IDA is the day of the year.

The day length is calculated with the equation

$$HRLT=7.72*H \quad (2.1.16)$$

where HRLT is the day length in h.

## WIND

The original EPIC wind model (Richardson and Wright, 1984) simulated mean daily wind speed and daily direction. The new APEX wind erosion model, WECS, (Wind Erosion Continuous Simulation) requires wind speed distribution within the day and the dominant direction. Daily wind speed distribution is simulated using the modified exponential equation

$$u_{10}=a_1*U_{10}*(-\ln(f))^{a_2} \quad (2.1.17)$$

where  $u_{10}$  is the wind speed at  $f$  fraction of the day,  $U_{10}$  is the mean wind speed for the day, and  $a_1$  and  $a_2$  are parameters. Eq 2.1.17 is an expression of wind speed probabilities rather than wind speed as a function of time during the day. The daily time distribution of wind speed is not required because all other APEX components operate on a daily time step. Experimental work with data from Bushland, TX and Temple, TX indicates that  $0.1 < a_2 < 0.6$ . Values of  $a_2$  are generated daily from a triangular distribution with base ranging from 0.1 to 0.6 and peak at 0.35. The value of  $a_1$  can be closely approximated with the equation

$$a_1=1.557*(a_2)^{0.1508}*\exp(-0.4336*a_2) \quad (2.1.18)$$

Eq 2.1.18 assures that the mean wind speed  $U_{10}$  is preserved.

Values of  $u_{10}$  are simulated with  $f$  starting with the threshold windspeed for erosion. The threshold  $f$  value ( $f_0$ ) is determined using the wind erosion Eq 2.3.25 and Eq 2.1.17 in the form

$$f_0=\exp((-u'/(0.0408*U_{10}))^{-a_2}) \quad (2.1.19)$$

where  $u'$  is the threshold friction velocity in  $m\ s^{-1}$ . Larger  $f$  values produce non-erosive wind speeds. Windspeeds greater than  $u'$  are produced as  $f$  is reduced. The mean daily wind speed is simulated using the modified exponential equation

$$U_{10}=bw_1*U_{10}(mo)*(-\ln(rnd))^{bw_2} \quad (2.1.20)$$

where  $U_{10}(mo)$  is the mean wind speed for month  $mo$ ,  $rnd$  is a random number,  $bw_2$  is a parameter for month  $mo$ , and  $bw_1$  is calculated directly using an approach similar to that described in Eq 2.1.18. Experimental work with data from Bushland, TX and Temple, TX indicates that  $bw_2$  is approximately 0.3.

Wind direction expressed as radians from north in a clockwise direction is generated from an empirical distribution specific for each location. The empirical distribution is simply the cumulative probability distribution of wind direction. The "Climatic Atlas of the United States" (U.S. Department of Commerce, 1968) gives monthly percentages of wind from each of 16 directions. Thus, to estimate wind direction for any day, the model draws a uniformly distributed random number and locates its position on the appropriate monthly cumulative probability distribution.

## RELATIVE HUMIDITY

The relative humidity model simulates daily average relative humidity from the monthly average by using a triangular distribution. As with temperature and radiation, the mean daily relative humidity is adjusted to account for wet- and dry-day effects. The assumed relation between relative humidity on wet and dry days is

$$RHW=RHD+bh_1*(1.0-RHD) \quad (2.1.21)$$



where RHW is the daily mean relative humidity on wet days, RHD is the daily mean relative humidity on dry days, and bh1 is a scaling factor ranging from 0.0 to 1.0. A bh1 value of 0.9 seems appropriate for many locations. Using the continuity equation as described in the temperature and radiation sections produces the equation

$$RHD=(RH(\text{mo})-bh1*NWD/ND)/(1.0-bh1*NWD/ND) \quad (2.1.22)$$

where RH is the long-term average relative humidity for month mo.

The appropriate value (RHW or RHD) is used as the peak of a triangular distribution to generate daily relative humidity. The upper limit of the triangular distribution is set with the equation

$$RHU=RHP+(1.0-RHP)*\exp(RHP-1.0) \quad (2.1.23)$$

where RHU is the largest relative humidity value that can be generated on the day and RHP is the peak of the triangular distribution (RHW or RHD). The lower limit is set with the equation

$$RHL=RHP*(1.0-\exp(-RHP)) \quad (2.1.24)$$

where RHL is the lowest relative humidity value that can be generated on the day. To assure that the simulated long-term value for mean relative humidity agrees with input RH, the generated value is adjusted by using the equation

$$RHG'=RHG*RHP/RH \quad (2.1.25)$$

where RHG' is the generated relative humidity adjusted to the mean of the triangle, RHG is the relative humidity generated from the triangle, and RH is the mean of the triangle.

If relative humidity data is not available, dew point temperature may be substituted and APEX estimates the monthly mean relative humidity using Eqs 2.2.78i and 2.2.78j. If dew point temperature is not available APEX estimates monthly mean relative humidity using the equation

$$RH=0.9-0.8*X1/(X1+\exp(5.12-0.127*X1)) \quad (2.1.26)$$

$$X1=TMX-TMN \quad (2.1.26a)$$

where TMX and TMN are monthly means in °C. Equation 2.1.26 was derived assuming that relative humidity varies inversely with temperature variations (Hargreaves and Samani, 1985).

## 2.2 HYDROLOGY

### RAINFALL INTERCEPTION

Rainfall interception by plant canopy is estimated with the equation

$$RFI=RIMX*(1.0-\exp(-bi*\sqrt{TAGP*SMLA})) \quad (2.2.1)$$

where RFI is the intercepted rainfall in mm, RIMX is the maximum possible intercepted rainfall for an event in mm, TAGP is the above ground plant material in  $t\ ha^{-1}$ , SMLA is the leaf-area-index of the plant stand, and bi is a constant (approximately 0.1). Eq 2.2.1 is constructed for general operation on a variety of land uses including cropland, pastureland, range, and forestland. When rainfall exceeds interception, the excess falls to the soil surface.

$$RFV=RF-RFI \quad (2.2.2)$$

where RFV is the rainfall that arrives on the soil surface in mm.

## SURFACE RUNOFF

The runoff model simulates surface runoff volumes and peak runoff rates, given daily rainfall amounts. Two methods are provided for estimating runoff volume – a modification of the Soil Conservation Service (SCS) curve number technique (U.S. Department of Agriculture, Soil Conservation Service 1972) and the Green and Ampt infiltration equation (Green and Ampt, 1911). The curve number technique was selected for use because (a) it is reliable and has been used for many years in the United States; (b) it is computationally efficient; (c) the required inputs are generally available; and (d) it relates runoff to soil type, land use, and management practices. The use of readily available daily rainfall data is a particularly important attribute of the curve number technique because for many locations, rainfall data with time increments of less than 1 day are not available. Also, rainfall data manipulations and runoff computations are more efficient for data taken daily than at shorter intervals. One of the major criticisms of the curve number method is its failure to account for rainfall intensity. Thus, the Green and Ampt method is offered as an option. Daily rainfall is distributed exponentially with parameters generated stochastically to provide rainfall rates needed for Green and Ampt.

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

## RUNOFF VOLUME

### The SCS Curve Number Method

Surface runoff is predicted for daily rainfall by using the SCS curve number equation (U.S. Department of Agriculture, Soil Conservation Service 1972)

$$Q = (RFV - 0.2*s)^2/(RFV + 0.8*s); \quad RFV > 0.2*s \quad (2.2.3)$$

$$Q = 0.0; \quad RFV < 0.2*s$$

where Q is the daily runoff, RFV is the daily rainfall, and s is a retention parameter (see "Notations" section). The retention parameter, s, varies (a) among watersheds because soils, land use, management, and slope all vary and (b) with time because of changes in soil water content. The parameter s is related to curve number (CN) by the SCS equation (U.S. Department of Agriculture, Soil Conservation Service 1972)

$$s = 254.*(100./CN - 1.) \quad (2.2.4)$$

The constant, 254, in Eq 2.2.4 gives s in mm. Thus, RFV and Q are also expressed in mm. CN<sub>2</sub>--the curve number for moisture condition 2, or average curve number--can be obtained easily for any area by using the SCS hydrology handbook (U.S. Department of Agriculture, Soil Conservation Service 1972). The handbook tables consider soils, land use, and management. Assuming that the handbook CN<sub>2</sub> value is appropriate for a 5% slope, we developed the following equation for adjusting that value for other slopes.

$$s_{2S} = s_2*(1.1 - STP/(STP + \exp(3.7 + 0.02117*STP))) \quad (2.2.5)$$

where s<sub>2S</sub> is the retention parameter associated with CN<sub>2</sub> adjusted for slope and STP is the average slope of the watershed in %. CN<sub>2</sub> and CN<sub>2S</sub> are calculated by substituting s<sub>2</sub> and s<sub>2S</sub> into Eq 2.2.4. Values of CN<sub>1</sub>, the curve number for moisture condition 1 (dry), and CN<sub>3</sub> (wet) corresponding to CN<sub>2</sub> are also tabulated in the handbook. For computing purposes, CN<sub>1</sub> and CN<sub>3</sub> were related to CN<sub>2</sub> with the equations

$$CN_1 = CN_{2S} - 20.*C2/(C2 + \exp(2.533 - 0.0636*C2)) \quad (2.2.6)$$

$$CN_3 = CN_{2S}*\exp(0.00673*C2) \quad (2.2.7)$$

$$C2 = 100. - CN_{2S} \quad (2.2.8)$$

The retention parameter varies with time mainly because of changes in soil water content. In the past hydrologist estimated the retention parameter based on antecedent rainfall (U.S. Department of Agriculture, Soil Conservation Service 1972). The CREAMS (Knisel, 1980) model related s directly to soil water content using the linear equation

$$s = s_1 *(1.0 - FFC) \quad (2.2.9)$$

where s<sub>1</sub> is the value of s associated with CN<sub>1</sub> and FFC is the fraction of field capacity. FFC is computed with the equation

$$FFC = (ST - WP)/(FC - WP) \quad (2.2.10)$$

where ST is the soil water content in the root zone, WP is the wilting point water content (1500 kPa for many soils) and FC is the field capacity water content (33 kPa for many soils). The linear equation 2.2.9 proved inadequate in many soils because it ranges from  $s_1$  at wilting point to 0.0 at field capacity.  $s=0.0$  gives  $CN=100$  which is much too high for many soils especially sands. EPIC (1984) introduced the nonlinear  $s$  - soil water equation.

$$s = s_1 * (1.0 - FFC / (FFC + \exp(w_1 - w_2 * FFC))) \quad (2.2.11)$$

Values for  $w_1$  and  $w_2$  are obtained from a simultaneous solution of Eq 2.2.11 according to the assumptions that  $s = s_2$  when  $FFC = 0.6$  and  $s = s_3$ , when  $(ST - FC) / (PO - FC) = 0.5$

$$w_1 = X_1 + 60. * w_2 \quad (2.2.12)$$

$$w_2 = (X_1 - X_2) / (POFC - 60.) \quad (2.2.13)$$

$$X_1 = \ln(60. / (1.0 - s_2 / s_1) - 60.) \quad (2.2.13a)$$

$$X_2 = \ln(POFC / (1.0 - s_3 / s_1) - POFC) \quad (2.2.13b)$$

$$POFC = 100. + 50. * X_3 / X_4 \quad (2.2.14)$$

$$X_3 = \sum(PO(l) - WP(l)), l=1, M \quad (2.2.14a)$$

$$X_4 = \sum(FC(l) - WP(l)), l=1, M \quad (2.2.14b)$$

where  $s_3$  is the  $CN_3$  retention parameter, PO is the porosity of soil layer  $l$  and  $M$  is the number of soil layers. Eqs 2.2.13 through 2.2.14 assure that  $CN_1$  corresponds with the wilting point and that the curve number cannot exceed 100.

The FFC value obtained in Eq 2.2.11 represents soil water uniformly distributed through the top 1.0 m of soil. Runoff estimates can be improved if the depth distribution of soil water is known. For example, a decreasing soil water depth distribution (more water near the soil surface) produces more runoff than a uniform distribution. Conversely, a uniform soil water depth distribution produces more runoff than an increasing soil water depth distribution (more water in lower soil layers). Since APEX estimates water content of each soil layer daily, the depth distribution is available. The effect of depth distribution on runoff is expressed in the depth weighting function

$$FFC' = X_1 / X_2 \quad (2.2.15)$$

$$X_1 = \sum(FFC(l) * X_2) \quad (2.2.15a)$$

$$X_2 = \sum((Z(l) - Z(l - 1)) / Z(l)); l=1, M \quad (2.2.15b)$$

$$Z(l) < 1.0m \quad (2.2.15c)$$

where  $FFC'$  is the depth weighted FFC value for use in Eq 2.2.11 and  $Z$  is the depth in m to the bottom of soil layer  $l$ . Eq 2.2.15 performs two functions: (1) it reduces the influence of lower layers because  $FFC(l)$  is divided by  $Z(l)$  and (2) it gives proper weight to thick layers relative to thin layers because  $FFC(l)$  is multiplied by the layer thickness.

In all APEX offers five options for estimating the daily CN values—the three described above plus a static CN (useful in situations like feedlots) and a soil water index (SWI) method. The SWI method was introduced in a daily water yield model in 1976 (Williams and Laseur). With slight modification it is now a part of APEX. The  $s$  is driven between near 0.0 and  $s_1$  or even greater depending on parameter settings using the equations

$$s = s_0 + PET * \exp(-P_{42} * s_0 / s_1) - RFV + Q \quad (2.2.16)$$

$$s < P_{44} * s_1 \quad (2.2.16a)$$

where  $s_0$  is the previous days retention parameter and PET is the potential evapotranspiration. Equation 2.2.16 increases  $s$  rapidly when PET is high and  $s_0$  is low (wet conditions). The SWI method has two distinct advantages over the methods that connect  $s$  to soil water directly; 1) The two parameters  $P_{42}$  and  $P_{44}$  are convenient for calibration; and 2) Soils with low soil water storage capacity (shallow or coarse textured soils) tend to present major problems for the direct coupled methods because there is double accounting. Usually these low capacity soils have low base  $CN_2$  values and they tend to stay dry most of the time because of the low storage capacity. Thus, runoff is underestimated.

There is also a provision for estimating runoff from frozen soil. If the temperature in the second soil layer is less than 0.0 °C, the retention parameter is reduced by using the equation

$$s' = 0.1 * s \quad (2.2.17)$$

where  $s'$  is the retention parameter for frozen ground. Eq 2.2.17 increases runoff for frozen soils but allows significant infiltration when soils are dry.

The final step in estimating the runoff volume is an attempt to account for uncertainty. The retention parameter or curve number estimate is based on land use, management, hydrologic soil group, land slope, and soil water content and distribution and is adjusted for frozen soil. However, many complex natural processes and artificial diversions that affect runoff are not accounted for in the model. Thus, the final curve number estimate is generated from a triangular distribution to account for this uncertain variation. The mean of the triangle is the estimated curve number based on using Eqs 2.2.4, 2.2.5, 2.2.9, 2.2.15, and 2.2.16. The uncertainty of the estimate is assumed to be within 5 curve numbers either positive or negative. Thus, the extremes of the triangular distributions are set at + and - 5 curve numbers from the mean. The generated curve number is substituted into Eq 2.2.4 to estimate runoff with Eq 2.2.3.

### **The Green and Ampt Method**

The Green and Ampt infiltration equation is offered as an option for estimating runoff volume. The original equation was modified to take advantage of the curve number method's link to soil properties and management. The modified equation is

$$f = \text{SATK} * (s / (FT + 1.)) \quad (2.2.18)$$

where  $f$  is the infiltration rate in  $\text{mm h}^{-1}$ ,  $\text{SATK}$  is the soil saturated conductivity in  $\text{mm h}^{-1}$ ,  $s$  is the curve number retention parameter at the beginning of the storm, and  $FT$  is the accumulated infiltration in  $\text{mm}$ .  
Runoff volume for a storm is calculated by summing the incremental estimates

$$Q = \sum(dt * (r - f)) \quad (2.2.19)$$

where  $dt$  is the time interval in  $h$  and  $r$  is the rainfall rate in  $\text{mm h}^{-1}$ .

Individual storm rainfall rates are generated from an exponential distribution taken from CLIGEN (Nicks, Lane, 1989).

$$r = r_p * (1. - (\text{RTP} - \sum(r * dt)) / \text{XKP}_1); \quad 0 < t < t_p \quad (2.2.20)$$

$$r = r_p * (1. - (\sum(r * dt) - \text{RTP}) / \text{XKP}_2); \quad t_p < t < \text{DUR} \quad (2.2.21)$$

where  $r_p$  is the peak rainfall rate in  $\text{mm h}^{-1}$ ,  $t_p$  is the time to peak of the storm in  $h$ ,  $\text{RTP}$  is the rainfall volume at  $t_p$  in  $\text{mm}$ ,  $\text{DUR}$  is the rainfall duration in  $h$ , and  $\text{XKP}_1$  and  $\text{XKP}_2$  are the exponential constants in  $h$ . The parameters are determined by considering a dimensionless distribution. Time to peak as a fraction of duration ( $t_{pu}$ ) is generated from a triangular distribution with lower limit at 0.05, peak at 0.25, and upper limit at 0.95. The constants  $\text{XKP}_1$  and  $\text{XKP}_2$  are determined by solving the dimensionless exponential equations between the limits  $0.01 < r/r_p < 1.0$ .

$$r = r_p * \exp((t - t_{pu}) / \text{XK}_1); \quad 0 < t < t_{pu} \quad (2.2.22)$$

$$\text{XK}_1 = t_{pu} / 4.605 \quad (2.2.22a)$$

$$r = r_p * \exp((t_{pu} - t) / \text{XK}_2); \quad t_{pu} < t < \text{DUR} \quad (2.2.23)$$

$$\text{XK}_2 = (1. - t_{pu}) / 4.605 \quad (2.2.23a)$$

Duration can be calculated by integrating the dimensionless distribution and dividing into the rainfall volume for the storm.

$$\text{DUR} = \text{RFV} / (r_p * (\text{XK}_1 + \text{XK}_2)) \quad (2.2.24)$$

Finally the storm parameters  $\text{XKP}_1$  and  $\text{XKP}_2$  are available.

$$\text{XKP}_1 = \text{XK}_1 * \text{DUR} \quad (2.2.25)$$

$$\text{XKP}_2 = \text{XK}_2 * \text{DUR} \quad (2.2.26)$$

The value of  $r_p$  is obtained as described in the water erosion section and  $\text{RTP}$  is the product of  $\text{RFV}$  and  $t_{pu}$ .

## PEAK RUNOFF RATE

APEX contains two methods for estimating peak runoff rate — the modified Rational formula and the SCS TR-55 method (USDA-SCS, 1986).

### **Rational Equation Method.**

The rational equation can be written in the form

$$q_p = b_q * r * WSA / 360. \quad (2.2.27)$$

where  $q_p$  is the peak runoff rate in  $m^3 s^{-1}$ ,  $b_q$  is a runoff coefficient expressing the watershed infiltration characteristics,  $r$  is the rainfall intensity in  $mm h^{-1}$  for the watershed's time of concentration, and  $WSA$  is the watershed area in ha. The runoff coefficient can be calculated for each storm if the amount of rainfall and runoff are known

$$b_q = Q / RFV \quad (2.2.27a)$$

Since  $RFV$  is input and  $Q$  is computed with Eqs 2.2.4 or 2.2.19,  $b_q$  can be calculated directly. Rainfall intensity can be expressed with the relationship

$$r = RFV_{TC} / TC \quad (2.2.27b)$$

where  $RFV_{TC}$  is the amount of rainfall in mm during the watershed's time of concentration,  $TC$  in h. The value of  $RFV_{TC}$  can be estimated by developing a relationship with total  $RFV$ . The Weather Service's TP-40 (Hershfield, 1961) provides accumulated rainfall amounts for various durations and frequencies. Generally,  $RFV_{TC}$  and  $RFV_{24}$  (24-h duration is appropriate for the daily time step model) are proportional for various frequencies. Thus,

$$RFV_{TC} = \alpha_p * RFV_{24} \quad (2.2.28)$$

where  $\alpha_p$  is a dimensionless parameter that expresses the proportion of total rainfall that occurs during  $TC$ .

The peak runoff equation is obtained by substituting Eqs 2.2.27a through 2.2.28 into Eq 2.2.17.

$$q_p = \alpha_p * Q * WSA / (360 * TC) \quad (2.2.29)$$

The time of concentration can be estimated by adding the surface and channel flow times

$$TC = TC_C + TC_S \quad (2.2.30)$$

where  $TC_C$  is the time of concentration for channel flow and  $TC_S$  is the time of concentration for surface flow in h. The  $TC_C$  can be computed by using the equation

$$TC_C = L_C / VCH \quad (2.2.30a)$$

where  $L_C$  is the average channel flow length for the watershed in km and  $VCH$  is average channel velocity in  $m s^{-1}$ . The average channel flow length can be estimated by using the equation

$$L_C = \sqrt{L * L_{CA}} \quad (2.2.30b)$$

where L is the channel length from the most distant point to the watershed outlet in km and  $L_{CA}$  is the distance from the outlet along the channel to the watershed centroid in km. Average velocity can be estimated by using Manning's equation and assuming a trapezoidal channel with 2:1 side slopes and a 10:1 bottom width/depth ratio. Substitution of these estimated and assumed values gives

$$TC_C = \sqrt{L * L_{CA} * n^{0.75} / (0.489 * q_c^{0.25} * CHS^{0.375})} \quad (2.2.31)$$

where n is Manning's n,  $q_c$  is the average flow rate in  $m^3 s^{-1}$ , and CHS is the average channel slope in  $m m^{-1}$ . Assuming that  $L_{CA} = 0.5L$  and converting units (L from m to km,  $TC_C$  from s to h, and  $q_c$  from  $m^3 s^{-1}$  to  $mm h^{-1}$ ) gives the equation

$$TC_C = 1.75 * L * n^{0.75} / (WSA^{0.125} * CHS^{0.375}) \quad (2.2.32)$$

The average flow rate  $q_c'$  in  $mm h^{-1}$  is obtained from the estimated average flow rate from a unit source in the watershed (1 ha area) and the relationship

$$q_c' = q_{c1} / \sqrt{WSA} \quad (2.2.33)$$

where  $q_{c1}$  is the average flow rate from a 1 ha area in  $mm h^{-1}$ . The unit source flow rate is estimated with the equation

$$q_{c1} = Q / DUR \quad (2.2.33a)$$

where DUR, the rainfall duration in h is calculated using the equation

$$DUR = -4.605 / (2 * \ln(1 - \alpha_{p.5})) \quad (2.2.33b)$$

where  $\alpha_{p.5}$  is computed with Eq 2.2.28 using  $RFV_{.5}$  instead of  $RFV_{TC}$ . Eq 2.2.33b is derived by assuming that rainfall intensity is exponentially distributed. Details of the procedure for estimating  $\alpha_{p.5}$  and DUR are given in the water erosion section of this chapter.

Substituting Eq 2.2.33a into Eq 2.2.32 gives the final equation for  $TC_C$

$$TC_C = 1.75 * L * n^{0.75} / (q_{c1}^{0.25} * WSA^{0.125} * CHS^{0.375}) \quad (2.2.34)$$

A similar approach is used to estimate  $TC_s$ :

$$TC_s = SPLG / OFV \quad (2.2.35)$$

where SPLG is the upland slope length in m and OFV is the overland flow velocity in  $m s^{-1}$ . Applying Manning's equation to a strip 1 m wide down the slope length, assuming flow is concentrated into a small trapezoidal channel with 1:1 side slopes and 5:1 bottom width depth ratio gives the velocity equation

$$OFV = 0.8375 * d^{0.667} * STP^{0.5} / n \quad (2.2.35a)$$



where  $d$  is flow depth in m and  $n$  is Manning's roughness coefficient for the surface. The average flow depth,  $d$ , can be calculated from Manning's equation as a function of flow rate

$$d=(q_o*n)^{0.375}/(5.025*STP^{0.5}) \quad (2.2.35b)$$

where  $q_o$  is the average flow rate in  $m^3 s^{-1}$ . Substituting Eqs 2.2.35a and 2.2.35b into Eq 2.2.35 gives

$$TC_S=0.0216*(SPLG*n)^{0.75}/(q_{cl}^{0.25}*STP^{0.375}) \quad (2.2.36)$$

To properly evaluate  $alp$ , variation in rainfall patterns must be considered. For some short duration storms, most or all the rain occurs during TC causing  $alp$  to approach its upper limit of 1.0. Other storms of uniform intensity cause  $alp$  to approach a minimum value. All other patterns cause higher  $alp$  values than the uniform pattern, because their TC rainfall rate is greater. By substituting the products of intensity and time into Eq 2.2.28, an expression for the minimum value of  $alp$ ,  $alpmn$ , is obtained

$$alpmn=TC/24. \quad (2.2.37)$$

Thus,  $alp$  ranges within the limits

$$alpmn < alp < 1. \quad (2.2.37a)$$

Although confined between limits, the value of  $alp$  is assigned with considerable uncertainty when only daily rainfall and simulated runoff amounts are given. Thus,  $alp$  is generated from a triangular distribution with the base ranging from  $TC/24$  to 1.0. The peak of the  $alp$  distribution changes monthly because of seasonal differences in rainfall intensities. The Weather Service (U.S. Department of Commerce, 1979) provides information on monthly maximum rainfall intensities that can be used to estimate the peak  $alp$  for each month.

### TR-55 Method

The SCS TR-55 Method for estimating peak runoff rate has been described in detail in USDA-SCS (1986). Only the essential equations are presented here. The peak runoff rate is dependent on the rainfall distribution and amount, the runoff curve number, and the time of concentration as expressed in the equation

$$q_p=q_p'*RFV \quad (2.2.38)$$

where  $q_p$  is the peak rate in  $mm h^{-1}$ ,  $q_p'$  is the peak rate per unit of rainfall in  $h^{-1}$ , and  $RFV$  is the storm rainfall amount in mm. A set of curves are available (USDA-SCS, 1986) for estimating  $q_p'$  given rainfall distribution (SCS Type I, IA, II, or III), the runoff curve number, and the watershed time of concentration. A map of the U.S. is given (USDA-SCS, 1986) to determine appropriate storm type. The curves relating  $q_p'$ ,  $TC$ , and  $CN$  have been fitted with a seventh degree polynomial for use in computer solutions.

Time of concentration is estimated with the equation

$$TC=TC_C+TC_S+TC_{SF} \quad (2.2.39)$$

where TC is the watershed time of concentration in h and TC<sub>C</sub>, TC<sub>S</sub>, and TC<sub>SF</sub> are the TC components attributed to channel flow, surface flow, and shallow channel flow. The channel component is computed with the equation

$$TC_C = (CHL - SPLG - SFL) * n / (3.6 * d^{0.667} * CHS^{0.5}) \quad (2.2.40)$$

where TC<sub>C</sub> is the channel time of concentration in h, CHL is the channel length from the most distant point to the watershed outlet in km, SPLG is the upland slope length in km, SFL is the shallow flow length in km, n is Manning's roughness coefficient, d is the average channel flow depth in m, and CHS is the channel slope in m m<sup>-1</sup>. The shallow flow component of TC is estimated with the equation

$$TC_{SF} = SFL / SFV \quad (2.2.41)$$

where SFV the average shallow flow velocity in km h<sup>-1</sup> is estimated with the equation

$$SFV = 17.7 * STP^{0.5}; \quad SFV < 2.19 \text{ km h}^{-1} \quad (2.2.42)$$

where STP is surface flow slope in m m<sup>-1</sup>. The length of shallow flow, SFL is estimated with the equations

$$SFL = 0.05; \quad L > 0.1 \text{ km} \quad (2.2.43)$$

$$SFL = L - 0.05; \quad 0.05 < L < 0.1 \text{ km} \quad (2.2.43a)$$

$$SFL = 0.0; \quad L < 0.05 \text{ km} \quad (2.2.43b)$$

Note that TC<sub>SF</sub> is constrained to less than 0.1 h even with S = 0.001. Thus, TC<sub>SF</sub> is generally insignificant. The surface flow component of TC is estimated with the equation

$$TC_S = 0.0913 * (SPLG * n)^{0.8} / (STP^{0.4} * RFV^{0.5}) \quad (2.2.44)$$

## SUBSURFACE FLOW

The subsurface flow model includes vertical and horizontal components. Vertical and horizontal subsurface flows are computed simultaneously using storage routing and pipe flow equations. The vertical or percolation component flows to groundwater storage and is subject to deep percolation from the system and return flow. Return flow is added to channel flow from the subarea. Horizontal flow is partitioned into lateral and quick return flow. Lateral subsurface flow enters the subarea immediately downstream and is added to that subareas soil water storage. Quick return flow is added to the channel flow from the subarea.

APEX offers three methods for estimating vertical percolation in the unsaturated rootzone: (1) the storage routing technique (a.k.a EPIC Percolation method) (Williams et al., 1984), the Variable Saturation Hydraulic Conductivity (VSHC) method (a.k.a 4mm slug method) (Doro et al., 2017), and the Richards equation (Jones et al., 2021).

## VERTICAL PERCOLATION VOLUME

### The Storage Routing Method

This method allows flow from a soil layer when soil water content exceeds field capacity. Water drains from the layer as a function of layer storage and saturated conductivity until the storage returns to field capacity. The reduction in soil water is simulated with the routing equation

$$ST(l) = (STo(l) - FC(l)) * \exp(-dt/TT(l)) + FC(l) \quad (2.2.45)$$

where ST and STo are the soil water contents at the end and the start of time interval dt (24 h) and TT is travel time through layer l in h. Thus, daily flow rate can be computed by taking the difference between ST and STo.

$$O(l) = (ST(l) - FC(l)) * (1 - \exp(-24./TT(l))) \quad (2.2.46)$$

where O is the flow rate for layer l in mm d<sup>-1</sup>. Travel time through a layer is computed with the linear storage equation

$$TT(l) = (PO(l) - FC(l)) / SC(l) \quad (2.2.47)$$

where PO is porosity in mm, FC is field capacity in mm, and SC is saturated conductivity in mm h<sup>-1</sup>. Vertical and horizontal flows are partitioned using the equation

$$QV(l) + QH(l) = (ST(l) - FC(l)) * X3; \quad ST(l) > FC(l) \quad (2.2.48)$$

$$X3 = 1 - \exp(-24./TT_v(l)) * \exp(-24./TT_H(l)) \quad (2.2.48a)$$

where QV is the vertical flow or percolation rate in mm d<sup>-1</sup>, QH is the horizontal flow or lateral subsurface flow rate in mm d<sup>-1</sup>, TT<sub>v</sub> is the vertical travel time in h, TT<sub>H</sub> is the horizontal travel time in h, and subscript l is the soil layer number. The vertical travel time is computed with Eq 2.2.47 and the horizontal travel time is computed with the equation

$$TT_H(l) = HST(l) / HCL(l) \quad (2.2.49)$$

where HST is the soil water storage in mm and HCL is the horizontal saturated flow rate in mm h<sup>-1</sup>. The horizontal saturated flow rate is computed with the equation

$$HCL(l) = SC(l) * STP \quad (2.2.50)$$

where STP is the land slope in m m<sup>-1</sup>. The horizontal storage is computed with the equation

$$ST(l) = (PO(l) - FC(l)) * 0.5 * SPLG / DZ \quad (2.2.51)$$

where SPLG is the land slope length in m and DZ is the soil layer thickness in m. Only half the slope length is considered because we are computing the travel time from the centroid of the slope to the outlet. Taking the ratio of QH/QV and substituting the resulting QH into Eq 2.2.48 leads to the equation

$$QV(l)+QV(l)*X2/X1=(ST(l)-FC(l))*X3 \quad (2.2.52)$$

$$X1=1.-\exp(-24./TT_v(l)) \quad (2.2.52a)$$

$$X2=1.-\exp(-24./TT_H(l)) \quad (2.2.52b)$$

Solving for QV gives the final percolation equation

$$QV(l)=(ST(l)-FC(l))*X3/(1.+X2/X1) \quad (2.2.53)$$

Lateral flow is partitioned between quick return flow and subsurface flow to the adjacent downstream subarea using the equations

$$SSF(l)=0.001*(ST(l)-FC(l)-QV(l))*SPLG/RCHL \quad (2.2.54)$$

$$QRF(l)=ST(l)-FC(l)-QV(l)-SSF(l) \quad (2.2.55)$$

where QRF is quick return flow rate in mm d<sup>-1</sup>, SSF is the subsurface flow rate in mm d<sup>-1</sup>, and RCHL is the reach channel length in km. As the ratio of SPLG/RCHL approaches 1.0 (very small hill slope watersheds) all of the subsurface flow remains below ground and enters the adjacent subareas soil water storage. Conversely, as the ratio approaches 0.0 all of the subsurface flow resurfaces as quick return flow.

Pipe flow is common in forested watersheds and must be simulated to properly account for the rapid vertical and horizontal flow. Flow through pipes created by decayed roots, animals, etc. is not included in the storage routing. Vertical pipe flow through a soil layer is estimated as a fraction of inflow using the equation

$$CPVV(l)=CPRV(l)*QI(l) \quad (2.2.56)$$

where CPVV is the vertical pipe flow rate in mm d<sup>-1</sup>, CPRV is the fraction of inflow partitioned to vertical pipe flow, QI is the inflow rate in mm d<sup>-1</sup>, and l is the soil layer number. Horizontal pipe flow is estimated with a similar equation.

$$CPVH(l)=CPRH(l)*(I(l)-CPVV(l)) \quad (2.2.57)$$

where CPVH is the horizontal pipe flow rate in mm d<sup>-1</sup> and CPRH is the fraction of inflow partitioned to horizontal pipe flow. CPRH is added to quick return flow. The operating sequence is Eq 2.2.56, Eq 2.2.67, Eqs 2.2.48-2.2.55.

The routing process is applied from the soil surface layer by layer through the deepest layer. Since the saturated conductivity of some layers may be much lower than that of others, the routing scheme can lead to an impossible situation (porosity of low saturated conductivity layers may be exceeded). For this reason, a back pass is executed from the bottom layer to the surface. If a layer's porosity is exceeded, the excess water is transferred to the layer above. This process continues through the top layer. There is also a provision for upward movement when a lower layer exceeds field capacity.

Movement from a lower layer to an adjoining upper layer is regulated by soil water tension in the two layers using the equations

$$UF(l)=bu1*(0.8*T_2+0.2*T_1)^{bu2} \quad (2.2.58)$$

$$bu2=(WP2-FC2)/1.6576 \quad (2.2.58a)$$

$$bu1=10^{(WP2-3.1761*bu2)} \quad (2.2.58b)$$

$$WP2=\log(WP(l)) \quad (2.2.58c)$$

$$FC2=\log(FC(l)) \quad (2.2.58d)$$

where UF is the upward flow from layer l to layer l-1 in mm and the water tension in layer l is T<sub>2</sub> and in layer l-1 is T<sub>1</sub>. Note that T<sub>2</sub> receives a greater weighting than T<sub>1</sub> in simulating the process. Water tension for any water content is estimated using the equation

$$T_2=10^{(3.1761-1.6576*(\log(ST(l))-WP2)/(FC2-WP2))} \quad (2.2.59)$$

The same equation with appropriate values is used to compute T<sub>1</sub>.

Saturated conductivity may be input or estimated for each soil layer by using the equation

$$SC(l)=12.7*X1*SS(l)/(X1+\exp(11.45-0.097*X1))+1.0 \quad (2.2.60)$$

$$X1=100.-CLA(l) \quad (2.2.60a)$$

where CLA is the percentage of clay in soil layer l and SS is the soil strength factor (described in the Growth Constraints section of this chapter).

Percolation is also affected by freezing temperature. Water can flow into a frozen layer but is not allowed to percolate from the layer.

### The VSHC (4mm slug) Method

The Storage Routing method (SRM) can overestimate percolation when soil is unsaturated because soil water flux is set by the saturated hydraulic conductivity rate regardless of the soil water content (SWC). Therefore, the SRM tends to overestimate soil water percolation when unsaturated flow occurs. To overcome the deficiency, the Variable Saturation Hydraulic Conductivity (VSHC) method (Doro et al., 2017) is developed to estimate variable percolation rates using a non-linear function. In this method, the volume of mobile water in a soil layer is discretized into small slugs which are small fractional volume of water. Then, percolation is simulated iteratively for each slug to discharge to the subsoil layer until all available slugs of soil water have passed. During each iteration, the effective hydraulic conductivity is calculated and updated based on hydraulic properties and the current SWC. In addition to this downward routing, an upward soil water flux, which may occur when water content is greater in subsoil layers due to soil evaporation or plant uptake in shallow soils, is estimated based on soil water tension and gravity.

In unsaturated soils, effective hydraulic conductivity of the soil reduces as SWC decreases due to increasing capillary tension in soil pores. The relationship between SWC and capillary force, referred to as the soil water characteristic curve, is highly nonlinear and its shape is determined by soil physical properties (Brooks and Corey, 1964; van Genuchten, 1980). In response to the decrease in SWC, the amount of percolation reduces as well in a piecewise nonlinear fashion as soil water flow slows down. In the formulation of the VSHC, the inflow to a soil layer is discretized into four-millimeter slugs for routing through soil layers using the effective soil hydraulic conductivity. The effective soil hydraulic conductivity is calculated for every four-millimeter slug similarly to Gardner (1958) by reducing the saturated hydraulic conductivity nonlinearly according to actual SWC as:

$$HCE(l)=HC\times[(ST-FC)/(PO-FC)]^\epsilon \quad (2.2.61)$$

where HCE(l) is the effective hydraulic conductivity (mm hr<sup>-1</sup>) of the soil layer l, HC is the saturated hydraulic conductivity (mm hr<sup>-1</sup>), ST and FC are the actual SWC and the SWC at field capacity (mm mm<sup>-1</sup>), PO is soil porosity (mm mm<sup>-1</sup>), and  $\epsilon$  is an exponent related to soil characteristics. Brooks and Corey (1964) suggests a relationship  $\epsilon=3+2/\lambda$  as they use a power law model in the Burdine (1953) equations, where  $\lambda$  is pore size distribution index varying from 0.09 for clayey soils to 1.68 for sandy soils (Charbeneau, 2000). APEX assumes that soil water percolates to deeper layers until the storage reduces to field capacity as a function of retention storage and saturated soil hydraulic conductivity. The reduction in soil water is estimated by Eq 2.2.45. The effective hydraulic conductivity is computed for each 4 mm slug using Eq 2.2.61.

### The Richards Method

To improve simulation of soil-water dynamics, we incorporated a Richards-based (Richards, 1931) soil-water flow model into APEX (Jones et al., 2021). Since the APEX model is traditionally applied at coarser resolution and larger time and space scales than typical Richards-based model applications, a solution to the Richards Equation proposed by Ross (Crevoisier et al., 2009; Ross, 2003) that minimizes the computational burden added. The solution developed by Ross has demonstrated computational efficiency, accuracy, robustness, and reliable convergence. The approach solves the mixed form of Richards equation, making it suitable for variably-saturated soils.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K(h) \left( \frac{\partial h}{\partial z} - 1 \right) \right] \quad (2.2.61)$$

where  $\theta$  is the soil water content (cm cm<sup>-1</sup>), t is time (hr), z is depth (cm), K is the unsaturated hydraulic conductivity (cm hr<sup>-1</sup>), and h is the soil matric pressure (cm H<sub>2</sub>O). The soil profile is discretized into n layers, and the model is applied to simulate vertical water flows through soil layers. The Richards equation is solved non-iteratively utilizing temporal linearization of fluxes as

$$q_i^\sigma = q_i^0 + \sigma \left( \frac{\partial q_i}{\partial S_i} \Big|_0 \Delta S_i + \frac{\partial q_i}{\partial S_{i+1}} \Big|_0 \Delta S_{i+1} \right), \text{ for } i = 1 \text{ to } n-1 \quad (2.2.62)$$

$$a_i \Delta S_{i-1} + b_i \Delta S_i + c_i \Delta S_{i+1} = d_i, \text{ for } i = 1 \text{ to } n \quad (2.2.62a)$$

$$\text{where } a_i = \frac{\partial q_{i-1}}{\partial S_{i-1}} \Big|_0 \quad (2.2.62b)$$

$$b_i = \frac{\partial q_{i-1}}{\partial S_i} \Big|_0 - \frac{\partial q_i}{\partial S_i} \Big|_0 - \frac{\Delta z_i (\theta_{S_i} - \theta_{r,i})}{\sigma \Delta t} \quad (2.2.62c)$$

$$c_i = \frac{\partial q_i}{\partial S_{i+1}} \Big|_0 \quad (2.2.62d)$$

$$d_i = - \frac{(q_{i-1}^0 - q_i^0)}{\sigma} \quad (2.2.62e)$$

$$S_i = \frac{\theta_i - \theta_{r,i}}{\theta_{s,i} - \theta_{r,i}} \quad (2.2.62f)$$

where  $q$  is the water flux (cm/hr),  $i$  is the soil layer number,  $\sigma$  is the fraction of the timestep,  $S$  is the degree of saturation,  $a$ - $d$  are equation coefficients,  $\Delta z$  is the layer thickness (cm),  $\theta$  is the soil water content (cm cm<sup>-1</sup>),  $\theta_r$  is the residual soil water content (cm cm<sup>-1</sup>),  $\theta_s$  is the saturated soil water content (cm cm<sup>-1</sup>). Note that  $\sigma = 1$  in the presence of saturated conditions and  $\sigma = 0.5$  under unsaturated conditions. The flow of water into a layer can then be calculate as

$$\frac{\Delta Q_i}{\Delta t} = q_{i-1}^\sigma - q_i^\sigma \quad (2.2.63)$$

where  $Q$  is the flow of water (cm), and  $t$  is the timestep (hr). The equations are solved on a sub-daily time step, with the time step varying to limit the maximum allowable change in degree of saturation.

$$\Delta t = \frac{\Delta S_{max}}{\left| \left( \frac{q_{i-1} - q_i}{(\theta_{s,i} - \theta_{r,i}) \Delta z} \right) (t) \right|_{max}} \quad (2.2.64)$$

where  $S_{max}$  is the largest allowable change in degree of saturation. Iteration is incurred as necessary to ensure the change in  $S$  in all soil layers falls below the  $S_{max}$  threshold. If this change threshold is exceeded, a smaller timestep is implemented as

$$\Delta t_{it} = \Delta t \frac{\Delta S_{max}}{\Delta S} \quad (2.2.65)$$

where  $\Delta t_{it}$  is the updated time step (hr). Percolation from the lowest soil layer is assumed to occur as either a free gravitational drainage, seepage, or constant head boundary condition, allowing flexibility as well as incorporation of more detailed elevated groundwater or subirrigation practices. Infiltration and evaporation from the surface soil layer as well as root water extraction from root-penetrated soil layers are simulated daily following standard APEX methodologies. Subsurface horizontal water flows, similarly to Warrick et al. (2008), were simulated assuming zero pressure gradients across horizontal boundaries such that gravity-driven Darcian flow occurs in the horizontal direction as a function of slope and soil hydraulic characteristics.

$$J_x = K(h) \quad (2.2.66)$$

where  $J_x$  is the horizontal subsurface flow (cm hr<sup>-1</sup>), and  $m$  is the slope gradient (cm cm<sup>-1</sup>).

In order to parameterize the model, soil-water-retention and unsaturated hydraulic conductivity functions were characterized using a modification similar to van Genuchten-Mualem (VGM) soil hydraulic models (Schaap and van Genuchten, 2006) but instead retaining the occurrence of saturation at zero matric pressure but allowing macropore flow in the unsaturated region (Ross, 2006). Hence the soil-water retention model is characterized as

$$S(h) = \left(1 + \left(\frac{h}{h_g}\right)^n\right)^{-m} \quad \text{for } h \geq h_{\text{thresh}} \quad (2.2.67)$$

$$S(h) = 1 + \frac{2(S_{\text{thresh}}-1)h_{\text{thresh}}}{a_1 + \sqrt{a_1^2 + 4a_2 h_{\text{thresh}}}} \quad \text{for } h < h_{\text{thresh}} \quad (2.2.67a)$$

$$m = 1 - \frac{1}{n} \quad (2.2.67b)$$

$$a_1 = 2h_{\text{thresh}} - (S_{\text{thresh}} - 1) \left. \frac{dh}{dS} \right|_{S_{\text{thresh}}} \quad (2.2.67c)$$

$$a_2 = h_{\text{thresh}} - a_1 \quad (2.2.67d)$$

where  $h_g$  (cm water) is a scaling parameter,  $m$  and  $n$  are shape parameters,  $S_{\text{thresh}}$  is the degree of saturation threshold for saturated conditions,  $h_{\text{thresh}}$  (cm water) is the soil matric pressure when  $S = S_{\text{thresh}}$ , and  $a_1$  and  $a_2$  are equation coefficients. Here it is assumed that  $S_{\text{thresh}}$  equals 0.99. The hydraulic conductivity model is defined as

$$K(h) = \left(\frac{K_s}{K_v(h)}\right)^{R(h)} K_v(h) \quad (2.2.68)$$

$$R(h) = 1 - \frac{(1-R_{\text{mac1}})h}{h_{\text{mac1}}} \quad \text{for } 0 \geq h \geq h_{\text{mac1}} \quad (2.2.69)$$

$$R(h) = \frac{R_{\text{mac1}}(h-h_{\text{mac2}})}{h_{\text{mac1}}-h_{\text{mac2}}} \quad \text{for } h_{\text{mac1}} > h > h_{\text{mac2}} \quad (2.2.70)$$

$$R(h) = 0 \quad \text{for } h < h_{\text{mac2}} \quad (2.2.71)$$

$$K_v(h) = K_s x^{mp} ((1 - (1 - x)^m)^2), \quad \text{for } h < h_s \quad (2.2.72)$$

$$K_v(h) = K_s, \quad \text{for } h \geq h_s \quad (2.2.73)$$

$$x = \frac{1}{1+h^n} \quad (2.2.74)$$

where  $K_s$  is the saturated hydraulic conductivity (cm hr<sup>-1</sup>),  $K_v$  is the macropore adjusted hydraulic conductivity (cm hr<sup>-1</sup>),  $R$  is an equation coefficient,  $h_{\text{mac1}}$  (cm water) and  $h_{\text{mac2}}$  (cm water) are soil matric pressure thresholds distinguishing between exponential macropore flow, non-exponential macropore flow, and soil matrix flow,  $R_{\text{mac1}}$  is the  $R$  at a soil matric pressure of  $h_{\text{mac1}}$ ,  $x$  is an equation coefficient, and  $p$  is a pore connectivity parameter. Here it is assumed that  $h_{\text{mac1}}$  equals -4 cm water,  $h_{\text{mac2}}$  equals -40 cm water,  $R_{\text{mac1}}$  equals 0.25, and  $p$  equals 0.5.



## TILE DRAINAGE

Tile in APEX is simulated by indicating the depth of the drainage system and the time required (days) for the drainage system to reduce plant stress. Storage routing in APEX allows percolation of soil moisture from a soil layer when the soil water content exceeds field capacity. Water drains from one layer to the layer below as a function of storage and saturated conductivity:

$$SWC_1 = (SWC_0 - FC) * \exp\left(\frac{-24}{TT_V}\right) + FC \quad (2.2.75)$$

Where  $SWC_1$  and  $SWC_0$  are the soil water contents at the end and start time interval (24 hours),  $FC$  is the field capacity in mm, and  $TT_V$  is the vertical travel time through a soil layer in hours. Travel time through a soil layer is calculated as:

$$TT_V = \frac{(PO - FC)}{SC} \quad (2.2.76)$$

Where  $PO$  is porosity in mm and  $SC$  is saturated conductivity in  $\text{mm h}^{-1}$ . The lateral subsurface flow rate ( $Q_H$ ) is estimated in  $\text{mm d}^{-1}$  by partitioning the changes in soil moisture storage between vertical and horizontal flow.

$$Q_H = (SWC - FC) * \frac{X_V \cdot X_{VH}}{X_V + X_H} \quad (2.2.77)$$

Where:

$$X_V = 1 - \exp(-24/TT_V)$$

$$X_H = 1 - \exp(-24/TT_H)$$

$$X_{VH} = 1 - \exp(-24/TT_V) + (-24/TT_H)$$

Where  $TT_H$  is the horizontal travel time h. Horizontal flow is partitioned into subsurface flow to the adjacent subarea and or outflow (tile) and quick return flow. Drainage is simulated by indicating the depth of the drainage system and the time required for the drainage system to reduce plant stress. The drainage time replaces the horizontal travel time ( $TT_H$ ) in Eq 2.2.77 for the layer containing the system.

## EVAPOTRANSPIRATION

The model offers five options for estimating potential evaporation--Hargreaves and Samani (1985), Penman (1948), Priestley-Taylor (1972), Penman-Monteith (Monteith, 1965), and Baier-Robertson (1965). The Penman and Penman-Monteith methods require solar radiation, air temperature, wind speed, and relative humidity as input. If wind speed, relative humidity, and solar radiation data are not available, the Hargreaves or Priestley-Taylor methods provide options that give realistic results in most cases. The Baier-Robertson method developed in Canada performs well in cold climates.

The model computes evaporation from soils and plants separately, as described by Ritchie(1972). Potential soil water evaporation is estimated as a function of potential evaporation and leaf

area index (LAI, area of plant leaves relative to the soil surface area). Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential evaporation and leaf area index.

## POTENTIAL EVAPORATION

### Penman

The Penman (1948) option for estimating potential evaporation is based on the equation

$$EO=(RN*DLT/HV+GMA*FWV*VPD)/(DLT+GMA) \quad (2.2.78)$$

$$RN=RA*(1.0-AB)-RBO*(0.9*RA/RAMX+0.1) \quad (2.2.78a)$$

$$DLT=EA*(6790.5/TK-5.029)/TK \quad (2.2.78b)$$

$$HV=2.501-0.0022*TX \quad (2.2.78c)$$

$$GMA=6.595E-4*PB \quad (2.2.78d)$$

$$PB=101.3-ELEV*(.01152-5.44E-7*ELEV) \quad (2.2.78e)$$

$$FWV=2.7+1.63*U10 \quad (2.2.78f)$$

$$RBO=(0.34-0.14*\sqrt{ED})*4.9E-9*TK^4 \quad (2.2.78g)$$

$$VPD=EA-ED \quad (2.2.78h)$$

$$EA=.1*\exp(54.879-5.029*\ln(TK)-6790.5/TK) \quad (2.2.78i)$$

$$ED=EA*RH \quad (2.2.78j)$$

where EO is the potential evaporation in  $\text{mm d}^{-1}$ , DLT is the slope of the saturation vapor pressure curve in  $\text{kPa } ^\circ\text{C}^{-1}$ , GMA is a psychrometer constant in  $\text{kPa } ^\circ\text{C}^{-1}$ , RN is the net radiation in  $\text{MJ m}^{-2} \text{d}^{-1}$ , HV is the latent heat of vaporization in  $\text{MJ kg}^{-1}$ , FWV is a wind speed function in  $\text{mm d}^{-1} \text{kPa}^{-1}$ , EA is the saturation vapor pressure at mean air temperature in kPa, ED is the vapor pressure at mean air temperature in kPa, TX and TK are the mean daily air temperature in  $^\circ\text{C}$  and  $^\circ\text{K}$ , VPD is the vapor pressure deficit in kPa, U10 is the mean wind speed at 10 m height in  $\text{m s}^{-1}$ , RA is the solar radiation in  $\text{MJ m}^{-2} \text{d}^{-1}$ , RAMX is the clear day radiation at the surface in  $\text{MJ m}^{-2} \text{d}^{-1}$ , RBO is the net outgoing long wave radiation in  $\text{MJ m}^{-2} \text{d}^{-1}$ , AB is the soil albedo, RH is the relative humidity, PB is the barometric pressure in kPa, ELEV is the elevation of the site in m.

### Penman-Monteith

The Penman-Monteith method (Monteith, 1965) was added to APEX to provide a means for estimating the effects of CO<sub>2</sub> changes (Stockle et al., 1992). The Penman-Monteith equation is expressed as

$$EO=(RN*DLT+86.66*AD*VPD*U10/350.)/(HV*(DLT+GMA)) \quad (2.2.79)$$

$$EP=(RN*DLT+86.66*AD*VPD/AR)/(HV*(DLT+GMA*(1.+CR/AR))) \quad (2.2.80)$$

$$AD=.01276*PB/(1.+0.00367*TX) \quad (2.2.80)$$

$$AR=6.25*(\ln((ZZ-Z_D)/Z_0))^2/UZZ \quad (2.2.80b)$$

$$\begin{aligned} UZZ=U10; \quad CPHT < 8. & \quad (2.2.80c) \\ ZZ=10. & \end{aligned}$$

$$\begin{aligned} UZZ=U10*LN(ZZ/.0005)/9.9035; \quad CPHT > 8. & \quad (2.2.80d) \\ ZZ=CHMX+2. & \end{aligned}$$

$$Z_0=0.131*CPHT^{0.997} \quad (2.2.80e)$$

$$Z_D=0.702*CPHT^{0.979} \quad (2.2.80f)$$

$$CR=p1/(SMLA*G1*\exp(.00155*(330.-CO_2))) \quad (2.2.80g)$$

$$G1=GSI*FVPD \quad (2.2.80h)$$

$$FVPD=1.0-bx*(VPD-VPTH); \quad 0.1 < FVPD < 1.0 \quad (2.2.80i)$$

where AD is the air density in kg m<sup>-3</sup>, EP is the potential plant evaporation in mm d<sup>-1</sup>, CR is the canopy resistance for vapor transfer in s m<sup>-1</sup>, AR is the aerodynamic resistance for heat and vapor transfer in s m<sup>-1</sup>, CPHT is crop height in m, CHMX is maximum potential crop height in m, Z<sub>D</sub> is the displacement height of the crop in m, Z<sub>0</sub> is the surface roughness parameter in m, UZZ is the daily mean wind speed adjusted for the crop height in m s<sup>-1</sup>, SMLA is the sum of the leaf-area-index values for all crops growing at the time, p1 is a parameter ranging from 1.0 to 2.0, GSI is the crops leaf resistance in s m<sup>-1</sup>, VPTH is the threshold vapor pressure for the crop, bx is a crop coefficient, and CO<sub>2</sub> is the atmospheric carbon dioxide concentration in g m<sup>-3</sup>.

### Priestley-Taylor

The Priestley-Taylor (1972) method provides estimates of potential evaporation without wind and relative humidity inputs. The simplified equation based only on temperature and radiation is

$$EO=1.28*(RN*(1.0-AB)/HV)*DLT/(DLT+GMA) \quad (2.2.81)$$

### Hargreaves

The Hargreaves method (Hargreaves and Samani, 1985) estimates potential evapotranspiration as a function of extraterrestrial radiation and air temperature. Hargreaves' method was modified to closely match Penman-Monteith annual EO estimates in many locations in the U. S. by increasing the temperature difference exponent from 0.5 to 0.6. Also, extraterrestrial radiation is replaced by RAMX and the coefficient is adjusted from 0.0023 to 0.0032 for proper conversion. The modified equation is

$$EO=0.0032*(RAMX/HV)*(TX+17.8)*(TMX-TMN)^{0.6} \quad (2.2.82)$$

where TMX and TMN are the daily maximum and minimum air temperatures in °C.

### **Baier-Robertson**

The Baier-Robertson method (1965) is popular in Canada and is provided mainly for use in cold climates. Like the Hargreaves method Baier-Robertson requires minimal data and is robust. The equation can be written in the form

$$EO=0.288*TMX-0.144*TMN+0.139*RAMX-4.931 \quad (2.2.83)$$

All five methods estimate albedo by considering the soil, crop, and snow cover. If a snow cover exists with 5 mm or greater water content, the value of albedo is set to 0.6. If the snow cover is less than 5 mm and no crop is growing, the soil albedo is the appropriate value. When crops are growing, albedo is determined by using the equation

$$AB=0.23*(1.-EAJ)+SALB*EAJ \quad (2.2.84)$$

where 0.23 is the albedo for plants, SALB is the soil albedo, and EAJ is a soil cover index. The value of EAJ ranges from 0 to 1.0 according to the equation

$$EAJ=\exp(-X1) \quad (2.2.85)$$

$$X1=\max(0.4*SMLA,0.1*(CV+.1)) \quad (2.2.85a)$$

where CV is the weight of all above ground plant material in t ha<sup>-1</sup>.

## **SOIL AND PLANT EVAPORATION**

The model computes evaporation from soils and plants separately by an approach similar to that of Ritchie (1972). For all methods except Penman-Monteith, potential plant water evaporation is computed with the equations

$$EP=LAI*EO/3.; \quad 0.0<LAI<3.0 \quad (2.2.86)$$

$$EP=EO; \quad LAI>3.0 \quad (2.2.86a)$$

where EP is the potential plant water evaporation rate in mm d<sup>-1</sup>. If soil water is limited, plant water evaporation will be reduced as described in the crop growth section of this chapter.

$$EO'=EO-RFI; \quad RFI < EO \quad (2.2.87)$$

$$EP'=\min(EO',EP) \quad (2.2.87a)$$

$$EO'=EO; \quad RFI > EO \quad (2.2.88)$$

$$SWLT=SWLT+RFI-EO \quad (2.2.88a)$$

$$EP'=0.0 \quad (2.2.88b)$$

$$ES=0.0 \quad (2.2.88c)$$

where EO' is the potential evaporation in mm d<sup>-1</sup> adjusted for rainfall interception, ES is potential soil evaporation, and SWLT is water stored in the litter. Thus, if rainfall interception is less than potential evaporation (Eq 2.2.87) the excess EO can be used for plant or soil evaporation. If the reverse is true (Eq 2.2.88) the excess interception is transferred to the litter water storage and soil and plant evaporation becomes 0.0. If there is EO available potential soil evaporation is estimated with the equations

$$ES=EO'*EAJ \quad (2.2.89)$$

$$ES'=\min(ES,ES*EO'/(ES+EP')) \quad (2.2.90)$$

where ES is the potential soil water evaporation rate in mm d<sup>-1</sup>. Eq 2.2.90 reduces potential soil water evaporation during periods of high plant water use. Actual soil water evaporation is estimated on the basis of the top 0.2 m of soil, litter storage, and snow cover. If 5 mm or more (water content) of snow is present albedo is set to 0.6 and EAJ to 0.5 for estimating EO and snow is evaporated at that rate. When all snow is evaporated, water contained in litter storage is evaporated, and finally soil water evaporation begins. Such evaporation is governed by soil depth and water content according to the equation

$$EVZ=ESR*Z/(Z+\exp(2.374-0.00713*Z)) \quad (2.2.91)$$

EVZ is the total potential soil water evaporation in mm d<sup>-1</sup> from soil of depth Z in mm and ESR is the potential soil evaporation remaining after snow and litter evaporation. The coefficients of Eq 2.2.91 are set to give EVZ=0.5\*ESR when Z=10 mm and EVZ=0.95\*ESR when Z=100 mm. Potential soil water evaporation for a layer is estimated by taking the difference between EVZ values at the layer boundaries

$$SEV(l)=EVZ(l)-EVZ(l-1) \quad (2.2.92)$$

where SEV is the potential soil evaporation for layer l in mm d<sup>-1</sup>. The depth distributed estimate of soil water evaporation may be reduced if soil water is limited in a layer

$$SEV'(l)=SEV(l)*\exp(2.5*(ST(l)-FC(l))/(FC(l)-WP(l))); \quad WP < ST < FC \quad (2.2.93)$$

$$SEV'(l)=SEV(l); \quad FC < ST \quad (2.2.93a)$$

$$SEV'(l)=ST(l)-p5*WP(l); (ST(l)-p5*WP(l))<SEV(l) \quad (2.2.93b)$$

where SEV' is the adjusted soil water evaporation estimate in mm and p5 may range from 0.0 to 1.0 in the top 0.5 m of soil and is set to 1.0 below 0.5 m. Thus, APEX can be adjusted to allow the top 0.5 m to dry down to any fraction of wilting point.

## SNOWMELT

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

$$SML=MAX(0.,X1*(1.52+.54*F*SNPKT)); 0.0<SML<SNO \quad (2.2.94)$$

$$SNPKT=.3333*(2.*X2+TX) \quad (2.2.94a)$$

$$X1=sqrt(TMX*RA) \quad (2.2.94b)$$

$$X2=min(DST0,STMP(2)) \quad (2.2.94c)$$

$$F=TSNO/(TSNO+exp(5.34-2.395*TSNO)) \quad (2.2.94d)$$

where SML is the snowmelt rate in mm d<sup>-1</sup>, SNO is the snow present in mm of water, STMP is the temperature in °C of soil layer 2, SNPKT is the snow pack temperature in °C, DST0 is the soil surface temperature in °C, and TSNO is the age of the snow pack in d. The equations for estimating STMP and DST0 are presented in the soil temperature section. Melted snow is treated the same as rainfall for estimating runoff volume and percolation, but rainfall energy is set to 0.0 and peak runoff rate is estimated by assuming uniformly distributed rainfall for a 24-h duration.

## WATER TABLE DYNAMICS

The water table height is simulated without direct linkage to other soil water processes in the root zone to allow for offsite water effects. The model drives the water table up and down between input values of maximum and minimum depths from the surface.

$$WTBL = WTBL0 - X2*(WTBL0 - XX) \quad (2.2.95)$$

$$X2 = MINIMUM (PARM 88) \text{ or } ABS(RTO)*X1 \quad X2<1.0 \quad (2.2.95a)$$

$$RTO = (SMRF - SMEO)/SMEO \quad (2.2.95b)$$

$$\begin{aligned} RTO > 0.0 \\ X1 &= 1.0 \\ XX &= WTMN \end{aligned}$$

$$\begin{aligned} RTO < 0.0 \\ X1 &= PARM(87) * (JULIAN DAY / TOTAL NUMBER OF DAYS IN YEAR)^{PARM 89} \\ XX &= WTMX \end{aligned}$$

where WTBL is today's water table depth in m, WTBL0 is yesterday's water table depth in m, SMRF is the sum of daily precipitation for the antecedent period in mm, SMEO is a climatic factor estimated from long-term precipitation and average temperature adjusted by soil temperature for the antecedent period in mm, WTMN is the minimum possible distance from the soil surface to the water table in m, WTMX is the maximum possible distance from the soil surface to the water table in m, PARM(87) is used to slow the water table recession, PARM(88) limits daily water table movement; it is the fraction of the difference between WTBL and WTMX, and PARM(89) is the exponent of the time ratio. The antecedent period (IWTB) is user specified and ranges from 5 to 30 days.

## 2.3 SOIL EROSION

### WATER

#### RAINFALL/RUNOFF

The APEX component for water-induced erosion simulates erosion caused by rainfall and runoff and by irrigation (sprinkler and furrow). To simulate rainfall/runoff erosion, APEX contains seven equations--the USLE (Wischmeier and Smith, 1978), the Onstad-Foster modification of the USLE (Onstad and Foster, 1975), RUSLE (Renard, et al., 1997), the MUSLE (Williams, 1975b), two recently developed variations of MUSLE, and a MUSLE structure that accepts input coefficients. Only one of the equations (user specified) interacts with other APEX components. The six equations are identical except for their energy components. The USLE depends strictly upon rainfall as an indicator of erosive energy. The MUSLE and its variations use only runoff variables to simulate erosion and sediment yield. Runoff variables increased the prediction accuracy, eliminated the need for a delivery ratio (used in the USLE to estimate sediment yield), and enabled the equation to give single storm estimates of sediment yields. The USLE gives only annual estimates. The Onstad-Foster equation contains a combination of the USLE and MUSLE energy factors.

Thus, the water erosion model uses an equation of the form

$$Y=X*EK*CVF*PE*SL*ROKF \quad (2.3.1)$$

$$X=EI \quad \text{USLE, RUSLE} \quad (2.3.1a)$$

$$X=0.646*EI+0.45*(Q*q_p)^{0.33} \quad \text{Onstad-Foster} \quad (2.3.1b)$$

$$X=1.586*(Q*q_p)^{0.56}*WSA^{0.12} \quad \text{MUSLE} \quad (2.3.1c)$$

$$X=2.5*(Q*q_p)^{0.5} \quad \text{MUST} \quad (2.3.1d)$$

$$X=0.79*(Q*q_p)^{0.65}*WSA^{0.009} \quad \text{MUSS} \quad (2.3.1e)$$

$$X=by1*Q^{by2}*q_p^{by3}*WSA^{by4} \quad \text{MUSI} \quad (2.3.1f)$$

where Y is the sediment yield in t ha<sup>-1</sup>, EK is the soil erodibility factor, CVF is the crop management factor, PE is the erosion control practice factor, SL is the slope length and steepness factor, ROKF is the coarse fragment factor, Q is the runoff volume in mm, q<sub>p</sub> is the peak runoff rate in mm h<sup>-1</sup>, and WSA is the watershed area in ha. MUST is a new equation theoretically developed from sediment concentration bases, MUSS is a new equation developed by fitting small watershed data (no channel erosion), and MUSI allows user input of four coefficients (by1 through by4). The PE value is determined initially by considering the conservation practices to be applied. The value of SL is calculated for the USLE with the equation (Wischmeier and Smith, 1978).

$$SL=(SPLG/22.127)^{XM}*(STP*(65.41*STP+4.56)+.065) \quad (2.3.2)$$

$$XM=0.3*STP/(STP+\exp(-1.47-61.09*STP))+0.2 \quad (2.3.2a)$$

where STP is the land surface slope in m m<sup>-1</sup> and SPLG is the slope length in m. The value of SL is calculated for RUSLE with the equation (Renard, et al., 1997).

$$SL=RSF*RLF \quad (2.3.3)$$

$$RSF=10.8*STP+0.03; \quad SPLG>4.57; \quad STP<0.09 \quad (2.3.3a)$$

$$RSF=16.8*STP-0.5; \quad SPLG>4.57; \quad STP>0.09 \quad (2.3.3b)$$

$$RSF=X1; \quad SPLG<4.57 \quad (2.3.3c)$$

$$X1=3.*STP^{0.8}+.56 \quad (2.3.3d)$$

$$RLF=(SPLG/22.127)^{RXM} \quad (2.3.3e)$$

$$RXM=B/(1.+B) \quad (2.3.3f)$$

$$B=STP/ (.0896*X1) \quad (2.3.3g)$$

The APEX user may choose Eq 2.3.2 or 2.3.3 to supply SL to the erosion equations.

The crop management factor is evaluated for all days when runoff occurs by using the modified RUSLE equation

$$CVF=FRSD*FBIO*FRUF \quad (2.3.4)$$

$$FRSD=\exp(-0.75*CVRS) \quad (2.3.4a)$$

$$FBIO=1.-FGC*\exp(-0.1*CPHT) \quad (2.3.4b)$$

$$FRUF=\exp(-.026*(RRUF-6.1)) \quad (2.3.4c)$$

$$FGC=STL/(STL+\exp(1.175-1.748*STL)) \quad (2.3.4d)$$

where FRSD is the crop residue factor, FBIO is the growing biomass factor, FRUF is the soil random roughness factor, CVRS is the above ground crop residue in t ha<sup>-1</sup>, CPHT is the crop height in m, RRUF



is the soil surface random roughness in mm, STL is the standing live biomass of the crop in t ha<sup>-1</sup>, and FGC is the fraction ground cover by the growing crop.

The soil erodibility factor, EK, is evaluated for the topsoil layer at the start of each year of simulation with the equation

$$EK=X1*X2*X3*X5 \quad (2.3.5)$$

$$X1=0.2+0.3*\exp(-0.0256*SAN*(1-.01*SIL)) \quad (2.3.5a)$$

$$X2=(SIL/(CLA+SIL))^{0.3} \quad (2.3.5b)$$

$$X3=1.0-0.25*WOC/(WOC+\exp(3.718-2.947*WOC)) \quad (2.3.5c)$$

$$X5=1.0-0.7*SN1/(XX+\exp(-5.509+22.899*SN1)) \quad (2.3.5d)$$

$$SN1=1.0-0.01*SAN \quad (2.3.5e)$$

where SAN, SIL, and CLA, and WOC are the sand, silt, clay, and organic carbon contents of the soil in % . Eq 2.3.5 allows EK to vary from about 0.1 to 0.5. The first term gives low EK values for soils with high coarse-sand contents and high values for soils with little sand. The fine sand content is estimated as the product of sand and silt divided by 100. The expression for coarse sand in the first term is simply the difference between sand and the estimated fine sand. The second term reduces EK for soils that have high clay to silt ratios. The third term reduces EK for soils with high organic carbon contents. The fourth term reduces EK further for soils with extremely high sand contents (SAN>70%).

The runoff model supplies estimates of Q and q<sub>p</sub>. To estimate the daily rainfall energy in the absence of time-distributed rainfall, it is assumed that the rainfall rate is exponentially distributed:

$$r_t=r_p*\exp(-t/k) \quad (2.3.6)$$

where r<sub>t</sub> is the rainfall rate at time t in mm h<sup>-1</sup>, r<sub>p</sub> is the peak rainfall rate in mm h<sup>-1</sup>, and k is the decay constant in h. Eq 2.3.6 contains no assumption about the sequence of rainfall rates (time distribution). The USLE energy equation in metric units is

$$RE=dRFV*(12.1+8.9*\log(dRFV/dt)) \quad (2.3.7)$$

where RE is the rainfall energy for water erosion equations and dRFV is a rainfall amount in mm during a time interval dt in h. The energy equation can be expressed analytically and integrated using Eq 2.3.6 for rainfall rate to yield the equation

$$RE=RFV*(12.1+8.9*(\log(r_p)-0.434)) \quad (2.3.8)$$

The rainfall energy factor, EI, is obtained by multiplying Eq 2.3.8 by the maximum 0.5-h rainfall intensity (r<sub>s</sub>) and converting to the proper units:

$$EI=RFV*(12.1+8.9*(\log(r_p)-0.434))*r_s/1000. \quad (2.3.9)$$

To compute values for r<sub>p</sub>, Eq 2.3.6 is integrated to give

$$RFV=r_p*k \quad (2.3.10)$$

$$RFV_t=RFV*(1.0-\exp(-t/k)) \quad (2.3.11)$$

The value of  $RFV_{.5}$  can be estimated by using  $alp_{.5}$ , from the Hydrology section of this chapter:

$$RFV_{.5}=RFV*alp_{.5} \quad (2.3.12)$$

To determine the value of  $r_p$ , Eqs 2.3.12 and 2.3.10 are substituted into Eq 2.3.11 to give

$$r_p=-2.0*RFV*\ln(1.0-alp_{.5}) \quad (2.3.13)$$

Since rainfall rates vary seasonally,  $alp_{.5}$  is evaluated for each month by using Weather Service information (U.S. Department of Commerce, 1979). The frequency with which the maximum 0.5-h rainfall amount occurs is estimated by using the Hazen plotting position equation (Hazen,1930).

$$F=1.0/(2.0*NWD*NY) \quad (2.3.14)$$

where F is the rainfall frequency of occurrence. The total number of events for each month is the product of the number of years of record (NY) and the average number of rainfall events for the month (NWD). To estimate the mean value of  $alp_{.5}$ , it is necessary to estimate the mean value of  $RFV_{.5}$ . The value of  $RFV_{.5}$  can be computed easily if the maximum 0.5-h rainfall amounts are assumed to be exponentially distributed. From the exponential distribution, the expression for the mean 0.5-h rainfall amount is

$$RFV_{.5a}=-RFV_{.5u}/\ln(F) \quad (2.3.15)$$

where  $RFV_{.5a}$  is the mean maximum 0.5-h rainfall amount for the month,  $RFV_{.5u}$  is the maximum 0.5-h rainfall amount for frequency F (input). The mean  $alp_{.5}$  is computed with the equation

$$alp_{.5}=RFV_{.5a}/RFV \quad (2.3.16)$$

where RFV is the mean amount of rainfall for each event (average monthly rainfall/average number of days of rainfall). Daily values of  $alp_{.5}$  are generated from a triangular distribution. The lower limit determined by a uniform rainfall rates gives  $alp_{.5}$  equal to 0.5/24 or 0.0208. The upper limit of  $alp_{.5}$  is set by considering a large rainfall event. In a large event, it is highly unlikely that all the rainfall occurs in 0.5 h ( $alp=1$ ). The upper limit of  $alp_{.5}$  can be estimated by substituting a high value for  $r_p$  (250 mm h<sup>-1</sup> is generally near the upper limit of rainfall intensity) into Eq 2.2.11

$$alp_{.5u}=1.0-\exp(125.0/RFV) \quad (2.3.17)$$

where  $alp_{.5u}$  is the upper limit of  $alp_{.5}$ . The peak of the .5 triangular distribution is  $alp_{.5}$  from Eq 2.3.16.

The coarse fragment factor is estimated with the equation (Simanton et al., 1984)

$$ROKF=\exp(-0.03*ROK) \quad (2.3.18)$$

where ROK is the percent of coarse fragments in the surface soil layer.

## IRRIGATION

Erosion caused by applying irrigation water is estimated for furrow or flat surface applications. In either case flow is constant and is estimated by the equation

$$QPX=QXM/24. \quad (2.3.19)$$

where QPX is the flow rate in mm h<sup>-1</sup> and QXM is the application rate in mm d<sup>-1</sup>. For furrow irrigation the flow rate is converted to m<sup>3</sup> s<sup>-1</sup> to determine the flow velocity.

$$QPX'=2.778E-6*QPX*RINT*WSA/FW \quad (2.3.20)$$

where QPX' is the flow rate in m<sup>3</sup> s<sup>-1</sup>, RINT is the ridge interval in m, WSA is the watershed area in ha, and FW is the field width in km. The flow velocity is estimated with Manning's equation assuming the furrow is a triangular shaped channel

$$VX=R^{0.667}*WSX \quad (2.3.21)$$

$$WSX=\text{sqrt}(STP)/n \quad (2.3.21a)$$

$$R=AX/PX \quad (2.3.21b)$$

$$AX=0.5*DX*X2 \quad (2.3.21c)$$

$$X2=DX*X1 \quad (2.3.21d)$$

$$X1=1000.*RINT/RHTT \quad (2.3.21e)$$

$$PX=2.0*\text{sqrt}(DX*DX+0.25*X2*X2) \quad (2.3.21f)$$

$$DX=(2.0* QPX'/(WSX*X1*(1.0/(4.0+16.0/(X1*X1))))^{0.333})^{0.375} \quad (2.3.21g)$$

where VX is the flow velocity in m s<sup>-1</sup>, STP is the field slope in m m<sup>-1</sup>, n is Manning's roughness coefficient, AX is the cross sectional area in m<sup>2</sup>, PX is the wetted perimeter in m, DX is the flow depth in m. Furrow erosion is estimated with the equation

$$Y=10.*QXM*CY*EK \quad (2.3.22)$$

where Y is the sediment yield for the field in t ha<sup>-1</sup> and CY is the sediment concentration in t m<sup>-3</sup>. The sediment concentration is computed with the modified Bagnold sediment transport equation (Bagnold, 1977)

$$CY=CY_1*VX^{p31} \quad (2.3.23)$$

where CY<sub>1</sub> is the sediment concentration at a velocity at of 1.0

$m s^{-1}$  and  $p_{31}$  is the sediment routing exponent ranging from 1.0 to 1.5 (1.5 in Bagnold's original equation).

Erosion from flat applications is estimated with MUST in the form

$$Y=2.5*(QXM*QPX)^{0.5}*EK*CVF*PE*SL \quad (2.3.24)$$

## WIND EROSION

The original APEX wind erosion model (WEQ) required daily mean wind speed as a driving variable. The new APEX wind erosion model (Wind Erosion Continuous Simulation) WECS requires the daily distribution of wind speed to take advantage of the more mechanistic erosion equation. The new approach estimates potential wind erosion for a smooth bare soil by integrating the erosion equation through a day using the wind speed distribution. Potential erosion is adjusted using four factors based on soil properties, surface roughness, cover, and distance across the field in the wind direction.

### WECS METHOD

The basic WECS wind erosion equation is

$$YW=FII*FRF*FV*FD*YWR \quad (2.3.25)$$

where  $YW$  is the wind erosion in  $kg m^{-1}$ ,  $FII$  is the soil erodibility factor,  $FRF$  is the surface roughness factor,  $FV$  is the vegetative cover factor,  $FD$  is the mean unsheltered travel distance of wind across a field factor,  $YWR$  is the integral of the wind erosion rate over the duration of wind greater than threshold velocity. The wind erosion rate is calculated with the equation of Skidmore (1986).

$$YWR'=wn4*(AD/AG)*(USTR^2-USTRT^2-0.5*(ST/WP)^2)^{1.5} \quad (2.3.26)$$

$$USTR=0.0408*DU10 \quad (2.3.26a)$$

$$USTRT=0.0161*\sqrt{DIAM} \quad (2.3.26b)$$

where  $YWR'$  is the wind erosion rate in  $kg m^{-1}s^{-1}$ ,  $wn4$  is a parameter (normal value = 2.5),  $AD$  is the air density in  $kg m^{-3}$ ,  $AG$  is the acceleration of gravity in  $m s^{-2}$ ,  $USTR$  is the friction velocity in  $m s^{-1}$ ,  $USTRT$  is the threshold friction velocity in  $m s^{-1}$ ,  $ST$  and  $WP$  are the actual and 1500 kPa water contents of the top soil layer (10 mm thick),  $DU10$  is the wind speed at time  $t$  in  $m s^{-1}$ , and  $DIAM$  is the soil particle diameter in  $m$ . The soil water term of Eq 2.3.26 was developed by Chepil (1956) and Skidmore (1986). Substituting acceleration of gravity ( $9.8 m s^{-2}$ ) and assuming air density is  $1 kg m^{-3}$  gives the final erosion rate equation

$$YWR'=0.255*(USTR^2-USTRT^2-0.5*(ST/WP)^2)^{1.5} \quad (2.3.27)$$

WECS uses the soil erodibility concept of WEQ expressed in dimensionless form with the equation

$$FI1=FI/695. \quad (2.3.28)$$

where FI is the soil erodibility factor of the Woodruff and Siddoway (1965) model in  $t\ ha^{-1}$  and FI1 is the dimensionless soil erodibility factor of the new model.

The surface roughness factor (FR) is based upon the shelter angle concept developed by Potter et al., (1990). This roughness index calculates the erodible fraction of the soil surface by estimating the portion susceptible to abrasion by saltating particles. The shelter angle index incorporates both roughness due to random cloddiness and oriented roughness (ridges) due to tillage operations. The effect of oriented roughness varies as a function of wind direction, which is selected each day so that the statistical distribution of wind direction approaches that of the simulation site. FR is estimated with the equation (Potter and Zobeck, 1990)

$$FR=1.0-\exp(-(wn1/RFB)^{RFC}) \quad (2.3.29)$$

where  $wn1$  is the descent angle of saltating sand grains (about  $10^\circ$  from horizontal). A  $15^\circ$  impact angle has been shown to cause maximum aggregate abrasion (Hagen et al., 1988).

The coefficient RFC is calculated with the equation

$$RFC=0.77*1.002^{RHTT} \quad (2.3.30)$$

where RHTT is the ridge height in mm. The coefficient RFB is estimated with the equations

$$RFB=RRF+RIF \quad (2.3.31)$$

$$RRF=11.9*(1.-\exp(-(RRUF/9.8)^{1.3})) \quad (2.3.31a)$$

$$RIF=\text{abs}(\sin(wn2))*1.27*RHTT^{0.52} \quad (2.3.31b)$$

where RRF is the clod roughness factor, RRUF is the random roughness in mm, RIF is the ridge roughness factor, and  $wn2$  is the angle of the wind relative to ridges. Both RRUF and RHTT are altered by wind and water erosion and tillage.

The vegetative cover factor is based on the approach used in the original EPIC model. A vegetative cover equivalent factor is simulated daily as a function of standing live biomass, standing dead residue, and flat crop residue.

$$VGF=1.-X1/(X1+\exp(-0.331-1.055*X1)) \quad (2.3.32)$$

$$X1=bwn(1)*STL+bwn(2)*STD+bwn(3)*RSD \quad (2.3.32a)$$

where VGF is the vegetative cover equivalent factor, STL is the standing biomass in  $t\ ha^{-1}$ , STD is the standing crop residue in  $t\ ha^{-1}$ , RSD is the flat residue in  $t\ ha^{-1}$ , and  $bwn\ 1, 2,$  and  $3$  are crop specific coefficients.

Field length along the prevailing wind direction is calculated as in the original model (Cole et al., 1982) by considering the field dimensions and orientation and the wind direction. The new model distance factor (FD) is calculated as described by Stout (1990) using the equation

$$FD=1.-\exp(-WL/wn3) \quad (2.3.33)$$

$$WL=FL*FW/(FL*\text{abs}(\cos(BT))+FW*\text{abs}(\sin(BT))) \quad (2.3.33a)$$

$$BT=1.571+THW-ANG \quad (2.3.33b)$$

where WL is the unsheltered field length along the prevailing wind direction in km, FL is the field length in km, FW is the field width in km, THW is the wind direction clockwise from north in radians, ANG is the clockwise angle between field length and north in radians, and wn3 is a parameter determined experimentally to lie in the range  $0.05 < wn3 < 0.09$ . A value of 0.07 is used in APEX. The integration of Eqs 2.3.17 and 2.1.17 is accomplished numerically using variable f steps. Large steps of  $f=0.1$  are taken initially in simulating low wind speeds. The step size is reduced as f is reduced to gain better definition of the wind speed distribution at high speeds.

## LWE METHOD

Aeolian transport equations developed for rangelands represent the horizontal sediment transport as a threshold-controlled process, where transport increases nonlinearly above the threshold shear velocity (Li et al., 2014). A series of models including the Okin (2008) model for surface shear stress partitioning, Iversen and white (1982) model for threshold shear velocity, Gillette and Passi (1988) model for horizontal sediment transport and Shao et al. (2011) for vertical particle transport were incorporated into APEX for estimating landscape wind erosion (LWE) processes in rangeland environments (Abitew et al., 2022).

Okin (2008) proposed a model that explicitly treats variability in surface shear stress by utilizing vegetation gap distances to characterize erodible soil surfaces. This model defines a landscape as a collection of vegetation gaps, each scaled by the height of the upwind sheltering plant, with a gamma probability distribution. The model uses the probability distribution of vegetation gaps between plants to determine the probability that any point in the landscape is distant from the nearest plant in the upwind direction (Okin, 2008). In addition, this model assumes that each plant is associated with a reduced shear stress wake zone using an exponential curve relationship:

$$u_* = u_{*w} \left( \left( \frac{u_*}{u_{*w}} \right)_{x=0} + \left( 1 - \left( \frac{u_*}{u_{*w}} \right)_{x=0} \right) (1 - e^{-C/(x/h)}) \right) \quad (2.3.34)$$

where  $u_*$  is the shear velocity in the leeward of a plant ( $\text{m s}^{-1}$ ),  $\left( \frac{u_*}{u_{*w}} \right)_{x=0}$  is the ratio of  $u_*$  and  $u_{*w}$  in the immediate leeward of a plant–shear velocity ratio,  $C$  is the  $e$ -folding distance for the recovery of the shear velocity ( $u_*$ ) in the lee of plants to the value it would have in the absence of vegetation ( $u_{*w}$ )  $x$  is the

distance to the nearest upwind plant (m), and  $h$  is the mean canopy height (m). The wind shear velocity without windbreak ( $u_{*w}$ ) is formulated as a function of the mean wind speed ( $u$ ) at the height  $z$ :

$$u_w = \frac{0.4u}{\ln\left(\frac{z}{z_0}\right)} \quad (2.3.35)$$

where  $z_0$  is the aerodynamic roughness length (m).

The threshold shear velocity ( $u_{*t}$ ) is the minimum shear velocity required to initiate the motion of soil particles. This variable depends on soil texture, soil moisture, salt concentration, surface crusting, and surface roughness elements. Iversen and White (1982) noted the importance of interparticle forces (cohesive forces) in determining threshold friction velocity. The threshold friction velocity for a dry condition ( $u_{*t\_dry}$ ) is determined first and subsequently modified for soil moisture and roughness factors.

$$u_{*t\_dry} = \sqrt{A_N \left( \frac{\rho_p g D}{\rho_a} + \frac{\Gamma}{\rho_a D} \right)} \quad (2.3.36)$$

where  $\rho_a$  and  $\rho_p$  are the air and particle density respectively,  $D$  is particle diameter,  $A_N$  and  $\Gamma$  are empirical coefficients. To account for soil moisture, we use the approach proposed by Fecan et al. (1999). The modifier for soil moisture ( $f_w$ ) is computed by considering clay content and soil-water content to account for the interstitial water space as follows:

$$f_w = \begin{cases} 1 & \text{for } w < w' \\ [1 + 1.21(w - w')^{0.68}]^{0.5} & \text{for } w > w' \end{cases} \quad (2.3.37)$$

$$w'(\%) = 0.0014(\%clay)^2 + 0.17(\%clay) \quad (2.3.37a)$$

where  $w$  is the mass fraction of soil moisture content.

The transport of particles is initiated when the wind shear velocity exceeds the threshold friction velocity. Li et al. (2013) compared the performance of several aeolian transport models in estimating the horizontal sediment flux. They suggested that the method Gillette and Passi (1988) proposed provides a more accurate estimation of horizontal sediment transport than other methods.

$$Q(d) = \begin{cases} (1 - FGC)A \frac{\rho_a}{g} u_*^4 \left(1 - \frac{u_{*t}}{u_*}\right) & u_* > u_{*t} \\ 0 & u_* < u_{*t} \end{cases} \quad (2.3.38)$$

where  $A$  is a dimensionless constant that may vary between 0 and 1, and FGC is the fraction of ground cover by vegetation.

Unlike particles in the horizontal sediment transport, vertical flux particles are transported long distances outside their source area (Li et al., 2014). Shao et al. (2011) proposed a scheme to estimate vertical particle transport that considers saltation bombardment and the disintegration of aggregates. In

this plan, vertical particle transport is proportional to the horizontal sediment flux, in which the proportionality depends on soil texture and soil plastic pressure. This strategy was evaluated using observation data from several locations globally (Shao, 2004; Shao et al., 2011). The same equation is incorporated into APEX to simulate the vertical particle transport as follows:

$$F(d_i, d) = c_y \eta_{fi} [(1 - \Upsilon) + \Upsilon \sigma_p] (1 + \sigma_m) \frac{gQ(d)}{u_*^2} \quad (2.3.39)$$

where  $F(d_i; d)$  is the vertical particle transport rate of the particle size  $d_i$  (from the  $i^{\text{th}}$  size bin) generated by saltation of particles,  $c_y$  is a dimensionless vertical particle transport coefficient and  $\eta_{fi}$  is the amount of vertical particles emitted from the  $i^{\text{th}}$  vertical particle bin in relation to the parent soil characteristics represented in the fully disturbed particle size distribution.

The bombardment efficiency ( $\sigma_m$ ) is the ratio between the mass of particles ejected by bombardment and the mass of impacting particles and is computed by

$$\sigma_m = 12u_*^2 \frac{\rho_b}{P} \left( 1 + 14u_* \sqrt{\frac{\rho_b}{P}} \right) \quad (2.3.39a)$$

where  $\rho_b$  is the soil bulk density ( $\text{kg m}^{-3}$ ), and  $P$  is the soil plastic pressure (Pa).  $\Upsilon$  is a function that describes how easily aggregated vertical particles can be released and estimated as:

$$\Upsilon = \exp[-k(u_* - u_{*t})] \left( 1 + 14 \sqrt{\frac{\rho_b}{P}} \right) \quad (2.3.39b)$$

Being a daily time-step model, APEX model, in general requires model input data pertinent to weather and state variables to be daily values. The main input requirements to simulate LWE within APEX are the daily wind speed distribution, fraction of vegetation cover, vegetation height and vegetation gaps distribution. Additionally, the LWE module requires simulated daily soil moisture fraction in the topsoil layer (i.e., 5 mm) and soil characteristics related to soil texture and particle size distribution.

## 2.4 MANURE EROSION

Manure is eroded from feeding areas and manure application fields. Depending on the amount of manure cover of the soil the erosion varies from essentially all manure to a combination of manure and soil. Since manure is considered residue, a heavy cover in a feedlot may completely eliminate soil erosion but create the potential for severe manure erosion. Soil erosion potential is also very low in manure application fields with a good grass cover but manure erosion can be high. Losses of organic nutrients and carbon are usually estimated using an enrichment ratio, the nutrient concentration in the soil, and the soil erosion rate as described in Eq 2.5.11 below. However, this approach under estimates organic nutrient and C losses because the soil erosion rates are near zero. This deficiency created the need for a manure erosion equation that provides direct estimates of organic nutrient and C losses. The equation is based on the soil erosion equation MUST.

$$YMNU = 0.25 * (Q * q_p)^{0.5} * PE * SL * RSDM^{0.5} * \exp(-1.15 * AGPM) \quad (2.4.1)$$



where YMNU is the manure erosion in  $t\ ha^{-1}$ , Q is the runoff volume in mm,  $q_p$  is the peak runoff rate in  $mm\ h^{-1}$ , PE is the erosion control practice factor, SL is the slope length and steepness factor, RSDM is the manure on the soil surface in  $t\ ha^{-1}$ , and AGPM is the standing live and dead plant material. The losses of organic nutrients and C are calculated as the product of YMNU and the fractions of organic N, P, and C in the manure.

## 2.5 NUTRIENTS

### NITROGEN

#### NITRATE LOSSES-LEACHING, SURFACE RUNOFF, LATERAL SUBSURFACE FLOW

The amount of  $NO_3-N$  lost when water flows through a layer is estimated by considering the change in concentration. Thus, the equation

$$Q_{NO_3} = QT * C_{NO_3} \quad (2.5.1)$$

where  $Q_{NO_3}$  is the amount of  $NO_3-N$  lost from a soil layer and  $C_{NO_3}$  is the average concentration of  $NO_3-N$  in the layer during the percolation of volume QT through the layer. At the end of the day, the amount of  $NO_3-N$  left in the layer is

$$W_{NO_3}' = W_{NO_3} - QT * C_{NO_3} \quad (2.5.2)$$

where  $W_{NO_3}$  and  $W_{NO_3}'$  are the weights of  $NO_3-N$  contained in the layer at the beginning and ending of the day. The  $NO_3-N$  concentration can be calculated by dividing the weight of  $NO_3-N$  by the water storage volume:

$$C_{NO_3}' = \frac{W_{NO_3}'}{bsl * PO(1 - 0.01 * ROK)^2} \quad (2.5.3)$$

where  $C_{NO_3}'$  is the concentration of  $NO_3-N$  at the end of a day, PO is soil porosity, and bsl is a fraction of the storage PO occupied by percolating water. Eq 2.5.3 is a finite difference approximation for the exponential equation

$$C_{NO_3}' = C_{NO_3} * \exp(-QT / (bsl * PO)) \quad (2.5.4)$$

Thus,  $Q_{NO_3}$  can be computed for any volume, QT, by integrating Eq 2.5.4

$$Q_{NO_3} = W_{NO_3} * (1.0 - \exp(-QT / (bsl * PO))) \quad (2.5.5)$$

The average concentration during the percolation of QT (1 day since APEX is a daily time step model) is

$$C_{NO3} = Q_{NO3} / QT \quad (2.5.6)$$

Since percolation usually starts before runoff, the vertical flow concentration is usually higher than that of the horizontal. The relative concentrations may be user specified with the parameter p14.

$$P14 = CS / CO \quad (2.5.7)$$

where p14 is a parameter ranging from near 0.0 to 1.0 (usually 0.5), CS is the horizontal concentration, and CO is the vertical concentration. QNO3 is partitioned into vertical and horizontal components using the equation

$$Q_{NO3} = CO * QV + CS * QH \quad (2.5.8)$$

Substituting Eq 2.5.7 into Eq 2.5.8 and solving for CO gives

$$CO = Q_{NO3} / (QV + p14 * QH) \quad (2.5.9)$$

$$CS = p14 * CO \quad (2.5.9a)$$

Amounts of NO3-N contained in runoff, lateral flow, quick return flow, and horizontal pipe flow are estimated as the products of the flow component and CS. Percolation and vertical pipe flow loads are estimated similarly using CO.

### **NO3-N TRANSPORT BY SOIL WATER EVAPORATION**

When water is evaporated from the soil, NO3-N is moved upward into the top soil layer by mass flow. The equation for estimating this NO3-N transport is

$$E_{NO3} = SEV(l) * C_{NO3}(l) \quad (2.5.10)$$

where ENO3 is the amount of NO3-N in kg ha<sup>-1</sup> moved from layer l to layer l-1 by soil water evaporation SEV in mm.

### **ORGANIC N TRANSPORT BY SEDIMENT**

A loading function developed by McElroy et al., (1976) and modified by Williams and Hann (1978) for application to individual runoff events is used to estimate organic N loss. The loading function is

$$Y_{ON} = 0.001 * Y * CON * ER \quad (2.5.11)$$

where YON is the organic N runoff loss in kg ha<sup>-1</sup>, Y is the sediment yield in t ha<sup>-1</sup>, CON is the concentration of organic N in the top soil layer in g t<sup>-1</sup>, and ER is the enrichment ratio. The enrichment ratio is the concentration of organic N in the sediment divided by that in the soil. Enrichment ratios are logarithmically related to sediment concentration as described by Menzel (1980). An individual event enrichment-sediment concentration relationship was developed for APEX considering upper and lower bounds. The upper bound of enrichment ratio is the inverse of the sediment delivery ratio. Exceeding the inverse of the delivery ratio implies that more organic N leaves the watershed than is dislodged from the soil. The delivery ratio is estimated for each runoff event by using the equation

$$DR=(q_p/rep)^{0.56} \quad (2.5.12)$$

where DR is the sediment delivery ratio (sediment yield divided by gross sheet erosion),  $q_p$  is the peak runoff rate in mm h<sup>-1</sup>, and rep is the peak rainfall excess rate in mm h<sup>-1</sup>. Eq 2.5.12 is based on sediment yield estimated by using MUSLE. The Green and Ampt infiltration equation calculates rainfall excess increments throughout each storm so rep can be extracted easily. Also when hydrographs are calculated (a part of the flood routing option presented later) rainfall excess is computed. However, when the runoff curve number is used and only daily runoff volumes are computed, the rainfall excess is not evaluated directly. An estimate of the rate can be obtained, however, using the equation

$$rep=r_p*(Q/RFV)^{0.1} \quad (2.5.13)$$

where  $r_p$  is the peak rainfall rate in mm h<sup>-1</sup> and the runoff-rainfall ratio Q/RFV is used to account for infiltration. The Q/RFV is raised to the 0.1 power to account for intensity effects on infiltration.

The lower limit of enrichment ratio is 1.0—sediment particle size distribution is the same as that of the soil. Thus,  $1 < ER < 1/DR$ . The logarithmic equation for estimating enrichment ratio is

$$ER=be1*CY^{be2} \quad (2.5.14)$$

where CY is the sediment concentration in t m<sup>-3</sup> and be1 and be2 are parameters set by the upper and lower limits. For the enrichment ratio to approach 1.0, the sediment concentration must be extremely high. Conversely, for the enrichment ratio to approach 1/DR, the sediment concentration must be low. The simultaneous solution of Eq 2.5.10 at the boundaries assuming that sediment concentrations range from 0.0002 to 0.1 t m<sup>-3</sup> gives

$$be2=\log(DR)/2.699 \quad (2.5.15)$$

$$be1=1.0/0.1^{be2} \quad (2.5.16)$$

## DENITRIFICATION – EMPIRICAL METHOD

As one of the microbial processes, denitrification is a function of temperature and water content. The equation used to estimate the denitrification rate is

$$DN=WNO3*(1.-\exp(-1.4*TFN*WOC)); \quad SWF>0.95 \quad (2.5.17)$$

$$DN=0.0; \text{ SWF}<0.95 \quad (2.5.17a)$$

where DN is the denitrification rate in  $\text{kg ha}^{-1} \text{ d}^{-1}$ , TFN is the nutrient cycling temperature factor, WOC is the organic carbon content in %, and SWF is the soil water factor. The temperature factor is expressed by the equation

$$TFN=STMP/(STMP+\exp(5.059-0.2504*STMP)) \quad (2.5.18)$$

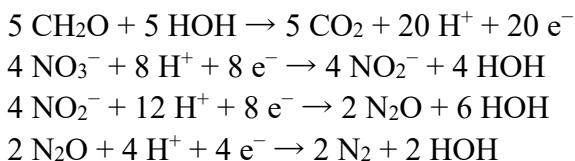
where STMP is soil temperature in  $^{\circ}\text{C}$  at the center of a soil layer. The soil water factor considers total soil water in the equation

$$\text{SWF}=0.1*(ST/WP)^2; \text{ ST}<WP \quad (2.5.19)$$

$$\text{SWF}=0.1+0.9*\sqrt{((ST-WP)/(FC-WP))}; \text{ ST}>WP \quad (2.5.19a)$$

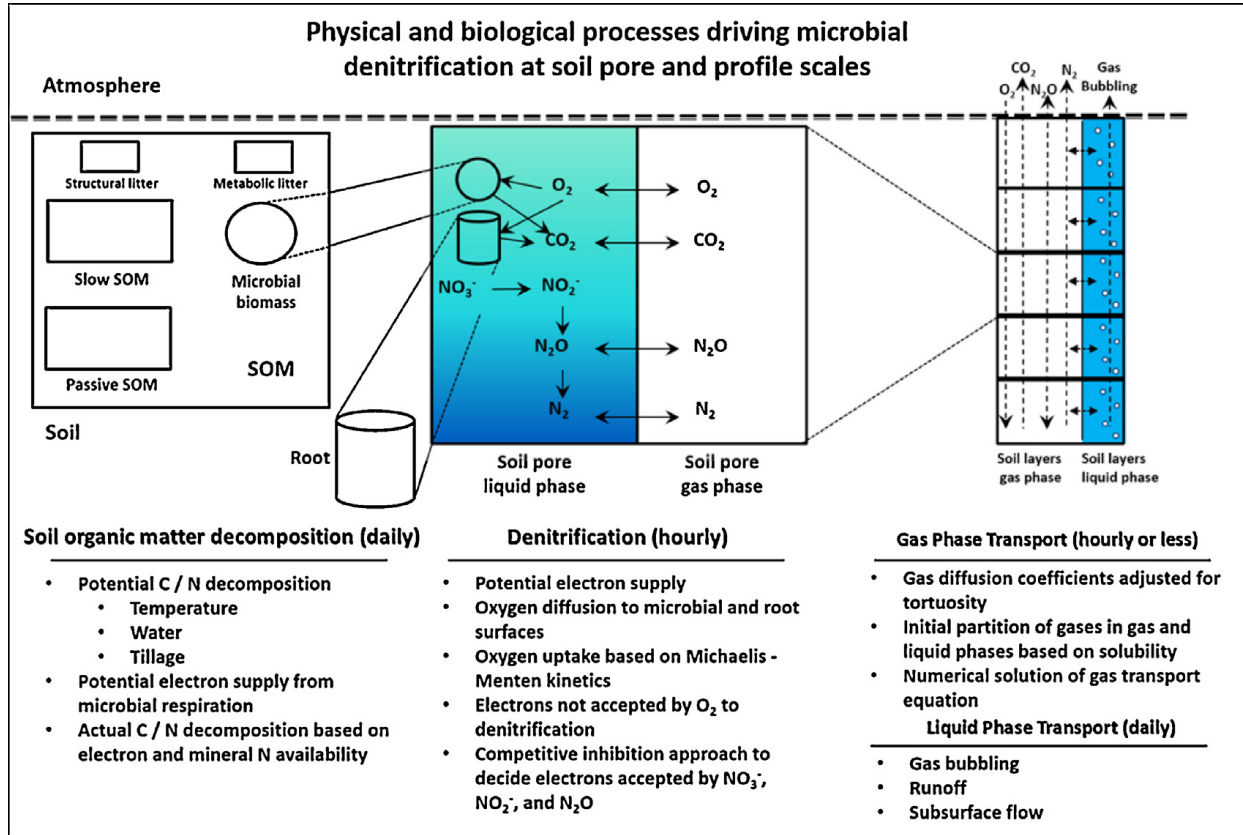
## DENITRIFICATION – PROCESS-BASED METHOD

This section summarizes a physically-based microbial denitrification method proposed by Izaurrealde et al. (2017). The method is called IMWJ denitrification option in EPIC/APEX. Microbial decomposition of soil organic matter and respiration by plant roots results in oxidation of carbon. Such oxidation produces electrons, typically carried within the cell as  $\text{H}^+$ , for which there must be an acceptor to allow decomposition or respiration to produce  $\text{CO}_2$ . Normally  $\text{O}_2$  is the acceptor but in cases of  $\text{O}_2$  deficiency electrons are transferred to N in  $\text{NO}_3^-$  to yield  $\text{NO}_2^-$  and thence  $\text{N}_2\text{O}$  and  $\text{N}_2$  through denitrification as shown in the following equations:



The potential supply of electrons is calculated based on moisture content and temperature coupled with the nature and supply of available substrates (Izaurrealde et al., 2006). Electrons are first passed to  $\text{O}_2$ , based on  $\text{O}_2$  concentration at the surface of both soil microorganisms and plant roots to form  $\text{CO}_2$ . Michaelis-Menten uptake kinetic equations are used to evaluate electron transfer to  $\text{O}_2$ . If the potential supply of electrons exceeds those accepted by  $\text{O}_2$ , and if oxides of N ( $\text{NO}_3^-$ ,  $\text{NO}_2^-$  or  $\text{N}_2\text{O}$ ) are present then electrons are passed to oxides of N to emulate denitrification. Uptake of electrons by organisms reducing oxides of N is quantified via Michaelis-Menten kinetics (Grant and Pattey, 1999). Complete reduction of 1 mole of  $\text{NO}_3^-$  consumes 5 moles of electrons, compared to 3 moles of electrons for 1 mole of  $\text{NO}_2^-$  and 1 mole of electrons per mole of  $\text{N}_2\text{O}$ . Accordingly, the concentrations of each of the oxides of N are weighted to account for the variation in numbers of moles of electrons that each species accepts. The energy gain from reducing  $\text{NO}_3^-$  exceeds that from reducing  $\text{NO}_2^-$ , which exceeds that from reducing  $\text{N}_2\text{O}$ . Consequently, the Michaelis-Menten expression contains terms for competitive inhibition such that  $\text{NO}_3^-$  inhibits reduction of  $\text{NO}_2^-$ , and both inhibit reduction of  $\text{N}_2\text{O}$ . A feedback mechanism based on electron acceptors controls decomposition. If potential supply of electrons is matched by the total

accepted by  $O_2$  plus oxides of N, then, decomposition equals potential decomposition, variables are updated and calculations start again for the next day. If, however, potential supply of electrons exceeds those accepted by  $O_2$  plus oxides of N, then actual decomposition is reduced sufficiently such that total electron supply equals total electrons accepted by  $O_2$  plus oxides of N.



**Figure 8.1: Spatial boundaries of the storm domain set for the Cowhouse watershed in Texas (adopted from Izaurre et al., 2017)**

The simultaneous diffusion of four gases ( $O_2$ ,  $CO_2$ ,  $N_2O$ , and  $N_2$ ) is modeled using the gas transport equation (Simunek and Suarez, 1993). Within each day, each gas is transferred within the gas phase of the soil profile and between the soil surface and the atmosphere above. The profile is divided into computational layers of equal thickness. Properties of the soil profile layers are interpolated among the computational layers. Gas diffusion within the gaseous-phase of the soil profile is calculated using the Crank-Nicolson procedure (Crank and Nicolson, 1996) as default although the implicit and explicit procedures are included as options. Like the implicit and explicit methods, the Crank-Nicolson procedure is a finite difference method for solving numerically the heat and other partial differential equations. Gas diffusivity in soil is modified from air diffusivity to account for tortuosity and water-filled pore space according to the Millington-Quirk approach (Millington and Quirk, 1961). The layer beneath the soil profile is considered a zero-flux boundary, while the atmospheric gas concentrations above the soil profile are fixed at  $I_{ic}$  levels. Each gas is redistributed hourly between gas and liquid phases using Henry's Law. Flux of each gas across the soil-atmosphere plane is calculated as a surface boundary term of the diffusion equation at each diffusion time step and is accumulated into daily fluxes. Gaseous flow through bubbling allows movement of dissolved gases through the liquid phase to the soil surface when aggregate partial

pressures exceed atmospheric pressure, which typically only occurs under highly anaerobic conditions. Detailed equations and parameters can be found in Izaurre et al. (2017).

## **CARBON AND NITROGEN CYCLING AND TRANSFORMATIONS**

APEX uses the soil organic matter model developed in EPIC to simulate the coupled cycling of C and N in soil (Izaurre et al., 2004). The soil organic matter model in EPIC follows the approach used in the Century model as reported by Parton et al., (1987, 1993, and 1994) and Vitousek et al., (1994). By this approach, C and N contained in soil organic matter are split into three compartments: microbial (or active), slow and passive. Besides differing in size and function, these compartments have different turnover times ranging from days to hundreds of years. Carbon and N can also be leached or lost in gaseous forms. Organic residues (plant residues, roots, and manure) added to the soil surface or belowground are split into two litter compartments (metabolic and structural) according to their N and lignin contents.

There are at least four major differences between the Century and EPIC models regarding the organic transformations. First, leaching equations currently in EPIC are used to move organic materials from surface litter to subsurface layers. Second, temperature and water controls affecting transformation rates are calculated with equations currently in EPIC. Third, the surface litter fraction in EPIC has a slow compartment but no passive compartment. Last, the lignin concentration in EPIC is modeled as a sigmoidal function of plant age

### **Litter Allocation and Potential C and N Transformations**

Initially, EPIC calculates potential transformations based on substrate-specific rate constants, temperature, and water content. Lignin content and soil texture also affect some of these transformations (e.g., structural litter and biomass). These transformations are considered potential, because they reach completion only when sufficient quantities of organic and inorganic N are available. Following is a description of equations leading to calculation of potential transformations of C and N in soil.

When organic residues are added to soil, a fraction of the soil mineral N is sorbed onto the litter N compartment (STDNE) (Parton et al., 1987):

$$\text{STDNE} = \text{STDN} + \text{Sf} * (\text{WNO}_3 + \text{WNH}_3); \quad \text{CNR} \geq 10 \quad (2.5.20)$$

$$\text{STDNE} = \text{STDN}; \quad \text{CNR} < 10 \quad (2.5.20a)$$

The litter compartment is then separated into metabolic (LM) and structural (LS) components by calculating the fractions of metabolic (LMF) and structural litter (LSF) (Parton et al., 1987):

$$\text{LMF} = 0.85 - 0.018 * \text{STDN} / \text{STDNE}; \quad \text{STDN} / \text{STDNE} < 47.22 \quad (2.5.21)$$

$$\text{LMF} = 0.0; \quad \text{STDN} / \text{STDNE} = 47.22 \quad (2.5.21a)$$

$$\text{LSF}=1.0\text{-LMF} \quad (2.5.21\text{b})$$

$$\text{LM}=\text{LMF}*\text{STD} \quad (2.5.22)$$

$$\text{LS}=\text{LSF}*\text{STD} \quad (2.5.23)$$

Next, all of the lignin in the standing dead (STD<sub>L</sub>) is transferred to the structural litter (Parton et al., 1987):

$$\text{LSL}=\text{STD}_L \quad (2.5.24)$$

$$\text{LSLF}=\text{LSL}/\text{LS} \quad (2.5.25)$$

The structural litter is assigned a C/N ratio of 150 (Parton et al., 1987). The mass of C (LSC) and N (LSN) and the N fraction (LSNF) of structural litter are calculated as:

$$\text{LSC}=\text{Cf}*\text{LSF}*\text{STD} \quad (2.5.26)$$

$$\text{LSN}=\text{LSC}/150; \quad \text{STDNE} \geq \text{LSC}/150 \quad (2.5.27)$$

$$\text{LSN}=\text{STDNE}; \quad \text{STDNE} < \text{LSC}/150 \quad (2.5.27\text{a})$$

$$\text{LSNF}=\text{LSN}/\text{LS} \quad (2.5.28)$$

where Cf is the carbon fraction of organic materials.

Similarly, the mass of C (LMC) and N (LMN) and the N fraction (LMNF) of metabolic litter are calculated as:

$$\text{LMC}=\text{Cf}*\text{LM} \quad (2.5.29)$$

$$\text{LMN}=\text{STDNE} - \text{LSN} \quad (2.5.30)$$

$$\text{LMNF}=\text{LMN}/\text{LM} \quad (2.5.31)$$

The potential transformation of C in structural litter (LSCTP) on the surface and subsurface is calculated with Eq 2.5.32 as a function of the C content in structural litter (LSC), the rate of potential transformation of structural litter under optimal conditions (LSR), a control of the lignin fraction of structural litter ( $X_{\text{LSLF}}$ , Eq 2.5.33), and a combined factor (CS, Eq 2.5.34) expressing the effects of temperature (TFN, Eq 2.5.18), soil water content (SWF, Eq 2.5.19), oxygen (OX, Eq 2.5.34a), and tillage (TBP, Eq 2.5.34b) on biological processes (Parton et al., 1993; 1994). This combined factor CS is different from the temperature and water controls on decomposition used in the Century model.

$$\text{LSCTP}=\text{LSC}*\text{LSR}*X_{\text{LSLF}}*\text{CS} \quad (2.5.32)$$

$$X_{\text{LSLF}}=\exp(-3*\text{LSLF}) \quad (2.5.33)$$

$$\text{CS}=\sqrt{(\text{TFN}*\text{SWF})*\text{PARM } 70*\text{OX}*TBA}; \quad \text{CS} < 10 \quad (2.5.34)$$

$$\text{OX}=1.0-0.9*Z_5/(Z_5+\exp(16.79-0.0196*Z_5)) \quad (2.5.34\text{a})$$

$$TBP = \exp(6.0 * (BD - BDP)) \quad (2.5.34b)$$

The potential transformation of C in lignin of structural litter (LSLCTP) is computed with Eq 2.5.35 while the potential transformations of C (LSL<sub>N</sub>CTP) and N (LSNTP) in non-lignin components of structural litter are calculated with Eqs 2.5.36 and 2.5.37.

$$LSLCTP = LSCTP * LSLF \quad (2.5.35)$$

$$LSL_NCTP = LSCTP * (1 - LSLF) \quad (2.5.36)$$

$$LSNTP = LSN * (LSCTP / LSC) \quad (2.5.37)$$

The metabolic litter is transformed into microbes (Active) (surface = 0.40; subsurface = 0.45) or CO<sub>2</sub> (surface = 0.60; subsurface = 0.55) under control of a temperature factor multiplied by a moisture factor. The potential rate of transformation of N and C in metabolic litter is (Parton et al., 1994):

$$LMCTP = CS * LMR * LMC \quad (2.5.38)$$

$$LMNTP = LMN * (LMCTP / LMC) \quad (2.5.39)$$

where LMR is the metabolic litter transformation rate under optimal conditions.

Equations for the potential transformations of microbial biomass C and N (Parton et al., 1993) are:

$$BMCTP = BMC * BMR * CS * X_{BMT} \quad (2.5.40)$$

$$BMNTP = BMN * (BMCTP / BMC) \quad (2.5.41)$$

The potential transformation of the slow humus compartment (Parton et al., 1993, 1994; Vitousek et al., 1994) is:

$$HSCTP = HSC * HSR * CS \quad (2.5.42)$$

$$HDNTP = HSN * (HSCTP / HSC) \quad (2.5.43)$$

The transformation of the passive humus compartment in subsurface layers is (Parton et al., 1993, 1994):

$$HPCTP = HPC * HPR * CS \quad (2.5.44)$$

$$HPNTP = HPN * (HPCTP / HPC) \quad (2.5.45)$$

The allocation from biomass to leaching (ABL) follows the treatment of Williams (1995) in EPIC:

$$ABL = BMC * (1.0 - \exp(-QV / (0.01 * ST + 0.1 * KdBM * BD))) \quad (2.5.46)$$



where BMC is the weight of C in soil microbial biomass and associated products in kg ha<sup>-1</sup>, ABL is the amount of C leached in kg ha<sup>-1</sup>, QV is the vertical flow in mm, ST is the volume of water stored in the soil layer in mm, KdBD is the linear adsorption coefficient for biomass, and BD is the soil layer bulk density in t m<sup>-3</sup>.

### Actual C and N Transformations

Actual C and N transformations are calculated based on the N supply available from each potential transformation. The demand for N is established by the potential C transformation of the source compartment and the C/N ratio of the receiving compartment. The N/C ratios of receiving compartments vary with substrate and soil conditions (Parton et al., 1993; Vitousek et al., 1994). For example, the N/C ratio of biomass formed from surface litter (NCBM) is calculated as a linear function of N content (Nf = 100 x STDNE/STD) of the material being decomposed (Parton et al., 1993):

$$\text{NCBM} = 1.0 / (-5.0251 * \text{Nf} + 20.05); \quad 2.0 \geq \text{Nf} \geq 0.01 \quad (2.5.47)$$

$$\text{NCBM} = 0.05; \quad \text{Nf} < 0.01 \quad (2.5.47a)$$

$$\text{CBM} = 0.1; \quad \text{Nf} > 2.0 \quad (2.5.47b)$$

The N/C ratio of the slow humus (NCHS) formed from surface microbes is five units greater than that of surface microbes (Parton et al., 1993). The N/C ratios of biomass, slow humus, and passive humus (NCHP) formed from sub-surface litter are calculated as a function of soil mineral N content (MINT). For the biomass, the N/C ratio is calculated as:

$$\text{NCBM} = 1 / (b * \text{MINT} + a); \quad \text{MINT} \leq 20 \text{ kg ha}^{-1} \quad (2.5.48)$$

$$\text{NCBM} = 0.33; \quad \text{MINT} > 20 \text{ kg ha}^{-1} \quad (2.5.49)$$

The values of coefficients *b* and *a* are -0.6 and 15, respectively. Correspondingly, the values of coefficients for NCHS are -0.4 and 20 while for NCHP these are -0.15 and 10. When MINT > 20 kg ha<sup>-1</sup> the value of NCHS is 0.083 while that of NCHP is 0.143.

The demand for N (PN) is then calculated for all potential transfers (PT) and compared with the supply of N. When N available exceeds the demand in all its receiving compartments, the potential transformation then becomes the actual transformation. Therefore, the calculated N and C flows are added to the receiving compartment and subtracted from the source compartment.

$$\text{PT}_1: \text{Structural litter} \rightarrow \text{Biomass} \quad \text{PN}_1 = \text{LSL}_N \text{CTP} * (1 - \text{ALSL}_N \text{CO}_2) * \text{NCBM} \quad (2.5.50)$$

$$\text{PT}_2: \text{Structural litter} \rightarrow \text{Slow} \quad \text{PN}_2 = \text{LSLCTP} * (1 - \text{ALSLCO}_2) * \text{NCHS} \quad (2.5.51)$$

$$\text{PT}_3: \text{Metabolic litter} \rightarrow \text{Biomass} \quad \text{PN}_3 = \text{LMCTP} * (1 - \text{ALMCO}_2) * \text{NCBM} \quad (2.5.52)$$

$$\text{PT}_4: \text{Biomass} \rightarrow \text{Leaching} \quad \text{PN}_4 = \text{BMCTP} * \text{ABL} * \text{NCBM} \quad (2.5.53)$$

$$\text{PT}_5: \text{Biomass} \rightarrow \text{Passive} \quad \text{PN}_5 = \text{BCTP} * \text{ABP} * \text{NCHP} \quad (2.5.54)$$

$$PT_6: \text{Biomass} \rightarrow \text{Slow} \quad PN_6 = \text{BMCTP} * (1 - \text{ABL} - \text{ABP} - \text{ABCO}_2) * \text{NCHS} \quad (2.5.55)$$

$$PT_7: \text{Slow} \rightarrow \text{Biomass} \quad PN_7 = \text{HSCTP} * (1 - \text{ASCO}_2 - \text{ASP}) * \text{NCBM} \quad (2.5.56)$$

$$PT_8: \text{Slow} \rightarrow \text{Passive} \quad PN_8 = \text{HSCTP} * \text{ASP} * \text{NCHP} \quad (2.5.57)$$

$$PT_9: \text{Passive} \rightarrow \text{Biomass} \quad PN_9 = \text{HPCTP} * (1 - \text{APCO}_2) * \text{NCBM} \quad (2.5.58)$$

$$PT_{10}: \text{Plant Demand} \quad PN_{10} = \text{UNDP} \quad (\text{UND, From Williams, 1995}). \quad (2.5.59)$$

$$\text{Total Demand for Nitrogen (NP}_T) \quad NP_T = \sum PN_i \quad (2.5.60)$$

Nitrogen mineralization (NMIN) or immobilization potential (competitive potential; CPN) is calculated for each of the N transformations (e.g., N from structural litter to biomass, NMIN<sub>1</sub>) as the difference between the potential transformation of N in structural litter (LSNTP) and the potential net demand for that transformation (PN<sub>1</sub> and PN<sub>2</sub>) upon the condition that LSNTP ≥ PN<sub>1</sub>+PN<sub>2</sub> (Eq 2.5.61). Otherwise, the model calculates the amount of N that has to be competed against other transformations (CPN<sub>1</sub>):

$$\text{NMIN}_1 = \text{LSNTP} - (\text{PN}_1 + \text{PN}_2); \quad \text{LSNTP} \geq (\text{PN}_1 + \text{PN}_2) \quad (2.5.61)$$

$$\text{CPN}_1 = \text{PN}_1 + \text{PN}_2 - \text{LSNTP}; \quad \text{LSNTP} < (\text{PN}_1 + \text{PN}_2) \quad (2.5.61a)$$

Similar calculations are made for the N transformations from metabolic litter to biomass (NMIN<sub>2</sub>, CPN<sub>2</sub>), biomass turnover (NMIN<sub>3</sub>, CPN<sub>3</sub>), slow turnover (NMIN<sub>4</sub>, CPN<sub>4</sub>), and passive turnover (NMIN<sub>5</sub>, CPN<sub>5</sub>):

$$\text{NMIN}_2 = \text{LMNTP} - \text{PN}_3; \quad \text{LMNTP} \geq \text{PN}_3 \quad (2.5.62)$$

$$\text{CPN}_2 = \text{PN}_3 - \text{LMNTP}; \quad \text{LMNTP} < \text{PN}_3 \quad (2.5.62a)$$

$$\text{NMIN}_3 = \text{BMNTP} - \text{PN}_4 + \text{PN}_5 + \text{PN}_6; \quad \text{BMNTP} \geq \text{PN}_4 + \text{PN}_5 + \text{PN}_6 \quad (2.5.63)$$

$$\text{CPN}_3 = \text{PN}_4 + \text{PN}_5 + \text{PN}_6 - \text{BMNTP}; \quad \text{BMNTP} < \text{PN}_4 + \text{PN}_5 + \text{PN}_6 \quad (2.5.63a)$$

$$\text{NMIN}_4 = \text{HSNTP} - \text{PN}_7 + \text{PN}_8; \quad \text{HSNTP} \geq \text{PN}_7 + \text{PN}_8 \quad (2.5.64)$$

$$\text{CPN}_4 = \text{PN}_7 + \text{PN}_8 - \text{HSNTP}; \quad \text{HSNTP} < \text{PN}_7 + \text{PN}_8 \quad (2.5.64a)$$

$$\text{NMIN}_5 = \text{HPNTP} - \text{PN}_9; \quad \text{HPNTP} \geq \text{PN}_9 \quad (2.5.65)$$

$$\text{CPN}_5 = \text{PN}_9 - \text{HPNTP}; \quad \text{HPNTP} < \text{PN}_9 \quad (2.5.65a)$$

Gross N mineralization (NMING) is calculated with Eq 2.5.66 as the sum of all partial N transformations (NMIN<sub>i</sub>). The total net competitive demand for N (SUMP) is calculated as the sum of all demands for transformations, including plant uptake (CPN<sub>6</sub> = PN<sub>10</sub>) that could not supply their own N (Eq 2.5.67).

$$\text{NMING} = \sum \text{NMIN}_i \quad (2.5.66)$$

$$\text{SUMP} = \sum \text{CPN}_i \quad (2.5.67)$$

This SUMP is then compared to the mineral N available (MINTMP). If  $SUMP \leq MINTMP$  then each net N demand is met; thus, each potential transformation becomes the actual transformation. When  $SUMP > MINTMP$  the total N demand exceeds the mineral N available; thus, the model calculates a proportional reduction in the net demand and each potential transformation (Eq 2.5.68).

$$CPNi = CPNi/SUMP*MINTMP \quad (2.5.68)$$

The sum of all recalculated CPNi, except plant N uptake (CPN6), is termed N immobilization (NIMMOB) (Eq 2.5.69). Net N mineralization (NMINET) is calculated with Eq 2.5.70.

$$NIMMOB = \sum CPNi \quad (2.5.69)$$

$$NMINET = NMING - NIMMOB \quad (2.5.70)$$

Next, the model calculates the actual C and N transformations based on N availability. If  $CPNi = 0$ , then each potential transformation (e.g., LSCTP) becomes the actual transformation (LSCTA). If  $CPNi > 0$ , the actual transformations are recalculated using Eqs 2.5.71-2.5.83.

$$LSCTA = LSCTP * CPN1 / (PN1 + PN2 - LSNTTP) \quad (2.5.71)$$

$$LSLCTA = LSLCTP * LSCTA / LSCTP \quad (2.5.72)$$

$$LSLNCTA = LSLNCTP * LSCTA / LSCTP \quad (2.5.73)$$

$$LSNTA = LSNTTP * LSCTA / LSCTP \quad (2.5.74)$$

$$LMCTA = LMCTP * CPN2 / (PN3 - LMNTTP) \quad (2.5.75)$$

$$LMNTA = LMNTTP * LMCTA / LMCTP \quad (2.5.76)$$

$$BMCTA = BMCTP * CPN3 / (PN4 + PN5 + PN6 - BMNTTP) \quad (2.5.77)$$

$$BMNTA = BMCTA / BMCTP \quad (2.5.78)$$

$$HSCTA = HSCTP * CPN4 / (PN7 + PN8 - HSNTTP) \quad (2.5.79)$$

$$HSNTA = HSNTTP * HSCTA / HSCTP \quad (2.5.80)$$

$$HPCTA = HPCTP * CPN5 / (PN9 - HPNTTP) \quad (2.5.81)$$

$$HPNTA = HPNTTP * HPCTA / HPCTP \quad (2.5.82)$$

$$UND = CPN6 \quad (2.5.83)$$

Lastly, all compartments are updated with respect to their C and N content based on the actual transformations that took place during the day. The update includes the calculation of the respiration term (RSPC) resulting from the allocation of C from the different compartments to CO<sub>2</sub>. Allocation values for the different compartments are given in the abbreviation section at the end of the paper. The movement of organic C and N due to leaching are also calculated.

## DYNAMICS OF SOIL BULK DENSITY AND LAYER DEPTH

Soil organic matter content has a strong effect on BD. As in EPIC (Izaurre et al., 2004), APEX calculates annual changes in BD due to changes in soil organic C (WOC) content using a modified version of the Adams equation (1973):

$$BD = 100/((WOC*1.724/0.244)+((100 - WOC*1.724)/BDM)); \quad (2.5.84)$$

$$0 \leq WOC < 58$$

$$BD = 0.244; \quad WOC > 58 \quad (2.5.84a)$$

While the BD of soil organic matter is fairly constant (0.244 t m<sup>-3</sup>), the mineral bulk density (BDM) is not and is not usually known. To avoid this problem, APEX estimates BDM at the initiation of the run based on initial values of BD and WOC. Values of BD are then updated annually based on the new calculations of WOC for each layer. Adjustments are also made to the depth of each soil layer to maintain the soil mass constant.

## NITRIFICATION

Nitrification, the conversion of ammonia N to nitrate N is estimated using a combination of the methods of Reddy et al., (1979) and Godwin et al., (1984). The approach is based on the first-order kinetic rate equation of Reddy et al., (1979)

$$RNV = WNH3 * (1.0 - \exp(-AKN - AKV)) \quad (2.5.85)$$

$$AKN = TF * SWF' * PHF \quad (2.5.85a)$$

$$TF = 0.041 * (STMP - 5.0); \quad STMP > 5.0 \quad (2.5.85b)$$

$$WF' = \max(0.1, SWF, (ST - WP) / (ST_{25} - WP)); \quad ST < ST_{25} \quad (2.5.85c)$$

$$SWF' = 1.0; \quad ST_{25} < ST < FC \quad (2.5.85d)$$

$$WF' = \max(0.1, 1.0 - (ST - FC) / (PO - FC)); \quad ST > FC \quad (2.5.85e)$$

$$PHF = 0.307 * PH - 1.269; \quad PH < 7.0 \quad (2.5.85f)$$

$$PHF = 1.0; \quad 7.0 < PH < 7.4 \quad (2.5.85g)$$

$$PHF = 5.367 - 0.599 * PH; \quad PH > 7.4 \quad (2.5.85h)$$

where RNV is the combined nitrification and volatilization kg ha<sup>-1</sup> d<sup>-1</sup>, WNH3 is the weight of NH3 in kg ha<sup>-1</sup>, AKN is the nitrification regulator, and AKV is the volatilization regulator, STMP is the soil temperature in °C, ST is the soil water content, WP is the wilting point soil water content, FC is the field capacity soil water content, ST<sub>25</sub> is the water content at WP+0.25(FC-WP) all in mm, and PH is the soil pH. The value of SWF is obtained from Eq 2.5.19.

## VOLATILIZATION

Volatilization, the loss of ammonia to the atmosphere, is estimated simultaneously with nitrification. Volatilization of surface-applied ammonia is estimated as a function of temperature and wind speed using the equation

$$AKV=TF*WNF; \text{ surface soil layer} \quad (2.5.86)$$

$$WNF=0.335+0.16*\ln(U10+0.2) \quad (2.5.86a)$$

$$AKV=TF*FCEC*FZ; \text{ all other layers} \quad (2.5.87)$$

$$FCEC=1.0-0.038*CEC ; FCEC>0.0 \quad (2.5.87a)$$

$$FZ=1.0-Z_5/(Z_5+\exp(4.55-0.00054*Z_5)) \quad (2.5.87b)$$

where WNF is the wind speed factor for surface application (soil layer 1), U10 is the mean wind speed in  $m s^{-1}$ , CEC is the cation exchange capacity,  $Z_5$  is the depth to the middle of a soil layer in mm. To partition nitrification and volatilization rates appropriately, Eq 2.5.85 is solved for each process separately and combined to give

$$RVOL=RNV*F1/(F1+F2) \quad (2.5.88)$$

$$F1=1.0-\exp(-AKV) \quad (2.5.88a)$$

$$F2=1.0-\exp(-AKN) \quad (2.5.88b)$$

$$RNIT=RNV-RVOL \quad (2.5.88c)$$

where RNIT and RVOL are the nitrification and volatilization rates in  $kg ha^{-1} d^{-1}$ .

## RAINFALL

To estimate the N contribution from rainfall, APEX uses an average rainfall N concentration for a location for all storms. The amount of N in rainfall is estimated as the product of rainfall amount and concentration.

## PHOSPHORUS

### SOLUBLE P LOSS IN SURFACE RUNOFF

The APEX approach is based on the concept of partitioning pesticides into the solution and sediment phases as described by Leonard and Wauchope (Knisel, 1980). Because P is mostly associated with the sediment phase, the soluble P runoff equation can be expressed in the simple form

$$YSP=0.01*CSP*Q/KD \quad (2.5.89)$$

where YSP is the soluble P in kg ha<sup>-1</sup> lost in runoff volume Q in mm, CSP is the concentration of labile P in soil layer 1 in g t<sup>-1</sup>, and KD is the P concentration of the sediment divided by that of the water in m<sup>3</sup> t<sup>-1</sup>. The value of KD used in APEX is 100.

A linear adsorption isotherm relation may be suitable at low soil P concentrations, however, it could likely underestimate solution P at greater soil P concentrations in cases where there is an application of animal waste or fertilizer application in excess of plant uptake requirement. Due to this limitation, the Langmuir isotherm (Olsen and Watanabe, 1957) was added to account for large soil P concentrations.

At equilibrium, the Langmuir isotherm model is described as:

$$C_S = S_{\max} * K_D * C_L / (1 + K_D * C_L) \quad (2.5.90)$$

where C<sub>S</sub> is the mass of labile P sorbed from the dissolved concentration, C<sub>L</sub> is the soluble P concentration in the liquid, and K<sub>D</sub> is a partitioning coefficient, which in APEX is the concentration of the labile P in the solid phase divided by that of the solution phase. The default K<sub>D</sub> value used in APEX is 1. However, this value can be modified for calibrating P in surface runoff and tile flow Soluble P (Steglich and Williams 2013).

$$S_{\max} = 1000 * \text{Clay} / (\text{Clay} + e^{3.519 - 0.027 * \text{Clay}}) \quad (2.5.91)$$

where S<sub>max</sub> is the maximum P sorption capacity of the soil and Clay is the percentage of clay in soil layer 2 and is a user input value dependent of the soil site characteristics. To determine soluble P in solution we rearranged to solve for C<sub>L</sub> given C<sub>S</sub>,

$$C_L = C_S / K_D * (S_{\max} - C_S) \quad (2.5.92)$$

As the C<sub>S</sub> approaches S<sub>max</sub>, the C<sub>L</sub> increases. In the current APEX model, transport of soluble P in runoff is estimated as:

$$QP_L = 0.01 * P_{LAB} * Q / K_D \quad (2.5.93)$$

where Q<sub>PL</sub> is the mass (kg ha<sup>-1</sup>) of soluble P lost in runoff volume, Q (mm) and P<sub>LAB</sub> is the concentration (g t<sup>-1</sup>) of labile P in soil layer 1. The inclusion of the Langmuir isotherm estimates soluble P in runoff (QP<sub>LAN</sub>) as:

$$QP_{LAN} = 0.01 * C_L * Q \quad (2.5.94)$$

The tillage component mixes P within the top layer which is then made available for plant uptake from the root zone soil solution. The current version of APEX simulates P only in this top layer. Routines in APEX were added to reflect labile P in subsurface drainage and are a modification of the LINEAR (Leonard et al., 1987) leaching component. Phosphorus leaching is expressed as a function of time, concentration, and flow rate through a soil layer using the equation

$$SP = SP_0 * e^{(-QT / (0.01 * ST + 0.1 * KD * BD))} \quad (2.5.95)$$

where SP is the change in P in the soil layer in g ha<sup>-1</sup>, SP<sub>0</sub> is the amount of P that remains after the amount of flow (QT) passes through a soil layer, and ST is the initial water storage in mm. The amount of P leached by the amount of water QT is obtained by subtracting SP from SP<sub>0</sub> using the equation

$$P_L = SP_0 \times (1 - e^{(-QT / (0.01 \times ST + 0.1 \times K_D \times BD))}) \quad (2.5.96)$$

where P<sub>L</sub> is the amount of P leached by QT.

## SOLUBLE P LEACHED

The tillage component in APEX mixes P within the top layer which is then made available for plant uptake from the root zone soil solution. Routines in APEX were added to reflect labile P in subsurface drainage and are a modification of the GLEAMS (Leonard et al., 1987) leaching component and the Langmuir Isotherm approach (Rossi et al., 2012).

### GLEAMS Method

Phosphorus leaching is expressed as a function of time, concentration, and flow rate through a soil layer using the equation

$$SP = SP_0 * \exp\left(\frac{-QT}{0.01*ST+0.1*K_D*BD}\right) \quad (2.5.97)$$

where SP<sub>0</sub> is the initial P in the soil layer in g ha<sup>-1</sup>, SP is the amount of P that remains after the amount of flow (QT) passes through a soil layer, ST is the initial water storage in mm, and BD is the bulk density. The amount of P leached by the amount of water QT is obtained by subtracting SP from SP<sub>0</sub> using the equation

$$P_L = SP_0 * \left(1 - \exp\left(\frac{-QT}{0.01*ST+0.1*K_D*BD}\right)\right) \quad (2.5.98)$$

where P<sub>L</sub> is the amount of P leached by QT.

### Langmuir Isotherm Method

At equilibrium, the Langmuir isotherm model is described as:

$$C_S = S_{max} * \frac{K_D * C_L}{(1 + K_D * C_L)} \quad (2.5.99)$$

Where  $C_s$  is the soluble P concentration sorbed in the soil,  $C_L$  is the soluble P concentration in the liquid, and  $K_D$  is a partitioning coefficient, which in APEX is the concentration of the labile P in the solid phase divided by that of the solution phase. The default  $K_D$  value used in APEX is 1 and can be modified.

$$S_{max} = \frac{Clay}{Clay + \exp(3.3519 - 0.027 * Clay)} \quad (2.5.100)$$

where  $S_{max}$  is the maximum P sorption capacity of the soil and Clay is the percentage of clay in soil layer 2. To determine soluble P in solution we rearranged to solve for  $C_L$  given  $C_s$ ,

$$C_L = \frac{C_s}{p96 * (S_{max} - C_s)} \quad (2.5.101)$$

As the  $C_s$  approaches  $S_{max}$ , the  $C_L$  increases. If the non-linear P equation is chosen, it will also be used to calculate P transport.

## P TRANSPORT BY SEDIMENT

Sediment transport of P is simulated with a loading function as described in organic N transport. The P loading function is

$$YP = 0.001 * Y * CP * ER \quad (2.5.102)$$

where YP is the sediment phase P lost in runoff in  $kg\ ha^{-1}$  and CP is the concentration of P in the top soil layer in  $g\ t^{-1}$ .

## MINERALIZATION

The P mineralization model developed by Jones et al., (1984) is a modification of the PAPRAN mineralization model (Seligman and van Keulen, 1981). The model considers two sources of mineralization: the fresh organic P pool, associated with crop residue and microbial biomass, and the stable organic P pool, associated with the soil humus. Mineralization from the fresh organic P pool is estimated for each soil layer with the equation

$$RMP = DECR * FOP \quad (2.5.103)$$

$$DECR = 0.05 * CPRF * CS \quad (2.5.103a)$$

$$CPRF = \exp(-.693 * (CPR - 200.) / 200.) \quad (2.5.103b)$$

$$CPR = 580 * RSD / (FOP + WPML) \quad (2.5.103c)$$



where RMP is the mineralization rate of fresh organic P in  $\text{kg ha}^{-1} \text{d}^{-1}$ , DECR is the decay rate constant for fresh organic P in  $\text{d}^{-1}$ , FOP is the fresh organic P in crop residue in  $\text{kg ha}^{-1}$ , CS is the biological process control factor, RSD is the crop residue in  $\text{t ha}^{-1}$ , and WPML is the labile P content in  $\text{kg ha}^{-1}$ .

Mineralization of organic P associated with humus is estimated using the equation

$$\text{HMP}=\text{CMP}*\text{CS}*\text{WPO} \quad (2.5.104)$$

where HMP is the humus P mineralization rate in  $\text{kg ha}^{-1} \text{d}^{-1}$ , CMP is the humus mineralization rate constant ( $0.0003 \text{d}^{-1}$ ), and WPO is the organic P content in  $\text{kg ha}^{-1}$ . To maintain the P balance at the end of a day, humus mineralization is subtracted from the organic P pool; residue mineralization is subtracted from the FOP pool; 20% of RMP is added to the WPO pool; and 80% of RMP is added to WPML.

## MINERAL P CYCLING

The mineral P model was developed by Jones et al., (1984). Mineral P is transferred among three pools: labile, active mineral, and stable mineral. Fertilizer P is labile (available for plant use) at application but may be quickly transferred to the active mineral pool. Flow between the labile and active mineral pools is governed by the equilibrium equation

$$\text{MPR}=\text{WPML}-\text{WPMA}*\text{PSP}/(1.-\text{PSP}) \quad (2.5.105)$$

where MPR is the mineral P flow rate in  $\text{kg ha}^{-1} \text{d}^{-1}$ , WPMA is the amount in the active mineral P pool in  $\text{kg ha}^{-1}$ , and PSP is the P sorption coefficient defined as the fraction of fertilizer P remaining in the labile pool after the initial rapid phase of P sorption is complete.

The daily amount of P computed with Eq 2.5.105 flows to the active mineral P pool and is, therefore, added to that pool and subtracted from the labile pool. Obviously, the flow reverses when labile P is less than  $\text{WPMA}*\text{PSP}/(1-\text{PSP})$ . Since reverse flow is much slower, Eq 2.5.105 is multiplied by 0.1 when the resulting MPR is negative. The P sorption coefficient is a function of chemical and physical soil properties as described by the following equations (Jones et al., 1984).

In calcareous soils

$$\text{PSP}=0.58-0.0061*\text{CAC} \quad (2.5.106)$$

In noncalcareous, slightly weathered soils

$$\text{PSP}=0.02+0.014*\text{WPML} \quad (2.5.107)$$

In noncalcareous, moderately weathered soils

$$\text{PSP}=0.0054*\text{BSA}+0.116*\text{PH}-0.73 \quad (2.5.108)$$

In noncalcareous, highly weathered soils

$$\text{PSP}=0.46-0.0916*\ln(\text{CLA}) \quad (2.5.109)$$

where PSP is the P sorption coefficient, CAC is the CaCO<sub>3</sub> concentration in g t<sup>-1</sup>, PH is the soil pH, CLA is the soil clay content in %, and BSA is the base saturation by the ammonium acetate (NH<sub>4</sub>Oac) method in %. PSP is constrained within the limits of 0.05 <PSP< 0.75. At equilibrium the stable P pool is assumed to be four times as large as the active mineral P pool. Flow between the P pools is governed by the equation

$$\text{ASPR}=\text{bo}*(4.0*\text{WPMA}-\text{WPMS}) \quad (2.5.110)$$

where ASPR is the flow rate between the active and stable mineral P pools in kg ha<sup>-1</sup> d<sup>-1</sup>, bo is the flow coefficient in d<sup>-1</sup>, and WPMS is the amount of stable mineral P in kg ha<sup>-1</sup>. The daily amount of P computed with Eq 2.5.110 flows into the stable pool and is subtracted from the active pool. Obviously, the flow reverses when WPMS>4\*WPMA. Since reverse flow is much slower, Eq 2.5.110 is multiplied by 0.1 when the resulting ASPR is negative. The flow coefficient, bo, is a function of PSP as expressed by the equations (Jones et al., 1984)

$$\text{bo}=\exp(-1.77*\text{PSP}-7.05) \quad (2.5.110a)$$

for noncalcareous soils, and

$$\text{bo}=0.0076 \quad (2.5.110b)$$

for calcareous soils.

## 2.6 PESTICIDE FATE

GLEAMS (Leonard et al., 1987) technology for simulating pesticide transport by runoff, percolate, soil evaporation, and sediment was added to APEX. Pesticides may be applied at any time and rate to plant foliage or below the soil surface at any depth. When pesticide is applied, there is a loss to the atmosphere. Thus, the amount that reaches the ground or plants is expressed by the equation

$$\text{PAPE}=\text{PAPR}*\text{PAEF} \quad (2.6.1)$$

where PAPE is the effective amount of pesticide applied in g ha<sup>-1</sup>, PAPR is the actual amount applied in g ha<sup>-1</sup>, and PAEF is an application efficiency factor.

To determine how much pesticide reaches the ground, the amount of ground cover provided by plants is estimated with the equation

$$\text{GC}=(1.0-\text{erfc}(1.33*\text{LAI}-2.))/2.0 \quad (2.6.2)$$

where GC is the fraction of the ground that is covered by plants, and LAI is the leaf area index. Therefore, the pesticide application is partitioned between plants and soil surface with the equations

$$FP=GC*PAPE \quad (2.6.3)$$

$$GP=PAPE-FP \quad (2.6.4)$$

where FP is the amount of pesticide that is intercepted by plants in  $g\ ha^{-1}$  and GP is the amount that reaches the ground in  $g\ ha^{-1}$ .

Pesticide that remains on the plant foliage can be washed off by rain storms. It is assumed that the fraction of pesticide that is potentially dislodgeable is washed off the plants once a threshold rainfall amount is exceeded. The model uses a threshold value of 2.5 mm and potential washoff fractions for various pesticides have been estimated (Leonard et al., 1987). The appropriate equations for computing washoff are:

$$WO=WOF*FP; \quad RFV>2.5mm \quad (2.6.5)$$

$$WO=0.0; \quad RFV<2.5mm \quad (2.6.5a)$$

where WO is the amount of pesticide washed off the plants by a rainstorm of RFV mm and WOF is the washoff fraction for the particular pesticide. Washed off pesticide is added to GP and subtracted from FP.

Pesticide on the plants and in the soil is lost from the system based on the decay equations

$$GP=GP_0*\exp(-0.693/HLS) \quad (2.6.6)$$

$$FP=FP_0*\exp(-0.693/HLP) \quad (2.6.7)$$

where  $GP_0$  and GP are the initial and final amounts of pesticide on the ground,  $FP_0$  and FP are the initial and final amounts of pesticide on the plants, HLS is the half life for pesticide in the soil in d, and HLP is the half life of the foliar residue in d. Values of HLP and HLS have been established for various pesticides (Leonard et al., 1987).

Another way that pesticide can be lost is through leaching. The GLEAMS leaching component is used here with slight modification. The change in the amount of pesticide contained in a soil layer is expressed as a function of time, concentration, and amount of flow from the layer using the equation

$$dGP/dt=PSQC*q \quad (2.6.8)$$

where GP is the amount of pesticide in the soil layer at time t, PSQC is the pesticide concentration in the water in  $g\ t^{-1}$ , and q is the water flow rate through the layer in  $mm\ h^{-1}$ . The total amount of pesticide contained in the soil layer is the sum of the adsorbed and mobile phases.

$$GP=10*(PSQC*ST+PSYC*BD*DZ) \quad (2.6.9)$$

where ST is the amount of water stored in the soil layer in mm, PSYC is the concentration of adsorbed pesticide in  $g\ t^{-1}$ , BD is the soil bulk density in  $t\ m^{-3}$  and DZ is the soil layer thickness in mm. The ratio of the concentration of pesticide adsorbed to the concentration of pesticide in the water has been estimated for various pesticides (Leonard et al., 1987) and is expressed by the equation

$$KD=PSYC/PSQC \quad (2.6.10)$$

where KD is the partitioning constant in m<sup>3</sup> t. The value of KD is computed from the equation

$$KD=0.01*KOC*WOC \quad (2.6.11)$$

where KOC is the linear adsorption coefficient for organic carbon and WOC is the organic carbon in the soil layer in %.

Substituting Eq 2.6.11 into Eq 2.6.9 gives

$$GP=10*(PSQC*ST+PSQC*KD*BD*DZ) \quad (2.6.12)$$

Solving Eq 2.6.12 for PSQC gives

$$PSQC=0.1*GP/(ST+KD*BD*DZ) \quad (2.6.13)$$

Substituting PSQC from Eq 2.6.13 into Eq 2.6.8 yields

$$dGP/dt=0.1*GP*q/(ST+KD*BD*DZ) \quad (2.6.14)$$

Rearranging Eq 2.6.14 and integrating gives the equation expressing the amount of pesticide as a function of the amount of water flowing through the zone.

$$GP=GP_0*\exp(-0.1*QT/(ST+KD*BD*DZ)) \quad (2.6.15)$$

where GP<sub>0</sub> is the initial amount of pesticide in the soil layer in g ha<sup>-1</sup>, GP is the amount that remains after the amount of flow (QT in mm) passes through the zone, ST is the initial water storage in mm. To obtain the amount of pesticide leached by the amount of water QT, GP is subtracted from GP<sub>0</sub> using the equation:

$$PSTL=GP_0*(1.0-\exp(-0.01*QT/(ST+KD*BD*DZ))) \quad (2.6.16)$$

where PSTL is the amount of pesticide leached by QT. The average concentration during the percolation of QT is

$$PSTC=PSTL/QT \quad (2.6.17)$$

Since percolation usually starts before runoff the vertical flow concentration is usually higher than that of the horizontal. The relative concentrations may be user specified with the parameter p24.

$$P24=PCH/PCV \quad (2.6.18)$$

where p24 is a parameter ranging from near 0.0 to 1.0 (usually 0.5), PCH is the horizontal concentration, and PCV is the vertical concentration. PSTL is partitioned into vertical and horizontal components using the equation

$$PSTL=PCV*QV+PCH*QH \quad (2.6.19)$$

Substituting Eq 2.6.18 into Eq 2.6.19 and solving for PCV gives

$$PCV = PSTL / (QV + p24 * QH) \quad (2.6.20)$$

$$PCH = p24 * PCV \quad (2.6.20a)$$

Amounts of PSTL contained in runoff, lateral flow, quick return flow, and horizontal pipe flow are estimated as the products of the flow component and PCH. Percolation and vertical pipe flow loads are estimated similarly using PCV.

The total amount of pesticide lost in the runoff is estimated by adding the soluble fraction computed with Eqs 2.6.16-2.6.20 to the amount that is adsorbed to the sediment. Pesticide yield from the adsorbed phase is computed with an enrichment ratio approach. The enrichment ratio equation is

$$PSTY = Y * PSYC * ER \quad (2.6.21)$$

where PSTY is the pesticide yield adsorbed to the sediment in  $g \text{ ha}^{-1}$ , Y is the sediment yield in  $t \text{ ha}^{-1}$ , and ER is the enrichment ratio (concentration of pesticide in the sediment divided by the pesticide concentration in the top 10 mm of soil) computed with Eq 2.5.15. The pesticide concentration in the soil is calculated by substituting Eq 2.6.11 into Eq 2.6.13 and solving for PSYC.

$$PSYC = 0.1 * KD * GP / (ST + KD * BD * DZ) \quad (2.6.22)$$

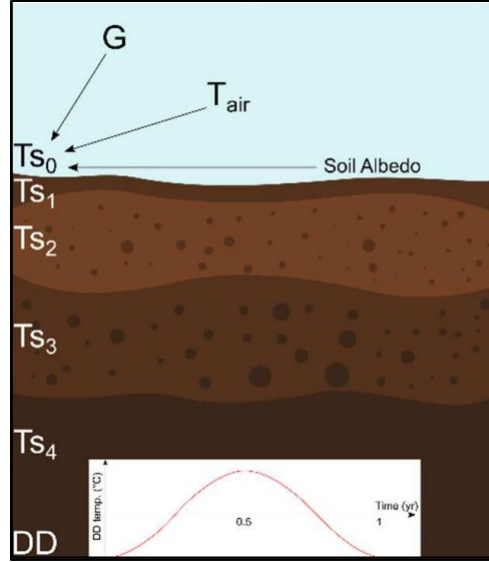
Soil layers with low storage volumes have high leaching potentials not only because percolation is greater, but also because storage volume displacement is greater (higher concentration). Pesticides with low KD values and high solubility are transported rapidly with water. Conversely, high KD value pesticides are adsorbed to soil particles and travel largely with sediment.

## 2.7 SOIL TEMPERATURE

Daily average soil temperature at the center of each soil layer is simulated for use in nutrient cycling and hydrology. In APEX, a cosine function is used to estimate a nonlinear soil temperature profile between the soil surface and the damping depth (Williams et al., 1984; Doro et al., 2021). The basic soil temperature equation is

$$STMP(Z,t) = AVT + \frac{AMP}{2} * EXP(-Z/DD) * COS(2\pi * \frac{t - t_{STMAX}}{365} - \frac{Z}{DD}) \quad (2.7.1)$$

where Z is depth from the soil surface in mm, t is time in day of year, AVT is the average annual air temperature in °C, AMP is the annual amplitude in daily average temperature °C, and DD is the damping depth for the soil in mm.  $t_{STMAX}$  is the average day of year when the average high soil temperature is reached, which equals to 200 (July 19) in the northern hemisphere and 20 (January 20) in the southern hemisphere.



**Figure 2.2: Illustration of the soil profile for soil temperature calculation in APEX. G: solar radiation (MJ m<sup>-2</sup> d<sup>-1</sup>), T<sub>air</sub>: air temperature (°C), T<sub>si</sub>: soil temperature (°C) at the center of each soil layer *I* with Ts<sub>0</sub> being the soil surface temperature, DD: damping depth (m). Adopted from Doro et al. (2021).**

Eq 2.7.1 provides estimates of air temperature ( $Z = 0$ ) as well as soil temperature. Since air temperature is provided by the weather component of APEX, the soil temperature model should be capable of using these air temperatures as drivers. Otherwise, Eq 2.7.1 would predict the same temperatures for a given day each year. To allow simulated air temperature to be used as the soil temperature driver, an equation was developed to estimate soil surface temperature.

$$GTMP(t) = (1 - AB) * \left( \frac{TMX + TMN}{2} \right) * \left( 1 - \frac{RA}{800} \right) + TMX * \frac{RA}{800} + AB * GTMP(t-1) \quad (2.7.2)$$

where GTMP is the soil surface temperature in °C, AB is the surface albedo, TMX is the maximum daily air temperature in °C, TMN is the minimum daily air temperature in °C, and RA is the daily solar adiation in the current soil layer (MJ m<sup>-2</sup> d<sup>-1</sup>). Besides providing a mechanism for using daily simulated air temperature, Eq 2.7.2 also expresses the effect of solar radiation and cover (a function of AB) on soil temperature. The values of GTMP on the day of interest and the four days immediately preceding are averaged for use in adjusting Eq 2.7.2. The adjustment is made by replacing STMP(0,t) with GTMP(t). GTMP(t) is a better estimate of the surface temperature than STMP(0,t) because current weather conditions are considered. Soil temperature at any depth is also corrected by damping the difference between TG and T(0,t) and adding it to the estimate from Eq 2.7.1. Thus, the final equation for estimating soil temperature at any depth is

$$STMP(Z,t) = AVT + \left( \frac{AMP}{2} * \cos\left(2\pi * \frac{t - t_{STMAX}}{365}\right) + GTMP(t) - STMP(0,t) \right) * \exp(-Z/DD) \quad (2.7.3)$$

The damping depth is a function of soil bulk density and water content as expressed in the equation

$$DD=DP*\exp(\ln(0.5/DP)*((1.-WC)/(1.+WC))^2) \quad (2.7.4)$$

$$DP=1.+2.5*ABD/(ABD+\exp(6.53-5.63*ABD)) \quad (2.7.4a)$$

$$WC=0.001*ST/(Z(n)*(0.356-0.144*ABD)) \quad (2.7.4b)$$

where DP is the maximum damping depth for the soil in m, ABD is the average soil bulk density of the profile in  $t\ m^{-3}$ , n is the number of soil layers in the profile, and ST is the water stored in the profile in mm.

## 2.8 CROP GROWTH MODEL

A single model is used in APEX for simulating all the crops considered (about 100). Of course, each crop has unique values for the model parameters. APEX is capable of simulating growth for both annual and perennial crops. Annual crops grow from planting date to harvest date or until the accumulated heat units equal the potential heat units for the crop. Perennial crops maintain their root systems throughout the year, although they may become dormant after frost. They start growing when the average daily air temperature exceeds their base temperature. The model is also capable of simulating mixed plant stands (up to ten crops can grow in the same space and time). The plant competition component was originally developed in the ALMANAC model (Kiniry, et al., 1992). Plants compete for light, water, and nutrients. Phenological development of the crop is based on daily heat unit accumulation.

It is computed by using the equation

$$HU=0.5*(TMX+TMN)-TBSC; \quad HU>0.0 \quad (2.8.1)$$

where HU is the number of heat units accumulated during a day, TMX and TMN are the maximum and minimum temperatures for the day, and TBSC is the crop-specific base temperature all variables in  $^{\circ}C$  (no growth occurs at or below TBSC). A heat unit index (HUI) ranging from 0 at planting to 1.0 at physiological maturity is computed by accumulating daily HU values and dividing by the potential heat units of the crop. Date of harvest, leaf area growth and senescence, optimum plant nutrient concentrations, and partition of dry matter among roots, shoots, and economic yield are affected by HUI.

### POTENTIAL GROWTH

Potential increase in biomass for a day can be estimated with the equation (Monteith, 1977),

$$DDM=0.001*PAR*(RUE-WAVP*X1) \quad (2.8.2)$$

$$PAR=0.5*RA*(1.0-\exp(-0.65*LAI)) \quad (2.8.2a)$$

$$X1=\max(VPD-1.,-.5) \quad (2.8.2b)$$

$$RUE=100.*CO_2/(CO_2+\exp(bc1-bc2*CO_2)) \quad (2.8.2c)$$

where DDM is the potential increase in biomass in  $t\ ha^{-1}\ d^{-1}$ , RUE is the radiation use efficiency factor for converting energy to biomass in  $(kg\ ha^{-1})/(MJ\ m^{-2})$ , PAR is intercepted photosynthetic active radiation in  $MJ\ m^{-2}\ d^{-1}$ , RA is solar radiation in  $MJ\ m^{-2}\ d^{-1}$ , LAI is the leaf area index, VPD is the vapor pressure deficit in kPa, WAVP is a crop parameter relating RUE and VPD,  $CO_2$  is the atmospheric  $CO_2$  level in ppm, bc1 and bc2 are crop parameters determined from two input points on the RUE- $CO_2$  curve (Stockle et al., 1992), the constant 0.5 is used to convert solar radiation to photosynthetically active radiation (Monteith, 1973), and the constant 0.65 is the extinction coefficient. Experimental studies indicate that the extinction coefficient varies with foliage characteristics, sun angle, row spacing, row direction, and latitude (Thornley, 1976). The value used in APEX (0.65) is representative of crops with narrow row spacings (Uchijima et al., 1968). A somewhat smaller value (0.4-0.6) might be appropriate for tropical areas in which average sun angle is higher and for wide row spacings (Begg et al., 1964; Bonhomme et al., 1982; Muchow et al., 1982).

In most crops, leaf area index (LAI) is initially zero or very small. It increases exponentially during early vegetative growth, when the rates of leaf primordia development, leaf tip appearance, and blade expansion are linear functions of heat unit accumulation (Tollenaar et al., 1979; Watts, 1972). In vegetative crops such as sugarcane and some forages, LAI reaches a plateau, at which time the rates of senescence and growth of leaf area are approximately equal. In many crops, LAI decreases after reaching a maximum and approaches zero at physiological maturity. In addition, leaf expansion, final LAI, and leaf duration are reduced by stresses (Acevedo et al., 1971; Eik and Hanway, 1965).

LAI is simulated as a function of heat units, crop stress, and crop development stages. From emergence to the start of leaf decline, LAI is estimated with the equations

$$LAI(i) = LAI_0(i) + dHUF(i) * XLAI(i) * \sqrt{REG(i)} * LAI_0(i) / TLAI \quad (2.8.3)$$

$$HUF(i) = HUI(i) / (HUI(i) + \exp(ah(1,i) - ah(2,i) * HUI(i))) \quad (2.8.3a)$$

where  $LAI_0$  and LAI are the leaf area index values at the beginning and end of the day, XLAI is the maximum leaf area index, TLAI is the total leaf area of all crops growing at the beginning of the day, HUF is the heat unit factor, dHUF is the daily change in HUF, the ah coefficients are crop parameters relating HUF and HUI for crop i, HUI is the heat unit index, and REG is the value of the minimum crop stress factor discussed in more detail below.

From the start of leaf decline to the end of the growing season, LAI is estimated with the equation

$$LAI(i) = LAI_0(i) * ((1.0 - HUI(i)) / (1.0 - HUI_D))^{ad} \quad (2.8.4)$$

where ad is a crop parameter that governs LAI decline rate and  $HUI_D$  is the value of HUI when LAI starts declining.

Crop height is estimated with the relationship

$$CHT(i) = HMX(i) * \sqrt{HUF(i)} \quad (2.8.5)$$

where CHT is the crop height in m and HMX is the maximum height for crop i.



The fraction of total biomass partitioned to the root system normally decreases from 0.3 to 0.5 in the seedling to 0.05 to 0.20 at maturity (Jones, 1985). The model simulates this partitioning by decreasing the fraction linearly from emergence to maturity. The change in root weight through the root zone is simulated as a function of plant water use and root weight in each soil layer. The potential daily change in root weight is computed with the equation

$$RWT(l,i)=RWT(l,i)+DRW*UTO \quad (2.8.6)$$

$$DRW=RW(i)-RW_0(i) \quad (2.8.6a)$$

$$RW(i)=DM(i)*(ar1(i)*(1.-HUI(i))+ar2(i)*HUI(i)) \quad (2.8.6b)$$

$$UTO=UW(l)/AEP(i); \quad DRW>0.0 \quad (2.8.6c)$$

$$UTO=RWT(l,i)/RW_0(i); \quad DRW<0.0 \quad (2.8.6d)$$

where  $RW_0$  and  $RW$  are the total root weight in  $t \text{ ha}^{-1}$  at the beginning and end of the day,  $RWT$  is the root weight by soil layer in  $t \text{ ha}^{-1}$ ,  $DM$  is the total biomass,  $UW$  is the daily water use rate by soil layer in  $\text{mm d}^{-1}$ ,  $AEP$  is the total water use rate in  $\text{mm d}^{-1}$ ,  $ar1$  and  $ar2$  are crop parameters, and subscripts  $I$  and  $l$  refer to the crop and the soil layer.

Rooting depth normally increases rapidly from the seeding depth to a crop-specific maximum. In many crops, the maximum is usually attained well before physiological maturity (Borg and Grimes, 1986). Rooting depth is simulated as a function of heat units and potential root zone depth:

$$RD(i)=\min(2.5*RDMX(i)*HUI(i),RDMX,RZ) \quad (2.8.7)$$

where  $RD$  is the root depth in  $m$ ,  $RDMX$  is the maximum root depth in  $m$  for crop  $I$ , and  $RZ$  is the soil profile depth in  $m$ .

The economic yield of most grain, pulse, and tuber crops is a reproductive organ. Crops have a variety of mechanisms which ensure that their production is neither too great to be supported by the vegetative components nor too small to ensure survival of the species. As a result, harvest index (economic yield/above-ground biomass) is often a relatively stable value across a range of environmental conditions. In APEX, crop yield is estimated by using the harvest index concept:

$$YLD(i)=HI(i)*STL(i) \quad (2.8.8)$$

where  $YLD$  is the amount of the crop removed from the field in  $t \text{ ha}^{-1}$ ,  $HI$  is the harvest index, and  $STL$  is the above-ground biomass in  $t \text{ ha}^{-1}$  for crop  $i$ . For non-stressed conditions harvest index increases nonlinearly from 0 at planting to  $HI$  at maturity according to the equation

$$HI(i)=F*(HIT(i)-HIMN(i))+HIMN(i) \quad (2.8.9)$$

$$F=SWH(i)/(SWH(i)+\exp(5.563-0.03155*SWH(i))) \quad (2.8.9a)$$

$$SWH(i)=\sum(AEP(i)); \quad 0.5<HUI(i)<1.0 \quad (2.8.9b)$$

$$HIT(i)=HIP(i)*X2/(X2+\exp(11.11-0.1*X2)) \quad (2.8.9c)$$

$$X2=100.*HUI(i) \quad (2.8.9d)$$

where HIT is the harvest index as a function of heat unit accumulation, HIMN is the minimum value of harvest index, HIP is the potential value of harvest index, and SWH is the accumulated plant water use in mm between HUI values of 0.5 and 1.0. Thus, potential harvest index may be reduced by a shorter than normal growing season or by water stress. The constants in Eq 2.8.9c are set to allow HIT to increase from 0.1 at HUI=0.5 to 0.95 at HUI=0.95. This is consistent with the economic yield development of grain crops, which produce the greatest economic yield in the second half of the growing season.

## WATER USE

The potential plant water use, EP, is estimated as described in the evapotranspiration section. The potential water use from the soil surface to any root depth is estimated with the function

$$UW(l)=(UX(l)-CU*AEP(i)-(1.-CU)*UX(l-1))*F*RGF \quad (2.8.10)$$

$$UX(l)=EP(i)*(1.-\exp(-5.0*RZ*Z(l)/RD(i)))/(1.-\exp(-5.0*RZ)) \quad (2.8.10a)$$

$$F=\min(1.0,4.0*(ST(l)-WP(l))/(FC(l)-WP(l))) \quad (2.8.10b)$$

where UW is the water use rate in layer l in mm d<sup>-1</sup>, UX is the potential water use rate in mm d<sup>-1</sup> at depth Z (bottom of layer l) in m, AEP is the sum of UW for all layers above layer l, RZ is the root zone depth in m, RD is the root depth for crop I in m, RGF is the root growth factor described later in the root growth constraint section, and CU is the product of all RGF values above depth Z. Eq 2.8.10 allows plants to compensate for water deficiencies in dry layers by using water from other layers for soils with good rooting environments (UC near 1.0). However, compensation is reduced and finally is not allowed as UC approaches 0.0.

## NUTRIENT UPTAKE

### NITROGEN

Soil supply of N is assumed to be limited by mass flow of NO<sub>3</sub>-N to the roots

$$UN(l)=WNO3(l)*UW(l)/ST(l) \quad (2.8.11)$$

where UN is the rate of N supplied by the soil in kg ha<sup>-1</sup> d<sup>-1</sup>, WNO<sub>3</sub> is the amount of NO<sub>3</sub>-N in layer l in kg ha<sup>-1</sup>, ST is the soil water content in mm, and UW is water use rate in mm d<sup>-1</sup>. The mass flow rates obtained in Eq 2.8.11 are constrained by considering N supply and demand using the equations

$$UN'(l)=UN(l)*DMN/SPN; \quad DMN<SPN \quad (2.8.12)$$

$$UN'(l)=UN(l)+DMN-SPN; \quad DMN>SPN \quad (2.8.13)$$

where UN' is the actual plant uptake of N from soil layer l in kg ha<sup>-1</sup>, DMN is the plant N demand for the day, and SPN is the total soil profile supply of N for the day. If demand is less than supply the N uptake estimated with mass flow in Eq 2.8.11 is reduced in Eq 2.8.12 using the ratio DMN/SPN. If the demand is greater than supply Eq 2.8.13 is used to assure that all available N is used. Computations proceed from the surface, layer by layer until SPN has been removed from the root zone and WNO3 is 0.0 for all layers.

The daily crop N demand is the difference between the crop N content and the optimal N content for that day. The demand is estimated with the equation

$$DMN=UNO-UN1 \quad (2.8.14)$$

$$UNO=DM(i)*(bn1+bn2*\exp(-bn3*HUI(i))) \quad (2.8.14a)$$

where DMN is the N demand rate of crop I in kg ha<sup>-1</sup> d<sup>-1</sup>, UN1 is the actual N content of the crop in kg ha<sup>-1</sup>, UNO is the optimal N content for the crop in kg ha<sup>-1</sup>, DM is the accumulated biomass in t ha<sup>-1</sup>, and bn1, bn2, and bn3 are crop parameters expressing optimal N concentration as a function of crop development (HUI). The optimal crop N concentration declines with increasing growth stage (Jones, 1983a).

### N Fixation

Daily N fixation is estimated as a fraction of daily plant N uptake for legumes:

$$WFX'=p7*WFX+(1.-p7)*UNM \quad (2.8.15)$$

$$WFX=FIXR*UNM; \quad ASW3>0.25; \text{ and } FXN>0.0 \quad (2.8.15a)$$

$$WFX=0.0; \quad ASW3<0.25; \text{ or } FXN<0.0 \quad (2.8.15b)$$

$$FIXR=\min(FXW,FXN,1.)*FXP \quad (2.8.15c)$$

$$FXP=\min(FXG,FXS,1.) \quad (2.8.15d)$$

$$FXS=4.0-5.0*HUI(i) \quad (2.8.15e)$$

$$FXG=(HUI(i)-0.1)*5.0 \quad (2.8.15f)$$

$$FXW=1.333*ASW3-0.333 \quad (2.8.15g)$$

$$FXN=1.5-0.005*TNO3/RD(i) \quad (2.8.15h)$$

$$ASW3=\sum(ST(l)-WP(l))/(FC(l)-WP(l)); \quad Z<0.3 \text{ m} \quad (2.8.15i)$$

where WFX' is the final adjusted N fixation rate in kg ha<sup>-1</sup> d<sup>-1</sup>, WFX is the calculated rate considering growth stage (FXP), soil water content (FXW), and soil N content (FXN), UNM is the crop N uptake rate in kg ha<sup>-1</sup> d<sup>-1</sup>, p7 is a weighting factor ranging from 0.0 to 1.0, and TNO3 is the NO<sub>3</sub>-N content in the soil to the depth RD (root depth) in m. The growth stage factor inhibits N fixation in young plants prior to development of functional nodules and in old plants with senescent nodules (Patterson and LaRue, 1983).

The soil water content factor reduces N fixation when the water content at the top 0.3 m is less than 75% of field capacity (Albrecht et al., 1984; Bouniols et al., 1991). The amount of NO<sub>3</sub> in the root zone can affect N fixation (Harper, 1976). This approach reduces N fixation when the NO<sub>3</sub>-N content of the root zone is greater than 100 kg ha<sup>-1</sup> m<sup>-1</sup> and prohibits N fixation at N contents greater than 300 kg ha<sup>-1</sup> m<sup>-1</sup>.

## PHOSPHORUS

Crop use of P is estimated with the supply and demand approach described in the N model.

$$UP(l)=1.5*DMP*LPF*RWT(l,i)/RW(i) \quad (2.8.16)$$

$$LPF=CSP(l)/(CSP(l)+\exp(8.01-0.3604*CSP(l))); \quad 0.0<CSP<30.0 \quad (2.8.16a)$$

$$LPF=1.0; \quad CSP>30.0 \quad (2.8.16b)$$

where UP is the rate of P supplied by the soil in kg ha<sup>-1</sup> d<sup>-1</sup>, DMP is the plant P demand for the day, CSP is the concentration of labile P in soil layer l in g t<sup>-1</sup>, RW is the root weight in layer l in kg ha<sup>-1</sup>, and RWT is the total root weight in kg ha<sup>-1</sup>. The constant 1.5 allows 2/3 of the roots to meet the P demand of the plant if labile P is not limiting. This approach is consistent with studies suggesting that roots of P-deficient plants (or plants whose root systems have been pruned) can absorb P faster than the roots of normal plants (Andrews and Newman, 1970; DeJager, 1979; Jungk and Barber, 1974).

The potential uptake rates obtained in Eq 2.8.16 are constrained by considering P supply and demand using the equations

$$UP'(l)=UP(l); \quad DMP<SPP \quad (2.8.17)$$

$$UP'(l)=UP(l)+DMP-SPP; \quad DMP>SPP \quad (2.8.18)$$

where UP' is the actual plant P uptake rate from soil layer l in kg ha<sup>-1</sup> d<sup>-1</sup>, and SPP is the total soil profile supply of P for the day. If the demand is greater than supply Eq 2.8.18 is used to assure that all available P is used. Computations proceed from the surface, layer by layer until SPP has been removed from the root zone and labile P is 0.0 for all layers.

The daily crop P demand is the difference between the crop P content and the ideal P content for that day. The demand is estimated with the equation

$$DMP=DM(i)*(bp1+bp2*\exp(-bp3*HUI(i)))-UP1 \quad (2.8.19)$$

where DMP is the P demand rate of crop I in kg ha<sup>-1</sup> d<sup>-1</sup>, DM is the accumulated biomass in t ha<sup>-1</sup>, UP1 is the actual P content of the crop, and bp1, bp2, and bp3 are crop parameters expressing optimal P

concentration as a function of crop development (HUI). The labile P concentration factor (LPF) allows optimum uptake rates when CSP is above 20 g t<sup>-1</sup>. This is consistent with critical labile P concentrations for a range of crops and soils (Sharpley et al., 1990). Sharpley et al., (1984, 1985) described methods of estimating CSP from soil test P and other soil characteristics.

Though the above relationships (linear) may be suitable at low soil P concentrations, it could likely underestimate solution P at higher soil P concentrations such as in cases where there is an application of animal waste or fertilizer application in excess of plant uptake requirements. Due to this limitation, the Langmuir isotherm (Olsen and Watanabe, 1957; Rossi et al., 2012) is available to account for large soil P concentrations (Eqs 2.5.99 through 2.5.101).

## **GROWTH CONSTRAINTS**

Potential crop growth and yield are usually not achieved because of constraints imposed by the plant environment. The model estimates stresses caused by water, nutrients, temperature, aeration, and radiation. These stresses range from 0.0 to 1.0 and affect plants in several ways. In APEX, the stresses are considered in estimating constraints on biomass accumulation, root growth, and yield. The biomass constraint is the minimum of the water, nutrient, temperature, and aeration stresses. The root growth constraint is the minimum of soil strength, temperature, and aluminum toxicity. Though topsoil aluminum toxicity can have a direct effect on shoot growth, APEX simulates only its indirect effects through its inhibition of root growth and water use. A description of the stress factors involved in determining each constraint follows.

### **Biomass**

The potential biomass predicted with Eq 2.8.2 is adjusted daily if any of the five plant stress factors is less than 1.0 using the equation

$$DDM' = DDM * REG \tag{2.8.20}$$

where REG is the crop growth regulating factor (the minimum stress factor).

### **Water Stress**

The water stress factor is computed by considering supply and demand in the equation

$$WS(i) = AEP(i) / EP(i) \tag{2.8.21}$$

where WS is the water stress factor for crop I, AEP is the plant water use rate in mm d<sup>-1</sup>, and EP is the potential plant water use rate in mm d<sup>-1</sup>. This is consistent with the concept that drought stresses biomass production in proportion to transpiration reduction (Hanks, 1983).

## Temperature Stress

The plant temperature stress is estimated with the equation

$$TS(i)=\sin(1.5707*RTO); \quad 0.0<RTO<2.0 \quad (2.8.22)$$

$$TS(i)=0.0; \quad RTO<0.0 \text{ or } RTO>2.0 \quad (2.8.22a)$$

$$RTO=(TX-TBSC(i))/(TOPC(i)-TBSC(i)) \quad (2.8.22b)$$

where TS is the plant temperature stress factor, TX is the average daily air temperature in °C, TBSC is the base temperature for crop I, and TOPC is the optimal temperature for crop i. Equation 2.8.22 produces symmetrical plant growth stress about the optimal temperature and it is driven by average daily temperature.

## Nutrient Stress

The N and P stress factors are based on the ratio of simulated plant N and P contents to the optimal values. The stress factors vary non-linearly from 1.0 at optimal N and P contents to 0.0 when N or P is half the optimal level (Jones, 1983a). In the case of N, the scaling equation is

$$SN(i)=SNS(i)/(SNS(i)+\exp(4.065-0.0535*SNS(i))) \quad (2.8.23)$$

$$SNS(i)=200.*(UN1/UNO) \quad (2.8.23a)$$

where SN is the daily N stress factor for crop I, SNS is a scaling factor for N stress, UN1 is the actual N content of the crop in kg ha<sup>-1</sup>, and UNO is the optimal N content for the crop in kg ha<sup>-1</sup> (calculated in Eq 2.8.14).

The P stress factor, SP, is computed with Eq 2.8.23 written in P terms.

## Aeration Stress

When soil water content approaches saturation, plants may suffer from aeration stress. The water content of the top 1 m of soil is considered in estimating the degree of stress:

$$AS(i)=1.0-SAT/(SAT+\exp(2.901-0.0387*SAT)); \quad SAT>0.0 \quad (2.8.24)$$

$$AS(i)=1.0; \quad SAT<0.0 \quad (2.8.24a)$$

$$SAT=100.*(ST_1/PO_1-CAF(i))/(1.0-CAF(i)) \quad (2.8.24b)$$

where AS is the aeration stress factor for crop I, SAT is the saturation factor, ST<sub>1</sub> is the water content minus field capacity of the top 1 m of soil in mm, PO<sub>1</sub> is the porosity minus field capacity of the top 1 m of soil in mm, and CAF is the critical aeration factor for crop I (0.85 for many crops). Finally, the value of REG is determined as the lowest of the stress factors, WS, TS, SN, SP, and AS.

## Root Growth

As described in Eq 2.8.6, root growth is proportional to water use. Water use from a soil layer is estimated as a function of soil depth, water content, and a compensation factor according to Eq 2.8.10. Soil strength, temperature, and aluminum toxicity stress factors are calculated from soil properties. The lowest of these three stress factors constrains root growth by governing the water use compensation factor.

Cold soil temperatures may limit root growth, especially when subsoil layers warm slowly in the spring (Taylor, 1983). The temperature stress for each soil layer is computed using the equation.

$$STS(l,i)=\sqrt{2.0*STMP(l)/(TOPC(i)+TBSC(i))}; \quad STMP>0.0 \quad (2.8.25)$$

$$STS(l,i)=0.0; \quad STMP<0.0 \quad (2.8.25a)$$

where STS is the temperature stress for crop I in soil layer l, STMP is the soil temperature in °C, and TOPC and TBSC are the optimal and base temperatures for crop i.

Numerous studies have shown that root growth is affected by soil strength. Three important strength determinants are bulk density, texture, and water content (Eavis, 1972; Monteith and Banath, 1965; Taylor et al., 1966). All three variables are considered in estimating the APEX soil strength stress factor by using the following equation:

$$SS(l)=BD(l)/(BD(l)+\exp(br1+br2*BD(l))) \quad (2.8.26)$$

$$br2=(\ln(0.01124*BDL)-\ln(8.0*BDU))/(BDL-BDU) \quad (2.8.26a)$$

$$br1=\ln(0.01124*BDL)-br2*BDL \quad (2.8.26b)$$

$$BDL=p2+0.00445*SAN(l) \quad (2.8.26c)$$

$$BDU=p2+0.35+0.005*SAN(l) \quad (2.8.26d)$$

where SS is the soil strength factor in layer l, BD is the soil bulk density in  $t\ m^{-3}$  adjusted for water content, SAN is the sand content of layer l in percent, p2 is the threshold bulk density for root stress for a soil of zero sand content, and br1 and br2 are parameters dependent upon soil texture. The values of br1 and br2 are obtained from a simultaneous solution of Eq 2.8.26 by substituting boundary conditions for stress. At the lower boundary (BDL), essentially no stress occurs—SS = 1.0 (Jones, 1983b). At the upper boundary (BDU) SS = 0.2.

The water-content-adjusted bulk density is estimated with Grossman's equation (Grossman et al., 1985)

$$BD(l)=BD3(l)+(BDD(l)-BD3(l))*RTO \quad (2.8.27)$$

$$RTO=(FC(l)-ST(l))/(FC(l)-S15(l)*(4.083-3.33*BDD(l)^{0.333})) \quad (2.8.27a)$$

where BD is the water-content-adjusted bulk density for soil layer 1, BD3 is the bulk density for 33 kPa water content, BDD is the bulk density of the oven dry soil (all bulk densities are in  $t\ m^{-3}$ ), FC, WP, and ST are the water contents in mm for layer 1 at field capacity, wilting point, and current conditions.

Aluminum (Al) toxicity can limit root growth in some acid soil layers, and Al saturation is a widely used index of its effects (Abruna et al., 1982; Brenes and Pearson, 1973; Pavan et al., 1982). Because crops and cultivars differ in sensitivity to Al toxicity (Foy et al., 1974; Mugwira et al., 1980), APEX expresses Al toxicity as a function of this sensitivity. The Al toxicity stress factor associated with root growth is estimated with the equations

$$ATS(l,i)=(100.-ALS(l))/(100.-AL0(i)) \quad (2.8.28)$$

$$AL0(i)=10.+(ALT(i)-1.0)*20.0 \quad (2.8.28a)$$

where ATS is the Al toxicity stress factor (0-1) for soil layer 1, ALS is the Al saturation in %, AL0 is the maximum ALS value crop I can tolerate without stress in %, and ALT is the Al tolerance index number for crop i. Values of ALT range from 1 to 5 (1 is sensitive; 5 is tolerant) for various crops. Finally, the root growth constraint, RGF, is the lowest of the stress factors SS, ATS, and TS.

### Crop Yield

Crop yield may be reduced through water-stress-induced reductions in the harvest index. Most grain crops are particularly sensitive to water stress from shortly before until shortly after anthesis, when major yield components are determined (Doorenbos and Kassam, 1979). Optimum conditions for growth may reduce harvest index slightly if dry matter accumulation is large and economic yield is limited by sink size. The harvest index is affected by water stress according to the equation

$$YLD(i)=HIA(i)*HE*PSTF(i)*STL(i) \quad (2.8.29)$$

$$HIA(i)=F*(AJHI(i)-WSYF(i))+WSYF(i) \quad (2.8.29a)$$

$$F=SWH(i)/(SWH(i)+\exp(5.563-0.0315*SWH(i))) \quad (2.8.29b)$$

$$AJHI(i)=HI(i)*X2/(X2+\exp(11.11-0.1*X2)) \quad (2.8.29c)$$

$$X2=100.*HUI(i) \quad (2.8.29d)$$

where HIA is the harvest index used to estimate yield of crop I, AJHI is the simulated potential harvest index, WSYF is the minimum harvest index, HI is the optimal harvest index, HE is the machine harvest efficiency, PSTF is the simulated pest factor described in the Pest section, STL is the standing live biomass at harvest, HUI is the heat unit index, and SWH is the simulated water use during the fraction of the growing season that has the greatest influence on harvest index (for many crops the last half of the growing season). The parameters in Eq 2.8.29c are set to give HIA=0.1 when HUI=0.5 and HIA=0.95 when HUI=0.95. Thus, if the growing season is shortened by frost or for other reasons, the potential harvest index HI is not attained. The parameters in Eq 2.8.29b are set to give F=0.05 when SWH=10.0 mm and F=0.90 when SWH=100.0 mm.



## PLANT COMPETITION

In addition to the normal crop growth simulation mode (a single crop either continuous or in rotation with other crops) the model is capable of simulating mixed plant stands (up to ten crops can grow in the same space and time). The plant competition component was originally developed in the ALMANAC model (Kiniry, et al., 1992). Plants compete for light, water, and nutrients. Light competition is a function of the LAIs of the competing plants. Water and nutrient competition are functions of plant demand and root depth and distribution.

## WINTER DORMANCY

The day length growth constraint is used to simulate a winter dormant period for fall planted crops. This constraint is only imposed for areas that have a growing season of fewer than 12 months. A 12-month growing season is defined in the model as having no month with mean minimum temperature of lower than 5 °C. If there is a dormant winter period, it is defined as the time when day length is within 1 h of the location's minimum day length.

If a crop becomes dormant in winter, the heat unit summation is set to zero. This provides for rapid new growth when temperatures increase in the spring. During the dormant period, the plants are not allowed to grow. The standing live biomass and the leaf-area-index are reduced during this period because of frost and short day length.

$$STL'(i)=STL(i)*(1.0-F) \quad (2.8.30)$$

$$LAI'(i)=LAI(i)*(1.0-F) \quad (2.8.30a)$$

$$F=\max(FTM,FHR) \quad (2.8.30b)$$

$$FTM=ATMN/(ATMN+\exp(bf1(i)-bf2(i)*ATMN)); \quad TMN<-1.0 \text{ } ^\circ\text{C} \quad (2.8.30c)$$

$$FTM=0.0; \quad TMN>-1.0 \text{ } ^\circ\text{C} \quad (2.8.30d)$$

$$FHR=1.-HRLT/WDRM; \quad HRLT<WDRM \quad (2.8.30e)$$

$$FHR=0.0; \quad HRLT>WDRM \quad (2.8.30f)$$

where STL and STL' are the standing live biomass at the start and end of the day, LAI and LAI' are the leaf-area-index values at the start and end of the day, FTM is the cold temperature reduction factor, FHR is the day length reduction factor, TMN is the minimum temperature for the day in °C, ATMN is the absolute value TMN, bf1 and bf2 are crop parameters, HRLT is the day length in h calculated in Eq 2.1.16, and WDRM is the minimum day length for the location plus 1.0 in h.

There is also a provision for frost kill of annual plants. Kill occurs if  $FTM*(1.-SNOF)>0.9$ . Where SNOF is a snow cover factor.

## 2.9 TILLAGE

The APEX tillage component was designed to mix nutrients and crop residues within the tillage depth, simulate the change in bulk density, and convert standing residue to flat residue. Other functions of the tillage component include simulating ridge height and surface roughness.

Each tillage operation is assigned a mixing efficiency (0-1). The tillage mixing equation is

$$X(l)=(1.0-EF)*X_0(l)+EF*SMX_0*(Z(l)-Z(l-1))/TLD \quad (2.9.1)$$

where  $X$  is the amount of the material in layer  $l$  after mixing in  $\text{kg ha}^{-1}$ ,  $X_0$  is the amount of the material before mixing  $\text{kg ha}^{-1}$ ,  $EF$  is the mixing efficiency of the tillage operation (0-1),  $TLD$  is the tillage depth in m,  $SMX_0$  is the sum of the material in  $TLD$  before mixing in  $\text{kg ha}^{-1}$ , and  $Z$  is the depth to the bottom of the plow layer in m. In Eq 2.9.1, a fraction of the material ( $1.0-EF$ ) in the tillage depth is not mixed and the remaining material ( $EF$ ) is mixed and distributed uniformly within the tillage depth.

The change in bulk density in the plow layer is simulated for each tillage operation by using the equation

$$BDP(l)=BDP_0(l)-(BDP_0(l)-0.667*BD(l))*EF \quad (2.9.2)$$

where  $BDP$  is the bulk density after tillage,  $BDP_0$  is the bulk density in soil layer  $l$  before tillage, and  $BD$  is the bulk density of the soil when it has completely settled after tillage. Between tillage operations, the soil settles with each rainfall event according to the equations

$$BDP(l)=BDP_0(l)+F*(BD(l)-BDP_0(l)) \quad (2.9.3)$$

$$F=SZ(l)/(SZ(l)+\exp(3.92-0.0226*SZ(l))) \quad (2.9.3a)$$

$$SZ(l)=0.2*XX*(1.0+2.0*SAN(l)/(SAN(l)+\exp(8.597-0.075*SAN(l))))/Z(l)^{0.6} \quad (2.9.3b)$$

where  $SZ$  is a scaling factor for soil layer  $l$ ,  $XX$  is the inflow rate into the layer in  $\text{mm d}^{-1}$  (RFV-Q for the top layer), and  $SAN$  is the percentage of sand in the layer. The exponential parameters of equation 2.9.3a are set to give 10% settling when  $SZ=5.0$  and 95.0 % settling when  $SZ=100.0$ . Thus, near the surface soils with little sand will almost completely settle with 100 mm percolation. Eq 2.9.3b causes fast settling when rainfall is large and soils are sandy and have been tilled recently. Also, settling is much faster near the surface (this allows simulation of 'o)g-term deep chiseling effects). Of course, settling is relatively slow for soils low in sand content, especially in low rainfall areas.

Another important function of the tillage model, converting standing residue to flat residue, is accomplished with the equation

$$STD=STD_0*\exp(-56.9*TLD*EF) \quad (2.9.4)$$

where  $STD_0$  and  $STD$  are the standing residue weights before and after tillage in  $t\ ha^{-1}$  and  $TLD$  is the tillage depth in m.

Other functions of the tillage component include simulating ridge height and interval and surface roughness. These variables are specified for each tillage implement. However, the ridge interval and height are computed after each tillage operation to reflect the combined effects of the current and previous operations. The ridge height is estimated by using the equations

$$RHTT=RHT(k)+(RHT(k-1)-RHT(k))*\exp(-TLD(k)/TLD(k-1)); \quad (2.9.5)$$

$$RHT(k)<RHT(k-1) \quad (2.9.5a)$$

$$RHTT=RHT(k); \quad RHT(k)>RHT(k-1) \quad (2.9.5b)$$

where  $RHTT$  is the ridge height after the tillage operation  $k$  in m,  $RHT$  is the input ridge height for the tillage operation in m. After each tillage operation, the ridge interval is set to the input ridge interval of the operation with the greater  $RHT$ .

The user specifies the date and depth for each tillage operation. The tillage operation is carried out on the specified date if the soil is dry enough. If not, the operation occurs on the next suitable day.

It is also possible to schedule operations by fraction of heat unit accumulations. The heat unit schedule may be user input or automatically developed by APEX. Various combinations of scheduling (by date, heat units input, or automatic heat units) are also permitted.

The harvest index and harvest efficiency provide adequate flexibility to accommodate almost any harvest strategy. The harvest index (HI) is input for each crop and adjusted during each year of simulation as described in the Crop Yield section. Normally, the adjusted HI dictates the fraction of the above ground biomass removed from the crop. Thus, for a grain crop like corn, about 40-50% is removed. However, if corn is cut for silage, the input HI would be about 0.95. An option to override HI allows single crops to be harvested in two different ways. For example, oats could be harvested for grain by using the model adjusted value of  $HI=0.4$  and then the straw could be baled by using the appropriate override value (0.5-0.95). The harvest efficiency (HE) indicates what portion of the harvested material actually leaves the field. For most operations, HE may range between 0.7 to 0.95. However, it can be set as low as 0.0 to simulate the plowing under of cover crops.

## 2.10 PLANT ENVIRONMENT CONTROL

The plant environment control component provides mechanisms for applying irrigation water, fertilizer, lime, and pesticide or for simulating grazing or drainage systems.

### DRAINAGE

Drainage via underground drainage systems is treated as a modification of the natural lateral subsurface flow of the area. Drainage is simulated by indicating the depth of the drainage system and the

time required for the drainage system to reduce plant stress. The drainage time in  $d$  replaces the travel time in Eq 2.2.48 for the layer containing the system.

## IRRIGATION

The APEX user has the option to simulate dryland or irrigated agricultural areas. Sprinkler or furrow irrigation may be simulated and the applications may be scheduled by the user or automatically. As implied, the user scheduled option allows application dates and rates to be inputted. With the automatic option, the model decides when and how much water to apply.

Required inputs for the automatic version include a signal to trigger applications (the three trigger choices include: plant water stress level (0-1), plow layer soil water tension in kPa, or root zone soil water deficit in mm); the maximum volume applied to each crop in mm; the runoff fraction; minimum and maximum single application volumes in mm; and the minimum time interval between applications in  $d$ .

Two modes of application, fixed and variable, are available.

Fixed mode:

1. User schedule—The exact input volumes are applied on specified dates.
2. Automatic option—Maximum single application volumes are applied when triggered.

Variable mode:

1. User schedule—The application volume is the minimum of the specified volume, the maximum single application volume, and the volume required to fill the root zone to field capacity.
2. Automatic option—The application volume is the minimum of the maximum single application volume and the volume required to fill the root zone to field capacity.

Also, irrigation does not occur when the application volume derived from the appropriate mode and option (except for fixed, user-scheduled) is less than the input minimum single application volume.

The application mode (fixed or variable) is fixed for the entire crop rotation. However, the trigger value and criterion (plant water stress level, soil water tension, or root zone water deficit) and the runoff fraction may be changed at any time during the operation schedule. Also, a combination of user and automatic scheduling is permitted.

## FERTILIZATION

Fertilizer application is similar to irrigation—scheduling may be input or automatic and fixed and variable modes are available. Required inputs for the automatic version include a trigger (plant N stress level (0-1)); maximum annual N applied to a crop in kg ha<sup>-1</sup>; and minimum time between applications in d.

Fixed mode:

1. User schedule—The exact fertilizer input mix and rate is applied at specified depths on scheduled dates.
2. Automatic option—A user specified fertilizer mix and rate is applied when triggered.

Variable mode:

1. User schedule—The model estimates annual crop N uptake initially and updates the estimate each year with simulated N uptake rates. When fertilizer is scheduled the application rate is the difference between the average annual N uptake rate and the amount of N present in the root zone.
2. Automatic option—Fertilizer is applied automatically when triggered. The application rate is calculated as the difference between the average annual N uptake rate and the amount of N present in the root zone.

Other features and limitations include the ability to change maximum annual N application for a crop at planting. A combination of user and automatic scheduling is permitted. Automatic applications occur only when N is the active crop growth constraint even though the trigger value is reached. Thus, the annual N and P application rates vary according to the crop's needs, the soil's ability to supply those needs, and the magnitude of the N stress relative to water and temperature stresses.

## LIMING

APEX simulates the use of lime to neutralize toxic levels of Al and/or to raise soil pH to near-optimum levels. Different algorithms are used to estimate lime requirements of “highly weathered” soils (Oxisols, Ultisols, Quartzipsamments, Ultic subgroups of Alfisols, and Dystric suborders of Inceptisols) (Sharpley et al., 1985) and other soils. The highly weathered soils have large amounts of variable-charge clays. Moderate amounts of lime are required to increase their pH to about 5.5 and convert extractable Al to more inactive forms. However, the pH of these soils is highly buffered above pH 5.5, and very large amounts of lime are required to raise the pH to near 7.0. As a result, soils with variable charge clays are usually limed only to reduce Al saturation to acceptable levels.

The Al saturation of each soil layer is estimated with the equation (Jones, 1984)

$$ALS(l)=154.2-1.017*BSA(l)-3.173*WOC(l)-14.23*PH(l); \quad PH<5.6 \quad (2.10.1)$$

$$ALS(l)=0.0; \quad PH>5.6 \quad (2.10.2)$$

where ALS is the Al saturation of soil layer l in % calculated as KCl-extractable Al divided by effective cation exchange capacity (ECEC), BSA is the base saturation calculated from cation exchange capacity (CEC) determined by the NH<sub>4</sub>Oac (pH=7.0) method in %, WOC is the organic carbon content in %, and PH is the soil pH. For highly weathered soils, the lime required to neutralize toxic Al in the plow layer is estimated with the equation

$$RLA=0.1*ALS*ECEC*BD*TLD \quad (2.10.3)$$

where RLA is the lime required to neutralize Al in t ha<sup>-1</sup>, ECEC is the effective cation exchange capacity in cmol(p+) kg<sup>-1</sup>, BD is the soil bulk density in t m<sup>-3</sup>, and TLD is the tillage depth in m.

ECEC is calculated as SMB/ALS (Soil Survey Staff, 1982), where SMB in cmol kg<sup>-1</sup> is the sum of the bases extracted by NH<sub>4</sub>Oac (pH=7.0). The constant 0.1 converts cmol(p+) kg<sup>-1</sup> extractable aluminum to equivalent CaCO<sub>3</sub> in t ha<sup>-1</sup>, assuming 2 cmol(p+) CaCO<sub>3</sub> are required to completely neutralize 1 cmol(p+) extractable Al (Kamprath, 1970). At the end of each year, enough lime is applied to meet the lime requirement. If RLA<1 t ha<sup>-1</sup> no lime is applied. When lime is applied, the plow layer PH is raised to 5.4 and ALS is reduced to 0.0.

For APEX, soil acidification and decreasing base saturation are caused by addition of fertilizer N and symbiotic N fixation by legumes. All fertilizer N is assumed to derive from anhydrous ammonia, urea, ammonium nitrate, or mixtures of these with equivalent acidifying effects. The CaCO<sub>3</sub> equivalent of fertilizer or fixed N is assumed to be 1.8 kg CaCO<sub>3</sub> kg<sup>-1</sup> N (Pesk et al.,1971). This is within the range of variation reported by Pierre et al., (1971) for fertilized corn and by Nyatsanga and Pierre (1973) and Jarvis and Robson (1983) for legumes.

At the end of each year of simulation, the plow layer PH is reduced to reflect the change in base saturation caused by N fertilizer and N fixation. The change in base saturation is computed with the equation

$$DSB=0.036*(FN+WFX)/(BD*TLD*CEC) \quad (2.10.4)$$

where FN is the amount of N fertilizer added during the year in kg ha<sup>-1</sup> and WFX is the amount of N fixation by legumes in kg ha<sup>-1</sup>. The PH value is reduced by using the equation

$$PH=Pho-0.05*DSB \quad (2.10.5)$$

where the constant 0.05 approximates the slope of the relationship between PH and DSB for several soils when the values of BSA are between 60 and 90 (Peech, 1965). For other soils, the lime requirement is the amount of lime needed to raise soil pH to 6.5 according to the equation

$$RLA=0.01*BD*TLD*CEC*DSB \quad (2.10.6)$$

where DSB is the change in base saturation needed to raise soil pH to 6.5. The constant 0.01 converts DSB in % to equivalent CaCO<sub>3</sub> in t ha<sup>-1</sup>, assuming that applied CaCO<sub>3</sub> reacts with equivalent unsaturated CEC. The DSB is estimated with the relation

$$DSB=\min((.5-PH)/0.023;90.0-BSA) \quad (2.10.6a)$$

For soils that are not highly weathered, lime is applied at the end of the year if  $RLA > 2.0 \text{ t ha}^{-1}$ . When lime is applied, PH is changed to 6.5, base saturation is increased by DSB, and ALS is set to 0.

## PESTS

The three pests considered by APEX are insects, weeds, and plant diseases. The effects of insects and diseases are expressed in the APEX pest factor—weed problems are simulated as crop competition described in the crop growth section. Crop yields are estimated at harvest as the product of simulated yield and pest factor. The pest factor ranges from 0.0 to 1.0—1.0 means no pest damage and 0.0 means total crop destruction by pests. The pest factor is simulated daily as a function of temperature, moisture, and ground cover.

$$PSTF = 1.0 - (1. - PST(i)) * Z1 / (Z1 + \exp(2.696 - 0.499 * Z1)); \quad PSTS > 0.0 \quad (2.10.7)$$

$$Z1 = PSTX * PSTS / IPST \quad (2.10.7a)$$

$$PSTF = 1.0; \quad PSTS < 0.0 \quad (2.10.7b)$$

$$PSTD = TMN * (0.01 * (ADRF - p9) + 1.0); \quad TMN > 0.0; \quad CV > p10 \quad (2.10.7c)$$

$$PSTD = TMN; \quad TMN < 0.0 \quad (2.10.7d)$$

where PSTF is the pest factor used to adjust crop yield, PST is the minimum pest factor value for a crop, PSTD is the daily pest index, PSTS is the accumulated daily pest index, IPST is the growing season length in d, PSTX is the pest damage scaling factor, TMN is the minimum temperature for the day in °C, ADRF is the accumulated rainfall in mm for 30 days preceding the daily estimate (PSTD)day I in mm, p9 is the threshold 30-day rainfall amount in mm, CV is the ground cover (live biomass and crop residue) in  $\text{t ha}^{-1}$ , and p10 is the threshold cover value in  $\text{t ha}^{-1}$ .

Thus, the pest index grows rapidly during warm moist periods with adequate ground cover and is reduced by cold temperatures. This general pest index is an attempt to account for major differences in pest problems related to climate variability.

When pesticides are applied, the pest index is reduced using the equation

$$PSTS = PSTS - 1000.0 * PSTE \quad (2.10.8)$$

where PSTE is the pesticide kill fraction ranging from near 0.0 to near 1.0. Thus, if the kill fraction approaches 1.0, the pest index is reduced nearly 1000 units.

## FURROW DIKING

Furrow diking is the practice of building small temporary dikes across furrows to conserve water for crop production. Since they reduce runoff, they may also aid in erosion control. The APEX furrow diking model allows construction of dikes for any ridge spacing and at any interval down the furrows. Dikes may be constructed or destroyed mechanically on any day of the year. If estimated runoff

for a particular event exceeds the dike storage volume, overtopping occurs and all of the estimated runoff is lost. If not, all of the rainfall infiltrates and is available for plant use. When runoff destroys the dikes, the model rebuilds them automatically. The storage volume for dikes is computed using the equations

$$DVOL=FDSF*(A_2*DH+0.5*(A_2+A_3)*(DI-4.*DH)+A_3*D_3)/(RINT*DKIN) \quad (2.10.9)$$

$$DVOL=FDSF*A_2*(DH+.5*(DH/STP-2.0*DH))/(RINT*DKIN) \quad (2.10.10)$$

$$A_2=.5*D_2*(TW_2+BW) \quad (2.10.10a)$$

$$A_3=.5*D_3*(TW_3+BW) \quad (2.10.10b)$$

$$TW=RINT-DH \quad (2.10.10c)$$

$$BW=\max(TW-4.0*DH,0.1*TW) \quad (2.10.10d)$$

$$DI=DKIN-DH \quad (2.10.10e)$$

$$D_2=DH*(1.0-2.0*STP) \quad (2.10.10f)$$

$$D_3=DH-STP*(DI-2.0*DH) \quad (2.10.10g)$$

$$TW_2=BW+D_2*(TW-BW)/DH \quad (2.10.10h)$$

$$TW_3=BW+D_3*(TW-BW)/DH$$

(2.10.10i where YON is the organic)

where DVOL is the dike volume in mm, DH is the dike height in m,  $D_2$  and  $A_2$  are the water depth in m and cross sectional area in  $m^2$  at the toe of the downstream dike,  $D_3$  and  $A_3$  are the water depth in m and the cross sectional area in  $m^2$  at the toe of the upstream dike in m, RINT is the distance between ridge centers in m, TW is the water surface width at depth DH in m,  $TW_2$  and  $TW_3$  are the water surface widths in m at depths  $D_2$  and  $D_3$ , BW is the furrow bottom width in m, DKIN is the distance between dike centers in m, DI is the water surface distance between dikes with maximum storage ( $STP=0.0$ ), STP is the slope of the furrow in  $m\ m^{-1}$ , and FDSF is the safety factor.

Eqs 2.10.9 and 2.10.10 were developed assuming that the furrow ridges and the dikes are trapezoidal with 2:1 side slopes and that the top width of the ridges and dikes is equal to H. There are two possible dike configurations that require slightly different solutions. Normally, the dike interval is relatively short (1.0-3.0 m) and the slope along the furrow is relatively flat (<1.0%). When the dike is full, water extends from the top of the downslope dike up the furrow to a point above the toe of the upslope dike. The volume is calculated by using cross-sectional areas at the toes of the two dikes. This approach resulting in Eq 2.10.9 computes the volume in three parts (between the top and the toe of the downslope dike; between the toes of the two dikes; and between the toe and the waterline on the upslope dike). In the simpler and more unusual dike configuration, the upslope waterline does not extend to the toe of the upslope dike. Only one cross section is involved and the volume is computed into two parts resulting in Eq 2.10.10. Thus, the average dike volume of a field is estimated with equation 2.10.9 or 2.10.10 as dictated by slope and dike height and interval. However, no field is exactly uniform in slope; dike and ridge heights vary, and furrow and dike side slopes may not be 2:1. Therefore, the model



provides a user-controlled dike safety factor (FDSF) to allow for varying conditions across a field. The dike safety factor also provides for conservative or optimistic dike system design.

Rainstorms that do not overtop the dikes cause settling and, thus, reduce storage volume. Settling is estimated with the equation

$$DH = DH_0 * \exp(-0.1 * YW - Y) \quad (2.10.11)$$

where  $DH_0$  and  $DH$  are the dike heights in m before and after settling, and  $Y$  and  $YW$  are the estimated soil loss in  $t\ ha^{-1}$  for the USLE and WECS. Ridge height is also reduced with the settling function contained in Eq 2.10.11. The dikes are rebuilt automatically when  $DH/DH_0 < 0.7$ .

## 2.11 ESTIMATION OF SOIL HYDRAULIC PROPERTIES

Accurate simulation can be performed if measured soil hydraulic properties are available. APEX offers two methods for estimating field capacity and wilting point based on soil physical properties. If soil hydraulics offers methods for estimating soil hydraulic properties.

### THE RAWLS METHOD

Rawls et al. (1982) compiled soil hydraulic conductivity and related soil water data for 1,323 soils with about 5,350 horizons from 32 states of the contiguous United States. From this data, relationships for predicting water retention volumes for soil moisture retention volumes at field capacity (FC, 0.33bar) and wilting point (WP, 15bar) were developed. The linear regression equations for estimating soil water contents are as follows.

$$WP = 0.026 + 0.005 * CL + 0.0158 * OC \quad (2.11.1)$$

$$FC = 0.2576 + 0.002 * SA + 0.0036 * CL + 0.0299 * OC \quad (2.11.2)$$

Where  $SA$  and  $CL$  are the volumetric fractions (%) of sand and clay, and  $OC$  is the mass fraction (%) in the soil.

### THE BEHRMAN-NORFLEET-WILLIAMS (BNW) METHOD

Behrman et al. (2016) proposed the BNW algorithm for plant available water (PAW) which is a critical soil hydraulic property for estimating soil hydrology. Laboratory soil measurements from the United States Department of Agriculture (USDA) National Cooperative Soil Survey (NCSS) Soil Characterization Data (NCSS, 2005) were used to validate the BNW algorithm. The test dataset is composed of 1,852 complete pedons with 10,890 layers.

The BNW method was used to estimate PAW from equations derived to represent an optimum PAW (PAW<sub>o</sub>) and optimum bulk density (BD<sub>o</sub>) based on percent sand (SA), silt (SI), clay (CL), and organic matter (OM). The conventional factor of 1.724 was used to convert OM to organic carbon (van Bemmelen 1890).

$$WP = 0.04285 + 0.0001041 * SI + 0.003958 * CL + 0.00001555 * CL * SI - 0.005606 * \log_{10} OC \quad (2.11.3)$$

$$FC = WP + PAW \quad (2.11.4)$$

$$BD_o = \frac{1.6*SA+1.3*SI+1.1*CL+0.224*1.724*OC}{SA+SI+CL+1.724*OC} \quad (2.11.4a)$$

$$PAW = \frac{BD_o}{BD} * \frac{0.05*SA+0.26*SI+0.08*CL+0.9*1.724*OC}{SA+SI+CL+1.724*OC} \quad (2.11.4b)$$

Where BD is soil bulk density (g cm<sup>-3</sup>) and BD<sub>o</sub> is the optimum bulk density of the soil (g cm<sup>-3</sup>). A bulk density (BD) higher than the maximum for ideal plant growth (BD<sub>o</sub>) indicates compaction and reduced soil porosity and pore connectivity that may restrict root growth and cause poor movement of water and air through the soil.

## 2.12 ECONOMICS

The economic component of APEX is more accurately represented as a crop budget and accounting subsystem. The algorithms keep track of the costs of producing and marketing the crops. Costs (and income) are divided into two groups: those costs which do not vary with yield and those that do. These groups will be addressed in turn. All cost registers are cleared at harvest. All operations after harvest are charged to the next crop in the cropping sequence.

Tillage and (pre-harvest) machine operation costs are assumed to be independent of yield. These operation costs must be calculated outside of APEX and are inputted as one variable into the tillage file. This cost cell contains all costs associated with the single operation or activity (e.g., a chiseling activity includes fuel, labor, depreciation, repair, interest, etc., for both the tractor and the chisel). A budget generator program like the Micro Budget Management System (MBMS) (McGrann et al., 1986) is convenient for making these calculations. This is an updated interaction program developed from the Enterprise Budget Generator (Kletke, 1979). The MBMS is more compatible with APEX in that it has output capabilities to itemize cost by machine operation. This information (when converted to metric units) can be inputted directly into the equipment file in APEX. Farm overhead, land rent, and other fixed costs can be charged to the crop by first creating null operations in the equipment file with machine number and cost information only and then triggering the cost in APEX with a null activity. Government payments can be credited by using negative cost entries in the same way. Costs which are yield and management dependent are entered into APEX in two

regions of the input data. Seed costs, seeding rates, and crop prices are entered in the crop parameter file for each crop code. Seed costs are calculated as the produce of seeding rate and cost per kg. Amendment costs are calculated similarly. The amendments include elemental N and P, irrigation water, and lime. Total cost per hectare is based on the sum of costs for machinery operations, seed, and amendments. Market value per hectare is based on the product of crop yield and net crop price. Net crop price is the market price minus the harvest, hauling, and other processing costs which are yield dependent. The net price must be determined outside APEX.

When valid cost figures are entered into these APEX input cells, the model will return annual cost and returns by crop. APEX budget information is valuable not only for profit analyses but also risk analyses, since the annual distributions of profits and costs can be captured. Risk analyses capability greatly enhances the analytical value of APEX for economic studies.

The greatest value of APEX to economic analyses is not its internal economic accounting, but the stream of physical outputs on daily, monthly, annual, or multi-year periods that can be input into economic models, budget generators, and risk analysis systems. APEX estimates crop yields, movement of nutrients and pesticides, and water and sediment yields. Changes in inputs necessary to respond to changes in management, soil quantity and quality, climate (i.e. global warming), droughts, etc., are also estimated. These outputs become inputs into economic and natural resource models facilitating comprehensive analyses of alternative policies and programs.

# CHAPTER 3

## THE APEX ROUTING COMPONENT

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### 3.1 WATER

APEX offers two options for routing water through channels and flood plains—a daily time step average flow method and a short time interval complete flood routing method. For many purposes where flooding is not a concern the daily time step method may be adequate. However, the complete flood routing provides estimates of actual stream flow and potentially increases accuracy in estimating pollutant transport.

#### DAILY TIME STEP METHOD

If the primary purpose is to simulate long-term water, sediment, nutrient, and pesticide yields from whole farms and small watersheds, the daily time step method should produce realistic estimates and is computationally efficient. The average flow rate for a runoff event can be estimated with the equation

$$q=Q*WSA/(360.*(DUR+TC)) \quad (3.1.1)$$

where  $q$  is the average flow rate for the reach inflow in  $m^3 s^{-1}$ ,  $Q$  is the inflow volume in mm,  $WSA$  is the area of the watershed above the reach in ha,  $DUR$  is the rainfall duration in h, and  $TC$  is the time of concentration of the watershed above the reach in h. The channel capacity is estimated using Mannings equation assuming a trapezoidal shape. The channel side slopes are computed with the equation

$$CSS=0.5*(CTW-CBW)/Z_{CH} \quad (3.1.2)$$

where CSS is the channel side slope in  $m\ m^{-1}$ , CTW is the channel top width in m, CBW is the channel bottom width in m, and  $Z_{CH}$  is the channel depth in m. The channel capacity is computed with the equation

$$q_{cp}=CHXA^{1.667}*\sqrt{(CHS/CHN)}/CHP^{0.667} \quad (3.1.3)$$

$$CHXA=0.5*Z_{CH}*(CBW+CTW) \quad (3.1.3a)$$

$$CHP=CBW+2.0*Z_{CH}*\sqrt{(CSS*CSS+1.0)} \quad (3.1.3b)$$

where  $q_{cp}$  is the channel capacity in  $m^3\ s^{-1}$ , CHXA is the cross sectional area at top bank in  $m^2$ , CHS is the slope in  $m\ m^{-1}$ , CHN is Manning's n value, and CHP is the wetted perimeter in m. If  $q < q_{cp}$  flow is contained in the channel and the flow velocity is calculated using Newton's method for solving nonlinear equations. The solution involves adjusting flow depth to give the correct flow rate (q). Then channel flow velocity is computed by dividing rate by cross sectional area

$$V_{CH}=q/(Z_{CH}'*(CBW+Z_{CH}'*CSS)) \quad (3.1.4)$$

where  $V_{CH}$  is the flow velocity in  $m\ s^{-1}$  for the event flow depth  $Z_{CH}'$  in m. If  $q > q_{cp}$  floodplain flow occurs and the rate is estimated with the equation

$$q_{fp}=q-q_{cp} \quad (3.1.5)$$

where  $q_{fp}$  is the flow rate in the floodplain in  $m^3\ s^{-1}$ . Flow depth is calculated using Manning's equation in the form

$$Z_{FP}=(q_{fp}*FPN/(FPW*\sqrt{(FPS)}))^{0.6} \quad (3.1.6)$$

where  $Z_{FP}$  is flow depth in the floodplain in m, FPN is Manning's n value, FPS is the slope in  $m\ m^{-1}$ , and FPW is the floodplain width in m. Flow velocity is computed by dividing rate by area in the equation

$$V_{FP}=q_{fp}/(Z_{FP}*FPW) \quad (3.1.7)$$

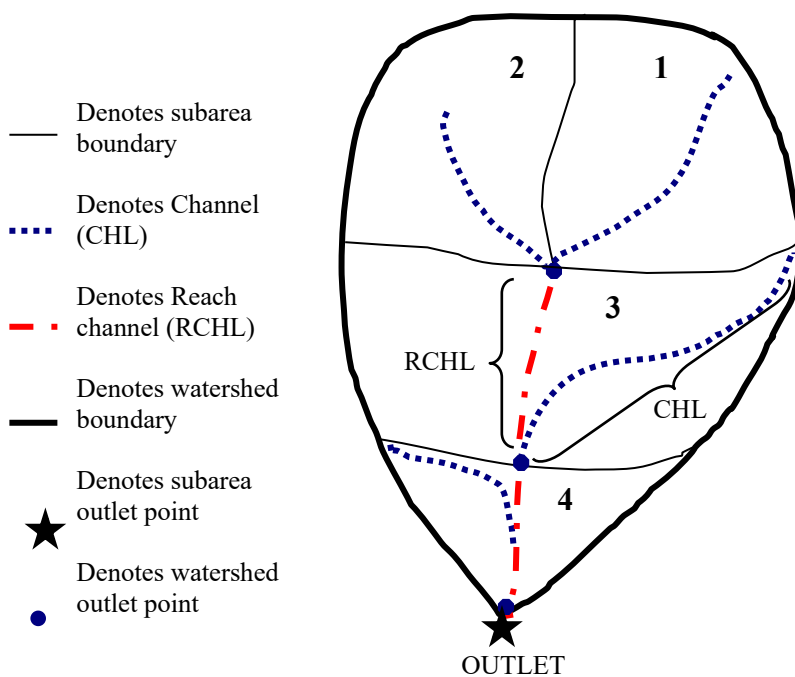
where  $V_{FP}$  and  $Z_{FP}$  are the floodplain flow velocity in  $m\ s^{-1}$  and depth in m. Travel time through the reach floodplain is length divided by velocity

$$TRT=FPL/(3.6*V_{FP}) \quad (3.1.8)$$

where TRT is the reach floodplain travel time in h and FPL is the floodplain length in km. The inflow volume is reduced by floodplain infiltration using the equation

$$q_{fp}'=q_{fp}-SC*TRT \quad (3.1.9)$$

where  $q_{fp}$  and  $q_{fp}'$  are the floodplain inflow and outflow volumes in mm and SC is the saturated conductivity of the floodplain in  $mm\ h^{-1}$ .



**Rules for routing:**

**1. CHL = RCHL**

Identifies an extreme (headwaters) area  
 CHL = distance from subarea outlet to most distant point of subarea  
 RCHL = distance of routing reach flow through the subarea. In the case of an extreme subarea, water is not being routed through the subarea, therefore, no true routing reach has been established at this point. A true routing reach is defined when the water moves from one end of the subarea (point at which water enters the subarea from the upstream subarea) completely through the subarea to the opposite end (outlet) of the subarea.

**2. CHL > RCHL**

Identifies a downstream subarea (only if subarea were a narrow canyon of 0. width would RCHL = CHL)

**3. -WSA**

A negative watershed area (WSA) causes stored information to be added (here, 2 is added to 1 before being routed through 3)

**Figure 3.1 Illustration of a watershed and rules for using the routing mechanism in APEX**

**SUBDAILY TIME STEP METHOD**

**THE VARIABLE STORAGE COEFFICIENT METHOD**

The Variable Storage Coefficient (VSC) flood routing method (Williams, 1975a) provides for simulating hydrographs with short (typically 0.1 to 1.0 h) time steps. Runoff hydrographs from subareas are simulated and routed downstream to the watershed outlet. This complete flood routing approach simulates dynamic stream flow whereas the daily time step method can only estimate daily water yield (daily simulated runoff from all subareas arrives at the watershed outlet at the end of the day). This is an important feature for watersheds with times of flow concentration of 0.5 d or more. It is also important in estimating flood stages and durations and pollutant transport capacities.

**Subarea Hydrographs**

Storm event rainfall-time distributions are derived from daily rainfall using Eqs 2.2.20 and 2.2.21. Rainfall excess is estimated by applying Eq 2.2.20 to the accumulated rainfall distributions in user specified time steps. Runoff hydrographs are simulated with a variation of the VSC method called the

storage depletion technique. The watershed storage volume is computed at each time interval by adding the simulated rainfall excess for that time interval to the existing storage volume.

$$STH = STH_0 + DQ \quad (3.1.10)$$

where  $STH_0$  and  $STH$  are the watershed storage volumes in mm at the beginning and ending of the time interval in h and  $DQ$  is the volume of rainfall excess in mm for the time interval.

During the time interval storage is depleted using a reservoir residence time approach.

$$STH = STH_0 \cdot \exp(-p73 \cdot DTHY / TC) \quad (3.1.11)$$

where  $p73$  is a parameter ( $0.1 < p73 < 1.0$ ),  $DTHY$  is the time interval in h, and  $TC$  is the watershed time of concentration in h. The watershed outflow rate can be computed by combining Eqs 3.1.10 and 3.1.11, subtracting the ending storage from the beginning storage, and converting from volume to rate.

$$Q_{hy} = (STH_0 \cdot (1.0 - \exp(p73 \cdot DTHY / TC)) + DQ) \cdot WSA / (DTHY \cdot 360.) \quad (3.1.12)$$

where  $q_{hy}$  is the watershed outflow rate in  $m^3 s^{-1}$  and  $WSA$  is the watershed area in ha. The storage depletion method produces reliable results comparable to those of the unit hydrograph approach and is much more computationally efficient. Computational efficiency is important in continuous simulation with complete flood routing. Traditionally flood routing is associated with event models.

## Flood Routing

The VSC flood routing method was developed and described previously (Williams, 1975a). As the most important component of the HYMO model (other components interact with or serve the VSC) it has been used worldwide for many years operating in an event mode. The VSC method is a variation of kinematic wave equation, which means that flow is estimated based on the continuity and the normal flow condition. While the normal flow condition is sufficient for flow estimation in most steep channels, other components are included in the momentum equation, such as diffusive forces and convection forces. Thus, the VSC method is enhanced for better prediction of flow by considering the diffusive force generated from the slope of the water surface by Jeong et al. (2014). The first is the continuity equation or conservation of mass.

$$\frac{I_1 + I_2}{2} \cdot \Delta t - \frac{O_1 + O_2}{2} \cdot \Delta t = S_2 - S_1 \quad (3.1.13)$$

where  $I$  is the inflow rate in  $m^3 s^{-1}$ ,  $O$  is the outflow rate in  $m^3 s^{-1}$ ,  $\Delta t$  is time difference between time 1 and time 2 in s,  $S$  is the reach storage in  $m^3$ , and subscripts 1 and 2 refer to the beginning and ending of the time interval. Travel time ( $T$ ) through a routing reach is computed with the equation

$$T = S / O \quad (3.1.14)$$

Substituting Eq 3.1.14 into Eq 3.1.13 yields

$$I_a = \frac{O_1 + O_2}{2} + \frac{T_2 * O_2 - T_1 * O_1}{\Delta t} \quad (3.1.15)$$

where  $I_a$  is the average inflow rate during the time interval. Solving for  $O_2$  gives the equation

$$O_2 = \frac{2 * \Delta t}{2 * T_2 + \Delta t} * I_a + \frac{(2 * T_1 - \Delta t)}{2 * T_2 + \Delta t} * O_1 \quad (3.1.16)$$

Eq 3.1.16 is further simplified by introducing the following non-dimensional coefficients

$$C_1 = \frac{2 * \Delta t}{2 * T_1 + \Delta t} \quad (3.1.17a)$$

$$C_2 = \frac{2 * \Delta t}{2 * T_2 + \Delta t} \quad (3.1.17b)$$

where  $C_1$  and  $C_2$  are dimensionless coefficients. Substituting Eq 3.1.17 into Eq 3.1.16 gives

$$O_2 = C_2 * \left( I_a + \left( \frac{1}{C_1} - 1 \right) * O_1 \right) \quad (3.1.18)$$

To assure volume conservation  $O_1$  can be replaced by storage and  $C_1$  can be eliminated by recognizing that

$$\frac{S}{\Delta t} = \frac{O_1}{C_1} - O_1 \quad (3.1.19)$$

Thus, the final VSC equation is

$$O_2 = C_2 * \left( I_a + \frac{S_1}{\Delta t} \right) \quad (3.1.20)$$

An iterative solution is used to solve Eq 3.1.20 considering variable water surface slope (Williams, 1975). The water surface slope is estimated using the normal flow depths for  $I_2$  and  $O_2$ . Flow velocity is then estimated using the equation

$$V_2 = V_n * \sqrt{\frac{F}{F_0}} \quad (3.1.21)$$

where  $V_n$  is the normal flow velocity,  $F$  is the water surface slope, and  $F_0$  is the channel slope. The water surface slope is estimated with the equation

$$F = F_0 + \frac{Z_I - Z_O}{RCHL} \quad (3.1.22)$$

where  $Z_I$  and  $Z_O$  are the inflow and outflow depths and RCHL is the channel length. The normal flow velocity is estimated with the equation

$$V_n = \frac{I_m + G}{A I_m + A O_m} \quad (3.1.23)$$



where  $G$  is the guess for  $O_2$  and  $A_1$  and  $A_0$  are the flow cross sectional areas at the end of the routing interval. The water surface slope using  $G$  as an approximation for  $O_2$  is estimated by combining Eqs 3.1.21, 3.1.22, and 3.1.23.

$$V_2 = \frac{I_2 + G}{A_{I_2} + A_{O_2}} * \sqrt{1 + \frac{ZI_2 - ZO_2}{RCHL * F_0}} \quad (3.1.24)$$

Travel time  $T_2$  is estimated with the equation

$$T_2 = RCHL / V_2 \quad (3.1.25)$$

$T_2$  is used to obtain a new value of  $O_2$  from Eqs 3.1.24. The process using Eqs 3.1.21 to 3.1.25 is repeated until  $G$  closely approaches  $O_2$ . The half interval method can be used to obtain rapid convergence. The VSC method is more accurate when  $C < 0.85$ . To assure that  $C$  does not exceed  $0.85 \Delta t$  must be  $< 1.5 * T$ .

## THE MUSKINGUM-CUNGE METHOD

The M-C channel routing method is based on same two equations as the traditional Muskingum routing method (Linsley, Kohler, Paulhus, 1982). The first is the continuity equation or conservation of mass (Eq 3.1.13). The second equation is a relationship of storage, inflow, and outflow of the reach.

$$S = K\{X * I + (1 - X) * O\} \quad (3.1.26)$$

Where  $X$  is a dimensionless weighting factor. Combining Eqs 3.1.13 and 3.1.26 and simplifying results (Ponce, 1981):

$$O_2 = C_1 * I_1 + C_2 * I_2 + C_3 * O_1 \quad (3.1.27)$$

where:  $C_1 = (\Delta t / K + 2X) / C_0$   
 $C_2 = (\Delta t / K - 2X) / C_0$   
 $C_3 = (2 * (1 - X) - \Delta t / K) / C_0$   
 $C_0 = \Delta t / K + 2 * (1 - X)$

$C_0, C_1, C_2,$  and  $C_3$  are dimensionless parameters. Cunge (1969) developed equations to estimate  $K$  and  $X$  from hydraulic properties of the reach. The mathematical derivation is condensed and presented by Ponce (1981 and 1989). The equation for  $X$  is:

$$X = \frac{1}{2} \left( 1 - \frac{Q}{B * S_0 * c * \Delta x} \right) \quad (3.1.28)$$

where  $X$  is a non-dimensional weighting factor,  $Q$  is reference discharge in  $m^3 s^{-1}$ ,  $B$  is the bottom width or average width in  $m$ ,  $S_0$  is the channel slope in  $m m^{-1}$ ,  $c$  is the flood wave celerity in  $m s^{-1}$ ,  $\Delta x$  is the distance increment in  $m$ , and  $K = \Delta x / c$ .

Time and distance steps ( $\Delta t$  and  $\Delta x$ ) are of critical importance in channel routing procedures. They are related in the M-C routing procedure (the selection of  $\Delta t$  impacts the selection of  $\Delta x$  and vice versa). This is also true for the solution of the dynamic wave equations. The limit on the value of  $\Delta x$  is recommended by Ponce (1983) as:

$$\Delta x \leq \frac{1}{2} \left( c \cdot \Delta t + \frac{Q}{B \cdot S_o \cdot c} \right) \quad (3.1.29)$$

The time step used in the routing needs to represent the inflow hydrograph shape adequately. The inflow hydrograph is determined from upstream land areas, reaches, reservoirs, etc. Selection of  $\Delta x$  depends on several factors. The reach length is determined by the user when the watershed is divided into subwatersheds. Obviously, smaller subwatersheds lead to shorter reach lengths and larger subwatersheds lead to longer reach lengths. Studies by Ponce documented in the 1981 report showed consistency of the M-C (constant coefficient) method to develop very similar (not exact) outflow hydrographs for various selections of  $\Delta t$  and  $\Delta x$ . This characteristic of the M-C is qualified in that the inflow hydrograph still needs to be defined adequately and that  $\Delta x$  is not significantly smaller than the distance traveled by the flood wave during a single time step. In other words, within a reasonable range of  $\Delta t$  and  $\Delta x$ , the M-C produces consistent results. This is because the M-C method selects  $\Delta x$  based on the desired  $\Delta t$ . Depending on the value of  $\Delta x$ , the reach is divided into an appropriate number of routing steps. If  $\Delta x$  is longer than the routing reach length, the reach is treated as a single step.

The M-C routing as implemented in WinTR-20 (USDA-NRCS, 2009) is described in more detail by Merkel (2002). Younkin and Merkel (1986 and 1988) reported a large number of routing comparisons of the M-C routing and the dynamic wave routing.

## THE STORAGE WITH VARIABLE SLOPE METHOD

The Storage with Variable Slope (SVS) method is a variation of the VSC method. It is also based on the continuity equation, but the SVS method solves Eq 3.1.13 directly with no coefficients. If the continuity equation is written in the form

$$I_1 + I_2 - O_1 - O_2 = 2 * (S_2 - S_1) / \Delta t \quad (3.1.30)$$

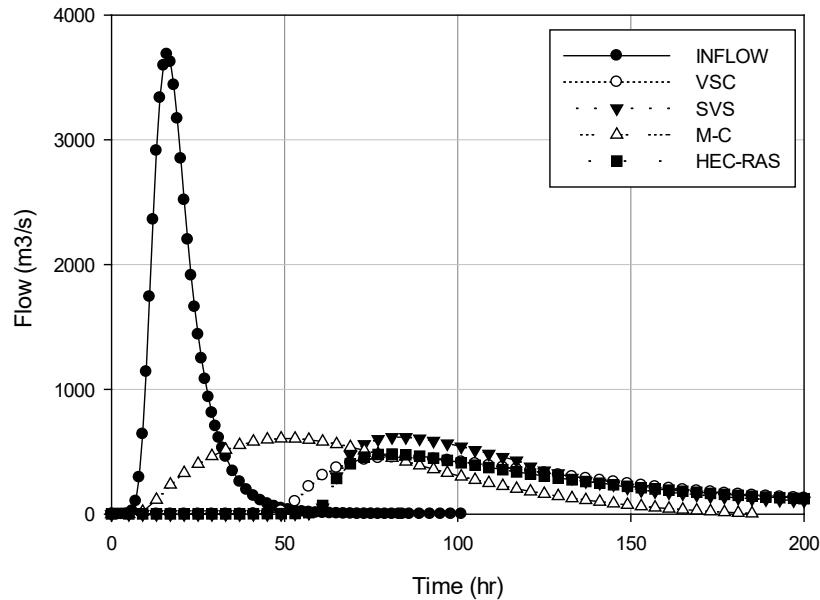
and summed over time the results are

$$O_m + I_1 + 2 * \sum (I_j - O_j) + I_m - 2 * (S_m - S_1) / \Delta t \quad (3.1.31)$$

where m represents the time of the solution and j ranges from 2 to m-1. The storage term in Eq 3.1.31 is computed with the equation

$$S_m = RCHL * (AI_m + AO_m) / 2 \quad (3.1.32)$$

An iterative solution is used to solve Eq 3.1.31 considering variable water surface slope. The water surface slope is estimated using the normal flow depths for  $I_m$  and  $O_m$ . Eqs 3.1.21-3.1.25 are used to solve Eq 3.1.31.



**Figure 3.2 Outflow hydrographs in a 50km channel with the slope of 0.0001 estimated by APEX and HEC-RAS (Jeong et al., 2014)**

## 3.2 SEDIMENT

Sediment is routed through the channel and floodplain separately. The same sediment routing equations are used for daily time step routing and for the VSC method. If daily time step routing is used the velocities and flow rates are the averages for the day and the volume is the total for the day. If the VSC method is used average velocity, flow rate, volume, and sediment transport are calculated for each time interval. Thus, the VSC produces time distributions of sediment concentration and transport (sediment graphs). The sediment routing equation is a variation of Bagnold's sediment transport equation (Bagnold, 1977). The new equation estimates the transport concentration capacity as a function of velocity.

$$CY_U = CY_1 * VCH^{p18} \quad (3.2.1)$$

where  $CY_U$  is the potential sediment concentration in  $t\ m^3$  for the flow velocity  $VCH$ ,  $CY_1$  is the potential sediment concentration for velocity equal  $1.0\ m\ s^{-1}$ , and  $p18$  is a parameter set at 1.5 in Bagnold's equation. The potential change in sediment yield through a routing reach is calculated as the difference between inflow and potential concentration.

$$YU = 10. * QCH * (CY_U - CIN) \quad (3.2.2)$$

where  $YU$  is the potential change in sediment yield in  $t\ ha^{-1}$ ,  $QCH$  is the volume of flow through the channel in  $mm$ , and  $CIN$  is the inflow sediment concentration in  $t\ m^{-3}$ . If  $YU$  is negative deposition occurs in the channel.

$$DEP_{ch} = -YU \quad (3.2.3)$$

where  $DEP_{ch}$  is sediment deposition in the channel in  $t\ ha^{-1}$ . If  $YU$  is positive channel degradation is calculated with the equation

$$DEG_{ch} = YU * EK * CVF \quad (3.2.4)$$

where  $DEG_{ch}$  is the channel degradation in  $t\ ha^{-1}$ ,  $EK$  is the USLE soil erodibility factor, and  $CVF$  is the USLE plant cover factor. Many natural channels have little vegetative cover ( $0.3 < CVF < 0.8$ ) but stable channels are composed of erosion resistant material ( $0.001 < EK < 0.05$ ). Degradation and deposition are computed for the floodplain in a similar manner. Sediment yield at the reach outlet is estimated by summing the changes.

$$YO = YI - DEP_{ch} + DEG_{ch} - DEP_{fp} + DEG_{fp} \quad (3.2.5)$$

where  $YI$  and  $YO$  are the inflow and outflow sediment yields in  $t\ ha^{-1}$  and  $fp$  refers to floodplain processes. As sediment is routed through a reach the particle size distribution also changes. APEX represents sand, silt, and clay with particle sizes of 200, 10, and 2  $\mu m$ . Deposition of particles of a certain size is estimated with the equation (Williams and Hann, 1978)

$$YO(i) = YI(i) * PCT(i) * \exp(-B1 * \sqrt{PSZ(i)}) \quad (3.2.6)$$

where  $PCT$  is the percent of particle size  $PSZ$  in  $\mu m$  in the inflow,  $B1$  is a coefficient, and subscript  $I$  refers to sand, silt, and clay. The coefficient  $B1$  is determined by solving Eq 3.2.6 using the mean particle size (20 $\mu m$ ) of Houston Black Clay (a very fine textured soil).

$$B1 = \ln(YO/YI) / 4.47 \quad (3.2.7)$$

Thus, the outflow particle size can be estimated using Eq 3.2.6 in the form

$$PCTO(i) = PCT(i) * \exp(-B1 * \sqrt{PSZ(i)}) \quad (3.2.8)$$

where  $PCTO$  is the percent of particle size  $I$  in the outflow. To assure continuity  $PCTO$  must be corrected by dividing by the sum of Eq 3.2.8 ( $i=1,3$ ). This simply assures that the sum of  $PCTO$  equals one.

### 3.3 NUTRIENTS

The organic forms of  $N$  and  $P$  are transported by sediment and are routed using an enrichment ratio approach.

$$YNO = 0.001 * CNI * ER * YO \quad (3.3.1)$$

where  $YNO$  is the organic nutrient ( $N$  or  $P$ ) outflow in  $kg\ ha^{-1}$ ,  $CNI$  is the inflow organic nutrient concentration in  $g\ t^{-1}$ , and  $ER$  is the enrichment ratio (organic nutrient content of the inflow divided by

that of the outflow). The enrichment ratio is estimated as the ratio of the mean sediment particle size distribution of the outflow divided by that of the inflow.

$$ER = \text{PSZM}_I / \text{PSZM}_O \quad (3.3.2)$$

where  $\text{PSZM}_I$  and  $\text{PSZM}_O$  are the mean sediment particle sizes of the inflow and the outflow. Mineral forms of N and P are considered conservative and thus maintain a constant concentration as they flow through a reach. Mineral nutrient losses occur only if flow is lost within the reach.

## 3.4 PESTICIDES

The pesticide routing approach is the same as described for nutrients. The adsorbed pesticide phase is transported with sediment using the enrichment ratio (Eqs 3.3.1 and 3.3.2) and the soluble phase is transported with flow in a conservative manner.

# CHAPTER 4

## THE RESERVOIR COMPONENT

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A reservoir may be placed at the outlet of any subarea and inflow is derived from the subarea plus all other contributing subareas. Reservoirs are designed with principal and emergency spillways to accommodate a variety of structures. The reservoir water balance is described in the equation

$$RSV = RSV_0 + QI + RFRA - EV - RSPK - IRR - QO \quad (4.1)$$

where  $RSV_0$  and  $RSV$  are the initial and final reservoir contents in  $m^3$ ,  $QI$  is the inflow rate,  $RFRA$  is the rainfall rate on the pool area,  $EV$  is the evaporation rate,  $RSPK$  is the seepage loss rate,  $IRR$  is the water transferred for irrigation, and  $QO$  is the outflow rate (all rates expressed in  $m^3 d^{-1}$ ). To estimate  $RFRA$ ,  $EV$ , and  $RSPK$ , the surface area of the water pool is calculated using the equation

$$RSSA = bv1 * RSV^{bv2} \quad (4.2)$$

where  $RSSA$  is the reservoir surface area in ha and  $bv1$  and  $bv2$  are coefficients derived from inputs for principal and emergency spillway elevations. Given the surface area at the beginning of the day  $RFRA$ ,  $EV$ , and  $RSPK$  are estimated using the equations

$$RFRA = 10 * RFV * RSSA \quad (4.3)$$

$$EV=10.*CLE*EO*RSSA \quad (4.4)$$

$$RSPK=10.*DT*RSHC*RSSA \quad (4.5)$$

where RFV is rainfall rate in mm d<sup>-1</sup>, CLE is a lake evaporation coefficient (0.6), EO is the potential evapotranspiration in mm d<sup>-1</sup>, DT is the time interval (24 h), and RSHC is the hydraulic conductivity of the reservoir bottom in mm h<sup>-1</sup>. RSPK is added to the soil water in the subarea in which the reservoir is located. The outflow is controlled by the two spillways.

$$QO=RSV-RSV_E; \quad RSV>RSV_E \quad (4.6)$$

$$QO=RR*DT; \quad RSV_P<RSV<RSV_E \quad (4.6a)$$

$$QO=0.0; \quad RSV<RSV_P \quad (4.6b)$$

where RSV<sub>E</sub> and RSV<sub>P</sub> are the reservoir storage volumes in m<sup>3</sup> at the emergency and principal spillway elevations and RR is the flow rate through the principal spillway in m<sup>3</sup> d<sup>-1</sup>.

Sediment content is calculated each day using the mass balance equation

$$RSY=RSY_0+YI-YO-DEP \quad (4.7)$$

where RSY<sub>0</sub> and RSY are the initial and final reservoir sediment contents, YI and YO are the sediment inflow and outflow, and DEP is sediment deposition (all in t). Sediment settles in the reservoir according to the equation

$$CY=(CY_0-CY_N)*\exp(-bv3*DT)+CY_N \quad (4.8)$$

where CY<sub>0</sub> and CY are the reservoir sediment concentrations in t m<sup>-3</sup> at the start and end of a day, CY<sub>N</sub> is the normal concentration after settling, and bv3 is the deposition coefficient. The value of bv3 is determined by considering the time required to return the sediment concentration to normal after a runoff event.

$$Bv3=\ln((CY-CY_N)/(CY_0-CY_N))/TDP \quad (4.9)$$

where TDP is the time required to return to normal concentration in d and (CY-CY<sub>N</sub>)/(CY<sub>0</sub>-CY<sub>N</sub>)=0.01. Deposition is determined from the change in concentration using the equation

$$DEP=RSV*(CY-CY_0) \quad (4.10)$$

Reservoir sediment outflow is computed with the equation

$$YO=CY*QO \quad (4.11)$$

Organic N and P are transported in the reservoir by sediment particles. The organic nutrient content is calculated each day using the equation

$$RSON = RSON_0 + YON_I - YON_O - DPON \quad (4.12)$$

where  $RSON_0$  and  $RSON$  are the initial and final organic N contents in kg,  $YON_I$  and  $YON_O$  are the organic N inflow and outflow rates in  $kg\ d^{-1}$ , and  $DPON$  is the organic N deposition rate in  $kg\ d^{-1}$ . The deposition rate is estimated with the equation

$$DPON = CON * DEP \quad (4.13)$$

where  $CON$  is the concentration of organic N on the sediment in  $kg\ t^{-1}$ . The ratio of organic N content to sediment content determines  $CON$ .

$$CON = (RSON_0 + YON_I) / (RSY_0 + YI) \quad (4.14)$$

The organic N outflow rate is computed as in Eq 4.13

$$YON_O = CON * YO \quad (4.15)$$

Similar calculations are performed on organic P.

Soluble N and P are considered conservative and the daily content is calculated with the mass balance equation

$$RSSN = RSSN_0 + QNI - QNO \quad (4.16)$$

where  $RSSN_0$  and  $RSSN$  are the initial and final soluble N contents in kg and  $QNI$  and  $QNO$  are the soluble N inflow and outflow rates in  $kg\ d^{-1}$ . The outflow rate is the product of flow and concentration.

$$QNO = CSN * QO \quad (4.17)$$

where  $CSN$  the soluble N concentration in the reservoir in  $kg\ m^3$  is estimated assuming complete mixing.

$$CSN = (RSSN + QNI) / RSV \quad (4.18)$$

Similar calculations are performed for soluble P.



# CHAPTER 5

## THE GROUNDWATER COMPONENT

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The groundwater mass balance equation is

$$GWST = GWST_0 + QV + SEP - DPRK - RSSF \quad (5.1)$$

where  $GWST_0$  and  $GWST$  are the groundwater volumes at the start and end of the day in mm,  $QV$  is the rootzone percolation rate in  $\text{mm d}^{-1}$ ,  $SEP$  is the reservoir seepage rate in  $\text{mm d}^{-1}$ ,  $DPRK$  is the percolation rate from the groundwater storage in  $\text{mm d}^{-1}$ , and  $RSSF$  is the return flow rate in  $\text{mm d}^{-1}$ . The  $DPRK$  and  $RSSF$  losses are estimated using the groundwater storage residence time and a partitioning coefficient.

$$DPRK + RSSF = GWST * (1.0 - \exp(-1.0/RFTT)) \quad (5.2)$$

where  $RFTT$  is the groundwater storage residence time in d. Partitioning of  $DPRK$  and  $RSSF$  is accomplished with the equation

$$RSSF = RFPK * (DPRK + RSSF) \quad (5.3)$$

where  $RFPK$  is the partitioning coefficient. Substituting Eq 5.2 into Eq 5.3 gives

$$RSSF = RFPK * GWST * (1.0 - \exp(-1.0/RFTT)); \quad GWST > GWSTH \quad (5.4)$$

$$RSSF = 0.0; \quad GWST < GWSTH \quad (5.4a)$$

where GWSTH is the threshold storage in mm. Although return flow stops when storage is below threshold, deep percolation continues.

Soluble N is considered conservative and the daily content is calculated with the mass balance equation

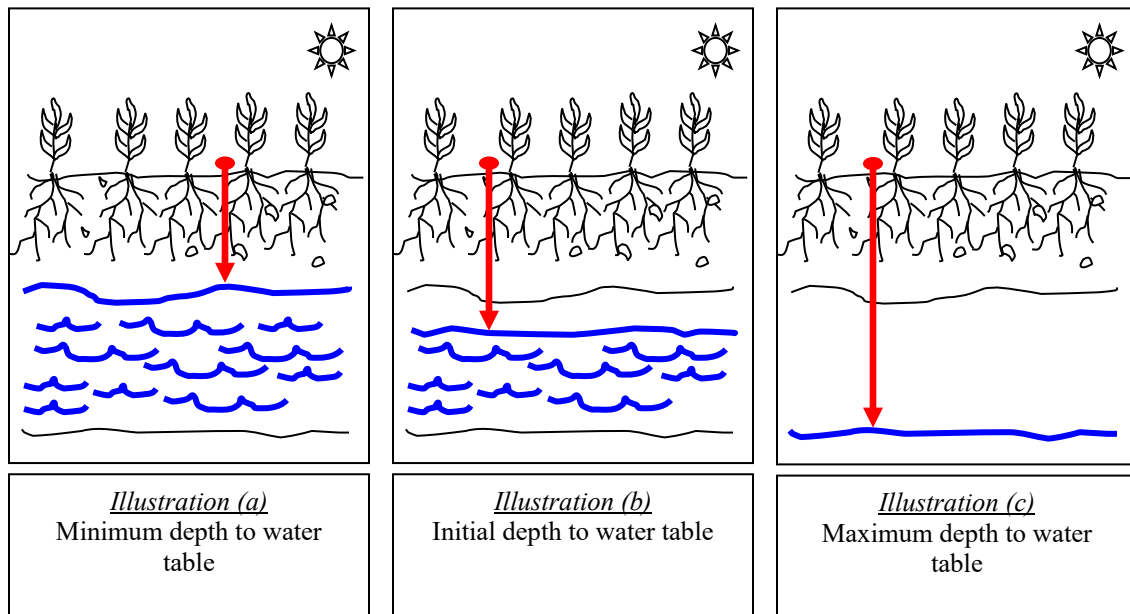
$$GWSN = GWSN_0 + RZLN - RSFN - GWLN \tag{5.5}$$

where  $GWSN_0$  and  $GWSN$  are the initial and final soluble N contents in  $kg\ ha^{-1}$ ,  $RZLN$  is the root zone N leaching rate in  $kg\ ha^{-1}\ d^{-1}$ ,  $RSFN$  is the return flow N rate in  $kg\ ha^{-1}\ d^{-1}$ , and  $GWLN$  is the groundwater N leaching rate in  $kg\ ha^{-1}\ d^{-1}$ . The return flow and leaching N rates are the products of flow rates and groundwater N concentration.

$$RSFN = CGWN * RSSF \tag{5.6}$$

$$GWLN = CGWN * DPRK \tag{5.7}$$

where  $CGWN$  is the concentration of N in the groundwater in  $kg\ mm^{-1}$ .



**Figure 5.1: Illustrations of depth to water table.**

# CHAPTER 6

## THE GRAZING COMPONENT

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All subareas are identified by an ownership number and each owner may have livestock and poultry. The owner may have up to ten herds or groups of animals. The identifying attributes of each herd are forage intake rate in  $\text{kg head}^{-1} \text{d}^{-1}$ , grazing efficiency (accounts for waste by trampling, etc.), manure production rate in  $\text{kg head}^{-1} \text{d}^{-1}$ , urine production in  $\text{l head}^{-1} \text{d}^{-1}$ , and C and soluble and organic N and P fractions in the manure. Thus, for example the owner could have poultry houses on one subarea, a dairy herd that is confined to a feeding subarea, a beef cow-calf herd that is allowed to graze several subareas, a stocker steer herd that is allowed to graze several subareas (some may be the same as those grazed by the cow-calf herd), and a replacement heifer herd that is allowed to graze several subareas. The owner could also own another ranch within the watershed but located several km away. Animals may or may not be moved from ranch to ranch. Only one herd may occupy a subarea at any time. All rotations among subareas are performed automatically by APEX within user constraints. There is a provision for leading and trailing rotations. For example the stocker steers could be rotated ahead of the cow-calf herd so that they always get the best quality forage. The complex grazing systems are created by indicating number of head in each herd, the herd identification numbers (in order of grazing priority) eligible to graze each subarea, and a lower grazing limit (above ground biomass in  $\text{t ha}^{-1}$ ) for each herd on each subarea. The animals may be confined to a feeding area totally or for a fraction of each day. If there is no confined area or if animals are confined only a fraction of each day, one or more of the owner's subareas must be designated as grazing areas for that particular herd. Grazing may occur throughout the year or may be

allowed only at certain times. Any subarea is eligible for grazing if it is a designated grazing area and if grazing has been initiated in the subareas operation schedule. Grazing may be stopped for any subarea by using a stop graze in the operation schedule. Grazing corn stubble after harvest is a good example of initiating and stopping grazing. Grazing stops automatically when the subarea lower limit is reached. If the owner has other eligible grazing areas the animals move automatically to the one with the most above ground biomass. If the owner has no more eligible grazing areas the animals remain on the overgrazed area and supplemental feeding is assumed. This rotational grazing process continues throughout the simulation. The grazing system provides flexibility for confined or partially confined area feeding, intensive rotational grazing, cropland grazing after harvest, etc.

# CHAPTER 7

# MANURE MANAGEMENT

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Manure may be applied as solid or liquid. Confined feeding areas may contain a lagoon to catch runoff from the feeding area plus wash water that is used in the barn. The lagoon is designed automatically by the model considering normal and maximum volumes. The storage between normal and maximum is set to contain the runoff from a design storm plus thirty days of wash water. The design storm is equal twice the largest value of average monthly rainfall and runoff is estimated assuming a NRCS runoff curve number of 90. The normal volume is a user supplied fraction of the maximum volume. Effluent from the lagoon is applied automatically to a field designated for liquid manure application. The liquid manure application rules are: (1) pumping begins when the lagoon volume exceeds 0.75 of the difference between maximum and normal lagoon volumes; (2) the pumping rate is set to reduce the lagoon volume from maximum to normal in a user supplied number of days; (3) pumping can also be triggered by a user supplied date—usually before winter or a high rainfall season. Solid manure is scraped from the feeding area automatically at a user input interval in days and stockpiled for automatic application to designated fields. An owner may have any number of solid manure application fields. When an application is triggered (the stockpile is adequate to supply the specified rate), manure is applied to the field with the lowest soluble P concentration in the top 50 mm of soil. Besides simulating manure management for the confined feeding area system the model provides for application of manure from outside sources. These applications may be scheduled on certain dates or automatically at regular intervals. Automatically scheduled applications may be fixed rates (N rate, P rate, or any other rate) or

they may vary with the soil soluble P content. N and P rates refer to the amounts of N or P removed from the field in plant harvest. In the variable application mode the model samples the soil at the beginning of each year and adjusts rates using rules with input thresholds. An example set of rules are: Soluble P concentration in the top 50 mm of soil < 60 ppm—application rate = 2.\*P rate; soluble P < 120ppm —rate = 1.5\*P rate; soluble P < 200 ppm—rate = P rate; soluble P > 200 ppm—rate = 0. Manure is also supplied to fields by grazing animals. The manure management model is flexible enough to simulate a variety of systems from confined feeding (with or without lagoons) to grazing animals plus manure from outside sources. A variety of livestock including cattle, swine, and poultry may be considered because manure production in kg head<sup>-1</sup> d<sup>-1</sup> and its ingredients (mineral and organic N and P) are inputs. APEX simulates runoff, soil erosion, and manure erosion. Routing mechanisms simulate soluble nutrient transport with water, organic nutrient transport by sediment, and manure transport by water.

# CHAPTER 8

## THE RICE PADDY COMPONENT

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Processes occurring in rice paddy fields including assessing the impact of paddy management practices on rice growth, water balance, and water quality are available for simulation at the subarea level (Choi et al., 2017). Therefore, the subarea module in APEX was recently enhanced to accommodate water ponding conditions with diking and outlet controls. The schematic of the APEX processes with the paddy module is illustrated in Figure 8.1.

When a subarea is set to simulate paddy rice management, APEX switches from the SCS-CN method to a weir discharge function to release edge-of-field discharge. Sediment yield is estimated based on the settling rate after puddling and then residual sediment concentration in the ponding water. Daily AET may exceed PET during the summer season after rice establishes full canopy. Infiltration of ponding water occurs continuously based on the saturated hydraulic conductivity of the top soil layer. During off-seasons or when paddy field management does not implement water ponding, APEX-Paddy switches back to default subarea modules to simulate upland non-ponding land processes such as the SCS-CN method for runoff estimation. A puddling operation results in a rapid resuspension of sediment and nutrient thus making sediment and nutrient concentration high in the ponding water before the suspended solids resettle.

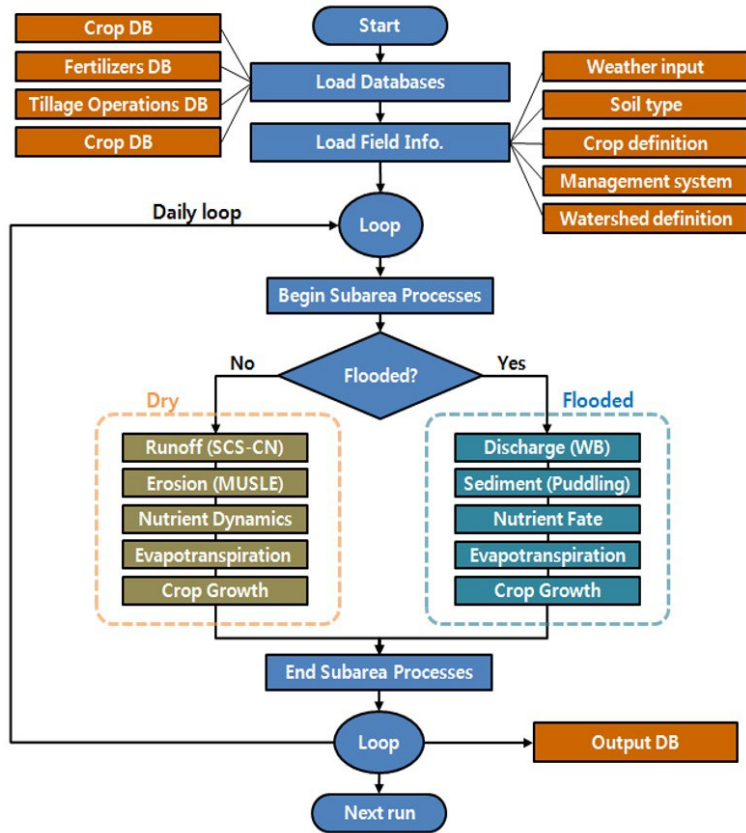


Figure 8.1: Schematic diagram of the Rice Paddy algorithm (adopted from Choi et al., 2017).

## 8.1 EVAPOTRANSPIRATION

APEX offers two options for routing water through channels and flood plains—a daily time step average flow method and a short time interval complete flood routing method. For many purposes where flooding is not a concern the daily time step method may be adequate. However, the complete flood routing provides estimates of actual stream flow and potentially increases accuracy in estimating pollutant transport.

When a rice paddy is flooded with standing water during growing seasons, the amount of daily evapotranspiration is calculated as the sum of water evaporation and crop transpiration using Sakaguchi's equations (2014):

$$EVAP = V_{evap} + EP \quad (8.1.1)$$

$$V_{evap} = \eta \left( 1 - \frac{LAI}{LAI_{evap}} \right) E_0 \quad LAI \leq LAI_{evap} \quad (8.1.1a)$$

$$V_{evap} = 0 \quad LAI > LAI_{evap} \quad (8.1.1b)$$



where,  $V_{evap}$  is daily evaporation (mm),  $EVAP$  is daily evapotranspiration (mm),  $LAI$  is leaf area index, and  $LAI_{evap}$  is leaf area index during the non-occurrence of evaporation from water surface.  $H$  refers to the coefficient of evaporation from the water surface. The default coefficient value was set as 0.6 and  $LAI_{evap}$  was set as 4.0, based on the work of Miyazaki et al. (2005), which was modified by Sakaguchi et al. (2014).

## 8.2 PUDDLING SIMULATION

Puddling is a tillage operation with shallow ponding water and thus soil is saturated in a paddy field. The top soil layer in the paddy becomes soft and suitable for transplanting rice seedlings after the puddling. Puddling is performed prior to transplanting as part of field preparation, to break clods and to flatten the rice paddy for transplantation. Somura et al. (2009) reported that discharge of pollutants (e.g. sediment, nitrogen, and phosphorous) can increase significantly during or shortly after a puddling practice. APEX simulates sediment resuspension process after a puddling operation. Sediment concentration in the ponding water and settling process are calculated using a modified Stokes equation and residual concentration of sediment (Neitsch et al., 2011)

$$C_{sed,f} = (C_{sed,i} - C_{sed,rsd}) \times e^{(-0.184 \cdot t \cdot d_{50})} + C_{sed,rsd} \quad (8.1.2)$$

$$d_{50} = e^{(0.41 \cdot F_{clay} + 0.27 \cdot F_{silt} + 0.57 \cdot F_{sand})} \quad (8.1.3)$$

where,  $C_{sed,f}$  is final soil concentration in the water body (mg/L),  $C_{sed,i}$  is soil concentration in the water body during day one of puddling (mg/L),  $t$  is time of occurrence (day), and  $C_{sed,rsd}$  is concentration of remaining soil in water body (mg/L).  $d_{50}$  refers to the diameter of the soil particles ( $\mu\text{m}$ ), and  $F_{clay}$ ,  $F_{silt}$ ,  $F_{sand}$ , refer to the ratios of clay, silt, and sand grain sizes, respectively, in the surface soil.

## 8.3 TRANSPLANTING SIMULATION

While other upland crops are directly seeded on cultivated land, paddy rice is seeded in seedbeds and grows for 25–30 days in a nursery before the seedlings are transplanted into a puddled field. The rice transplanting promotes higher yields and less weeding. The transplanting operation simulates the start of the crop growth with non-zero LAI, biomass amount, and controlled plant population, which otherwise are forced to start from zero after a seed-planting operation. The Leaf Area Index (LAI), during the emergence and falling of leaves, was calculated using the following equation after Williams et al. (1984):

$$LAI_i = LAI_{0,i} + \Delta HUF_i \cdot XLAI_i \cdot \sqrt{REG_i} \cdot \frac{LAI_{0,i}}{TLAI} \quad (8.1.4)$$

$$HUF_i = \frac{HUI_i}{HUI_i + e^{\alpha - \beta \cdot HUI_i}} \quad (8.1.5)$$

where,  $LAI_{0,i}$  and  $LAI_i$  are the daily initial LAI, and final LAI, of a crop ( $i$ ), respectively,  $XLAI_i$  is the maximum LAI,  $TLAI$  is the total LAI during a growth period,  $REG_i$  is the stress factor of the crop, and  $\Delta HUF_i$  is the daily amount of change of the heat unit. In Eq 8.1.5,  $HUI_i$  refers to the heat unit index of the

crop,  $HUF_i$  refers to the heat unit factor of the crop, and  $\alpha$  and  $\beta$  refer to coefficients related to the growth characteristics of the crop.

APEX's crop growth module does not simulate tillering for rice. In crops such as rice, wheat and sugarcane which produce higher numbers of yielding tillers compared to the number of seeds or shoots planted, the plant population must be estimated based on the number of tillers producing the final yield.

# APPENDIX A

## NOTATIONS

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a1	Coefficient in wind speed equation.
A2	Exponent in wind speed equation.
A <sub>2</sub>	Cross sectional area in m <sup>2</sup> at the toe of the downstream dike.
A <sub>3</sub>	Cross sectional area in m <sup>2</sup> at the toe of the upstream dike.
AB	Soil albedo.
ABCO <sub>2</sub>	Allocation from biomass to CO <sub>2</sub> ; 0.6 (surface layer), 0.85-0.068*(CLA+SIL)(all other layers)
ABD	Average soil bulk density of the profile in t m <sup>-3</sup> .
ABL	Carbon allocation from biomass to leaching.
ABP	Allocation from biomass to passive humus; 0 (surface layer), 0.003+0.00032 x CLA (all other layers).
Ad	Crop parameter that governs LAI decline rate.
AD	Air density in kg m <sup>-3</sup>
ADRF	Accumulated 30 day rainfall in mm.
AEP	Total plant water use rate in mm d <sup>-1</sup> .

AG	Acceleration of gravity in $m\ s^{-2}$
AGPM	Standing live and dead plant material in $t\ ha^{-1}$ .
Ah1,2	Crop parameters relating HUF and HUI.
$A_{i2}$	Cross sectional area in $m^2$ for flow $q_{i2}$ .
AJHI	Simulated potential harvest index.
AKN	Nitrification regulator.
AKV	Volatilization regulator.
ALMCO2	Allocation from metabolic litter to $CO_2$ ; 0.6 (surface layer), 0.55 (all other layers).
ALO	Maximum ALS value a crop tolerate without stress in %.
Alp	Maximum fraction of total rainfall that occurs during TC.
Alp.5	Maximum fraction of total rainfall that occurs during 0.5 h.
alp.5u	Upper limit of alp.5.
ALS	Soil layer Al saturation in %.
ALSLCO2	Allocation from lignin of structural litter to $CO_2$ ; 0.3.
ALSLNCO2	Allocation from non-lignin of structural litter to $CO_2$ ; 0.6 (surface layer), 0.55 (all other layers).
ALT	Al tolerance index number for a crop.
ANG	Clockwise angle between field length and north in radians.
$A_{o2}$	Cross sectional area in $m^2$ for flow $q_{o2}$ .
APCO	Allocation from passive humus to $CO_2$ ; 0.55.
AR	Aerodynamic resistance for heat and vapor transfer in $s\ m^{-1}$ .
Ar1,2	Crop parameters used to partition root weight as a function of total biomass and HUI
AS	Aeration stress factor for a crop.
ASCO2	Allocation from slow humus to $CO_2$ ; 0.55.
ASP	Allocation from slow humus to passive; 0 (surface layer), $0.003-0.00009 \times CLA$ (all other layers).
ASPR	Mineral P flow rate between the active and stable pools in $kg\ ha^{-1}\ d^{-1}$ .
ATMN	Absolute value of TMN.
ATS	Root growth Al toxicity stress factor.
AVT	Long-term average annual air temperature in $^{\circ}C$ .
AX	Furrow cross sectional area in $m^2$ .
B1	Probability of a wet day following a dry day divided by probability of a wet day.

B1	Parameter in sediment particle size equation.
B2	Temperature for wet and dry days.
B3	Ratio of mean solar radiation on wet days to mean solar radiation on dry days.
Bc1,2	Crop parameters relating RUE and CO <sup>2</sup> .
BCV	Lagging factor for simulating residue and snow cover affects on surface temperature.
BD	Soil layer bulk density in t m <sup>-3</sup>
BD3	Bulk density for 33 kPa water content in t m <sup>-3</sup> .
BDD	Bulk density of the oven dry soil in t m <sup>-3</sup> .
BDP	Soil layer tillage/compaction affected bulk density in t m <sup>-3</sup> .
BDPo	Bulk density in a soil layer before tillage in t m <sup>-3</sup> .
Be1	Coefficient in enrichment ratio equation.
Be2	Exponent in enrichment ratio equation.
Bf1,2	Winter dormancy temperature crop parameters.
Bh1	Parameter relating mean relative humidity for wet and dry days.
Bi	Rainfall interception constant
BMC	Weight of C in soil microbial biomass and associated products in kg ha <sup>-1</sup> .
BMCTP	Potential C transformation rate in microbial biomass in kg ha <sup>-1</sup> d <sup>-1</sup> .
BMN	Weight of N in soil microbial biomass and associated products in kg ha <sup>-1</sup> .
BMNTP	Potential N transformation rate in microbial biomass in kg ha <sup>-1</sup> d <sup>-1</sup> .
BMR	Transformation rate of microbial biomass and associated products under optimal conditions surface = 0.0164 d <sup>-1</sup> ; all other layers = 0.02 d <sup>-1</sup> (Parton et al., 1993, 1994)
bn1,2,3	Crop parameters expressing optimal N concentration as a function of crop development (HUI).
Bp1,2,3	Crop parameters expressing optimal P concentration as a function of crop development.
Bq	Runoff coefficient in rational equation.
Br1,2	root growth parameters dependent upon soil texture
bsa	Mineral P flow coefficient.
BSA	Soil layer base saturation in %.
Bsl	A fraction of the storage PO occupied by percolating water.
Bv1,2	Parameters in reservoir volume-surface area equation.
Bv3	Parameter in reservoir sediment deposition equation.
BW	Furrow bottom width in m.

bw1	Parameter in mean wind speed equation.
Bw2	Parameter in mean wind speed equation.
Bwn(1)	Wind erosion crop specific coefficient for STL
bwn(2)	Wind erosion crop specific coefficient for STD
bwn(3)	Wind erosion crop specific coefficient for RSD
bx	Crop parameter in Penman-Monteith PET equation
BXCT	Rate of change in annual rainfall from east to west in $\text{mm km}^{-1}$ .
BYCT	Rate of change in annual rainfall from south to north in $\text{mm km}^{-1}$ .
CAC	Soil layer $\text{CaCO}_3$ concentration in $\text{g t}^{-1}$ .
CAF	Critical aeration factor for a crop.
CBW	Channel bottom width in m.
CEC	Soil layer cation exchange capacity.
Cf	Carbon fraction of organic materials (0.42; from data of Pinck et al., 1950)
CGWN	Concentration of N in the groundwater in $\text{kg mm}^{-1}$ .
CHMX	Maximum potential crop height in m.
CHN	Manning's n value of a channel.
CHP	Wetted perimeter of a channel in m.
CHS	Channel slope in $\text{m m}^{-1}$ .
CHT	Crop height in m.
CHXA	Channel cross sectional area at top bank in $\text{m}^2$
CIN	Inflow sediment concentration in $\text{t m}^{-3}$
CLA	Clay content in soil layer in %.
CLE	Lake evaporation coefficient.
CLP	Concentration of labile P in the soil layer in $\text{g t}^{-1}$ .
CMP	Humus mineralization rate constant in $\text{d}^{-1}$ .
CN <sub>1</sub>	SCS runoff curve number for moisture condition 1 (dry).
CN <sub>2</sub>	SCS runoff curve number for moisture condition 2 (average).
CN <sub>2s</sub>	CN <sub>2</sub> value adjusted for watershed slope.
CN <sub>3</sub>	SCS runoff curve number for moisture condition 3 (wet).
CNI	Inflow organic nutrient concentration in $\text{g t}^{-1}$ .

CNO3	Concentration of NO <sub>3</sub> -N in kg mm <sup>-1</sup> .
CNR	C/N ratio of standing dead crop residue.
CO <sub>2</sub>	Atmospheric carbon dioxide concentration in g m <sup>-3</sup> .
CON	Concentration of organic N in g t <sup>-1</sup> .
CP	Concentration of P in the top soil layer in g t <sup>-1</sup> .
CPHT	Crop height in m.
CPRH	Fraction of inflow partitioned to horizontal pipe flow
CPRV	Fraction of inflow partitioned to vertical pipe flow.
CPVH	Horizontal pipe flow rate in mm d <sup>-1</sup> .
CPVV	Vertical pipe flow rate in mm d <sup>-1</sup> .
CR	Canopy resistance for vapor transfer in s m <sup>-1</sup> .
CS	Factor controlling biological processes.
CSN	Soluble N concentration in the reservoir in kg m <sup>-3</sup> .
CSP	Soil layer concentration of labile P in g t <sup>-1</sup> .
CSS	Channel side slope in m m <sup>-1</sup> .
CTW	Channel top width in m.
CU	Product of all RGF values above depth Z.
CV	Weight of all above ground plant material in t ha <sup>-1</sup> .
CVF	USLE crop management factor.
CVRS	Aboveground crop residue in t ha <sup>-1</sup> .
CVSC	VSC routing coefficient.
CY	sediment concentration in t m <sup>-3</sup>
CY <sub>0</sub>	Reservoir sediment concentration in t m <sup>-3</sup> at the start of a day.
CY <sub>1</sub>	Potential sediment concentration for 1.0 m s <sup>-1</sup> velocity.
CY <sub>N</sub>	Normal sediment concentration in a reservoir in t m <sup>-3</sup> .
CY <sub>U</sub>	Potential sediment concentration in t m <sup>-3</sup> for the flow velocity VCH.
D	flow depth in m.
D	Distance between the subarea centroid and the storm center in km.
D <sub>2</sub>	Water depth in m at the toe of the downstream dike.
D <sub>3</sub>	Water depth in m at the toe of the upstream dike.

DD	Soil temperature damping depth in m.
DDM	Daily potential increase in biomass in $t\ ha^{-1}$ .
DECR	Decay rate constant for fresh organic P in $d^{-1}$ .
DEG <sub>ch</sub>	Channel degradation in $t\ ha^{-1}$ .
DEG <sub>fp</sub>	Floodplain degradation in $t\ ha^{-1}$ .
DEP	Sediment deposition in a reservoir in t.
DEP <sub>ch</sub>	Sediment deposition in the channel in $t\ ha^{-1}$ .
DEP <sub>fp</sub>	Sediment deposition in the floodplain in $t\ ha^{-1}$ .
DH	Furrow dike height in m.
DH <sub>0</sub>	Dike height in m before settling.
dHUF	Daily change in HUF.
DI	Water surface distance between dikes in m.
D <sub>i2</sub>	Inflow depth in m for $q_{i2}$ .
DIAM	Soil particle diameter in m.
DKIN	Distance between dike centers in m.
DLT	Slope of the saturation vapor pressure curve in $kPa\ ^{\circ}C^{-1}$ .
DM	Total crop biomass in $t\ ha^{-1}$ .
DMN	Plant N demand in $kg\ ha^{-1}\ d^{-1}$ .
DMP	Plant P demand in $kg\ ha^{-1}\ d^{-1}$ .
DN	Denitrification rate in $kg\ ha^{-1}\ d^{-1}$ .
D <sub>o2</sub>	Outflow depth in m for $q_{o2}$ .
DP	Maximum damping depth for the soil in m.
DPON	Organic N reservoir deposition rate in $kg\ d^{-1}$ .
DPRK	Percolation rate from the groundwater storage in $mm\ d^{-1}$ .
DQ	Volume of rainfall excess in mm for the time interval.
DR	Sediment delivery ratio (sediment yield divided by gross sheet erosion).
dRFV	rainfall amount in mm during a time interval DT in h.
DSB	Change in base saturation needed to raise soil PH to 6.5.
DST0	Soil surface temperature in $^{\circ}C$ .
Dt	Time interval in h.



DT	Reservoir routing time interval in h.
DTHY	Routing time interval in h.
DU10	Wind speed in $\text{m s}^{-1}$ .
DUR	Storm duration in h.
DVOL	Furrow dike volume in mm.
DX	Furrow flow depth in m.
DZ	Soil layer thickness in m.
EA	Saturation vapor pressure at mean air temperature in kPa.
EAJ	Soil cover index.
ECEC	Effective cation exchange capacity in $\text{cmol}(p+) \text{ kg}^{-1}$ .
ECF	Correction factor that preserves long-term mean rainfall.
ED	Vapor pressure at mean air temperature in kPa
EF	Tillage mixing efficiency.
EI	USLE rainfall energy factor.
EK	USLE soil erodibility factor.
ELEV	Elevation of the site in m.
ENO3	Amount of $\text{NO}_3\text{-N}$ in $\text{kg ha}^{-1}$ moved upward by soil water evaporation.
EO	Potential evaporation in $\text{mm d}^{-1}$
EO'	Potential evaporation rate in $\text{mm d}^{-1}$ adjusted for rainfall interception.
EP	Potential plant evaporation rate in $\text{mm d}^{-1}$
ER	Enrichment ratio (organic N concentration in sediment to that of the top soil).
ES	Potential soil water evaporation rate in $\text{mm d}^{-1}$ .
ESR	Potential soil evaporation remaining after snow and litter evaporation in mm.
EV	Evaporation from the reservoir in $\text{m}^3$ .
EVZ	Total potential soil water evaporation in mm
EXPK	Power parameter in modified exponential rainfall distribution
f	Infiltration rate in $\text{mm h}^{-1}$
F	Rainfall frequency of occurrence.
FBIO	RUSLE growing biomass factor.
FC	Field capacity soil water content (33 kPa for many soils) in mm.

FD	Mean wind unsheltered travel distance factor
FDSF	Furrow dike safety factor.
FFC	Fraction of field capacity soil water storage.
FFC'	Depth weighted FFC value.
FGC	Fraction ground cover by the growing crop.
FHR	Winter dormancy day length reduction factor.
FI	Soil erodibility factor of the Woodruff and Siddoway (1965) model in $t\ ha^{-1}$ .
FI1	Dimensionless soil erodibility factor of the new model.
FL	Field length in km.
FN	N fertilizer application rate in $kg\ ha^{-1}$
FOP	Fresh organic P in crop residue in $kg\ ha^{-1}$ .
FP	Amount of pesticide that is intercepted by plants $g\ ha^{-1}$ .
FP0	Pesticide on the plants at the start of the day in $g\ ha^{-1}$ .
FPL	Floodplain length in km.
FPN	Manning's n value in a floodplain.
FPS	Floodplain slope in $m\ m^{-1}$
FPW	Floodplain width in m.
FR	Soil layer content of fresh crop residue in $t\ ha^{-1}$ .
FRF	Wind erosion surface roughness factor.
FRSD	RUSLE crop residue factor.
FRUF	RUSLE soil random roughness factor.
FT	Accumulated infiltration in mm.
FTM	Winter dormancy cold temperature reduction factor.
FV	Wind erosion vegetative cover factor.
FW	Field width in km.
FWV	Wind speed function in $mm\ d^{-1}\ kPa^{-1}$ .
GC	Fraction of the ground that is covered by plants.
GMA	Psychomotor constant in $kPa\ ^{\circ}C^{-1}$ .
GP	Amount of pesticide that reaches the ground in $g\ ha^{-1}$ .
GP <sub>0</sub>	Pesticide in the soil at the start of the day in $g\ ha^{-1}$ .

GSI	Crops leaf resistance in $s\ m^{-1}$
GWLN	Groundwater N leaching rate in $kg\ d^{-1}$ .
GWMX	Maximum groundwater storage in mm.
GWSN	Soluble N content of groundwater in kg.
GWSN <sub>0</sub>	Soluble N content of groundwater at the start of a day in kg.
GWST	Groundwater storage volume in mm.
GWST <sub>0</sub>	Groundwater volume at the start of a day in mm
GWSTH	Groundwater threshold storage in mm.
HCL	Horizontal saturated flow rate in $mm\ h^{-1}$ .
HE	Machine harvest efficiency.
HI	Optimal harvest index for a crop.
HIA	Harvest index used to estimate yield of a crop.
HIMN	Minimum value of harvest index.
HIP	Potential value of harvest index.
HIT	Harvest index as a function of heat unit accumulation
HLP	Pesticide half life on the plants in d.
HLS	Pesticide half life in the soil in d.
HMP	Humus P mineralization rate in $kg\ ha^{-1}\ d^{-1}$ .
HMX	Maximum height for a particular crop in m.
HPC	Weight of C present in passive humus in $kg\ ha^{-1}$ .
HPCTP	Potential C transformation rate in passive humus in $kg\ ha^{-1}\ d^{-1}$ .
HPN	Weight of N present in passive humus in $kg\ ha^{-1}$ .
HPNTP	Potential N transformation rate in passive humus in $kg\ ha^{-1}\ d^{-1}$ .
HPR	Passive humus transformation rate under optimal conditions (subsurface layers = $0.000012\ d^{-1}$ ) (Parton et al., 1993, 1994)
HRLT	Day length in h.
HSC	Weight of C present in slow humus in $kg\ ha^{-1}$ .
HSCTP	Potential C transformation rate of slow humus in $kg\ ha^{-1}\ d^{-1}$ .
HSN	Weight of N in slow humus in $kg\ ha^{-1}$ .
HSNTP	Potential N transformation rate in slow humus in $kg\ ha^{-1}\ d^{-1}$ .
HSR	Slow humus transformation rate under optimal conditions (all layers = $0.0005\ d^{-1}$ ) (Parton et al., 1993, 1994; Vitousek et al., 1993)

HST	Soil water storage in a soil layer for half SPLG in mm.
HU	Number of heat units accumulated during a day in °C.
HUF	Heat unit factor.
HUI	Heat unit index (accumulated HU/PHU).
HUI <sub>D</sub>	Value of HUI when LAI starts declining.
HV	Latent heat of vaporization in MJ kg <sup>-1</sup>
IDA	Day of the year.
IPST	Growing season length in d.
k	Decay constant in exponential rainfall rate distribution in h.
KD	P sorption coefficient (P concentration of the sediment divided by that of the water in m <sup>3</sup> t <sup>-1</sup> ).
KOC	Linear adsorption coefficient for organic carbon.
L	Channel length from the most distant point to the watershed outlet in km.
LAG	Soil temperature lag coefficient (considers previous day's temperature).
LAI	Leaf area index of the crop.
LAI'	LAI at the end of the day.
LAI <sub>0</sub>	LAI at the beginning of the day.
Lc	Average channel flow length for the watershed in km.
Lca	Distance from the outlet along the channel to the watershed centroid in km.
LM	Weight of metabolic litter in kg ha <sup>-1</sup>
LMC	Weight of C in metabolic litter in kg ha <sup>-1</sup> .
LMCTP	Potential transformation of C in metabolic litter in kg ha <sup>-1</sup> d <sup>-1</sup> .
LMF	Fraction of the litter that is metabolic.
LMN	Mass of N in metabolic litter in kg ha <sup>-1</sup> .
LMNF	Fraction of metabolic litter that is N in kg kg <sup>-1</sup> .
LMNTP	Potential transformation of N in metabolic litter in kg ha <sup>-1</sup> d <sup>-1</sup> .
LMR	Metabolic litter transformation rate under optimal conditions (surface = 0.0405 d <sup>-1</sup> ; all other layers = 0.0507 d <sup>-1</sup> ) (Parton et al., 1994)
LPF	Labile P uptake factor—allows optimum uptake rates when CSP is above 20 g t <sup>-1</sup> .
LS	Weight of structural litter in kg ha <sup>-1</sup>
LSC	Weight of C in structural litter in kg ha <sup>-1</sup> .
LSCTP	Potential transformation of C in structural litter in kg ha <sup>-1</sup> d <sup>-1</sup> .

LSF	Fraction of the litter that is structural.
LSL	Weight of lignin in structural litter in $\text{kg ha}^{-1}$ .
LSLCTP	Potential transformation of C in lignin of structural litter in $\text{kg ha}^{-1} \text{ d}^{-1}$ .
LSLF	Fraction of structural litter that is lignin in $\text{kg kg}^{-1}$ .
LSL <sub>N</sub> CTP	Potential transformation of C in non-lignin structural litter in $\text{kg ha}^{-1} \text{ d}^{-1}$ .
LSN	Weight of N in structural litter in $\text{kg ha}^{-1}$ .
LSNF	Fraction of structural litter that is N in $\text{kg kg}^{-1}$ .
LSNTP	Potential transformation of N in structural litter in $\text{kg ha}^{-1} \text{ d}^{-1}$ .
LSR	Structural litter potential transformation rate under optimal conditions (surface = $0.0107 \text{ d}^{-1}$ ; all other layers = $0.0132 \text{ d}^{-1}$ ) (Parton et al., 1994)
MPR	Mineral P flow rate in $\text{kg ha}^{-1} \text{ d}^{-1}$ .
N	Manning's channel roughness factor.
ND	Number of days in a month.
NDD	Number of dry days in a month.
NSA	Number of subareas in the watershed.
NWD	Number of wet days in a month.
NY	Rainfall record length in y.
O	Percolation flow rate for a soil layer in $\text{mm d}^{-1}$ .
OFV	Overland flow velocity in $\text{m s}^{-1}$ .
OX	Oxygen factor controlling biological processes as a function of depth.
P(W D)	Probability of a wet day following a dry day.
P(W W)	Probability of a wet day after a wet day.
P1	Parameter in Penman-Monteith PET equation.
P14	Ratio of $\text{NO}_3\text{-N}$ runoff concentration to that of percolate.
P18	Exponential parameter in Bagnold's sediment transport equation.
P2	Threshold bulk density for root stress for a soil of zero sand content.
P24	Ratio of pesticide concentration in runoff to that of percolate.
P31	Sediment routing exponent ranging from 1.0 to 1.5.
p5	Fraction of wilting point—lower limit of plant water use.
P7	Weights N fixation between basic estimate and plant N demand.
P73	Parameter in hydrograph development equation.

P9	Threshold 30-day rainfall amount for pest damage in mm.
PAEF	Pesticide application efficiency.
PAPE	Effective amount of pesticide applied in $\text{kg ha}^{-1}$ .
PAPR	Actual amount of pesticide applied in $\text{kg ha}^{-1}$ .
PAR	Intercepted photosynthetic active radiation in $\text{MJ m}^{-2} \text{d}^{-1}$ .
PB	Barometric pressure in kPa.
PCH	Pesticide concentration in horizontal flow in $\text{g t}^{-1}$ .
PCT	Sediment particle size distribution in %.
PCTO	Outflow sediment particle size distribution in %.
PCV	Pesticide concentration in vertical flow in $\text{g t}^{-1}$ .
PE	USLE erosion control practice factor.
PH	Soil layer pH.
PO	Soil porosity volume in mm.
PO <sub>1</sub>	Porosity minus field capacity of the top 1 m of soil in mm.
PSP	P sorption coefficient.
PSQC	Pesticide concentration in the water in $\text{g t}^{-1}$ .
PST	Minimum pest factor value for a crop.
PSTD	Daily pest index.
PSTE	Pesticide kill fraction.
PSTF	Simulated pest factor.
PSTL	Amount of pesticide leached in $\text{g ha}^{-1}$ .
PSTS	Accumulated daily pest index.
PSTX	Pest damage scaling factor.
PSTY	Pesticide yield adsorbed to the sediment in $\text{kg ha}^{-1}$ .
PSYC	Concentration of adsorbed pesticide in $\text{g t}^{-1}$ .
PSZM <sub>1</sub>	Mean sediment particle size of the inflow in $\mu\text{m}$ .
PSZM <sub>0</sub>	Mean sediment particle size of the outflow in $\mu\text{m}$ .
PW	Probability of a wet day.
PX	Furrow wetted perimeter in m.
Q	Runoff volume in mm.

q	Flow rate in $\text{m}^3 \text{s}^{-1}$
$q_c$	Average flow rate in $\text{m}^3 \text{s}^{-1}$
$q_{c1}$	Average flow rate from a 1-ha area in $\text{mm h}^{-1}$ .
$Q_c'$	Average flow rate in $\text{mm h}^{-1}$
QCH	Volume of flow through a reach channel in mm.
$q_{cp}$	Channel capacity in $\text{m}^3 \text{s}^{-1}$
$q_{fp}$	Floodplain flow rate in $\text{m}^3 \text{s}^{-1}$
QH	Horizontal flow rate in soil layer in $\text{mm d}^{-1}$
$q_{hy}$	Subarea hydrograph outflow rate in $\text{m}^3 \text{s}^{-1}$
QI	Inflow rate in $\text{mm d}^{-1}$ or $\text{m}^3 \text{d}^{-1}$ .
$Q_{i1}$	Reach inflow rate in $\text{m}^3 \text{s}^{-1}$ at the start of the routing interval.
$Q_{i2}$	Reach inflow rate in $\text{m}^3 \text{s}^{-1}$ at the end of the routing interval.
QNI	Soluble N reservoir inflow rate in $\text{kg d}^{-1}$
QNO	Soluble N reservoir outflow rate in $\text{kg d}^{-1}$ .
QNO3	Amount of $\text{NO}_3\text{-N}$ lost from a soil layer by runoff and leaching $\text{kg ha}^{-1}$ .
QO	Outflow from reservoir in $\text{m}^3$ .
$Q_{o1}$	Reach outflow rates in $\text{m}^3 \text{s}^{-1}$ at the start of the routing interval.
$Q_{o2}$	Reach outflow rates in $\text{m}^3 \text{s}^{-1}$ at the end of the routing interval.
$Q_p$	Peak runoff rate in $\text{m}^3 \text{s}^{-1}$
$q_p'$	TR-55 peak rate per unit of rainfall in $\text{h}^{-1}$ .
QPX	Furrow irrigation flow rate in $\text{mm h}^{-1}$ .
$QPX'$	Furrow irrigation flow rate in $\text{m}^3 \text{s}^{-1}$ .
QRF	Quick return flow rate in $\text{mm d}^{-1}$ .
QT	Percolation volume in mm.
QV	Vertical flow rate in soil layer in $\text{mm d}^{-1}$
QXM	Irrigation application volume in mm.
r	Rainfall rate in $\text{mm h}^{-1}$
RA	Mean daily solar radiation in $\text{MJ m}^{-2} \text{d}^{-1}$ .
RAD	Daily mean solar radiation on dry days in $\text{MJ m}^{-2} \text{d}^{-1}$ .
RAMX	Maximum daily solar radiation in $\text{MJ m}^{-2} \text{d}^{-1}$ .

RAW	Daily mean solar radiation on wet days in $\text{MJ m}^{-2} \text{d}^{-1}$ .
RBO	Net outgoing long wave radiation in $\text{MJ m}^{-2} \text{d}^{-1}$ .
RCHL	Routing reach channel length in km.
RD	Root depth in m.
RDMX	Maximum root depth for a crop in m.
RE	Rainfall energy for water erosion equations.
Rep	Peak rainfall excess rate in $\text{mm h}^{-1}$
RFI	Intercepted rainfall in mm.
RFPK	Groundwater flow partitioning coefficient.
RFPL	Reach floodplain length in m.
RFPS	Reach floodplain slope in $\text{m m}^{-1}$ .
RFRA	Rainfall on the reservoir in $\text{m}^3$ .
RFTT	Groundwater storage residence time in d.
RFV	Rainfall that arrives on the soil surface in mm
RFV <sub>.5</sub>	Maximum storm rainfall in mm occurring in 0.5 h.
RFV <sub>.5a</sub>	Mean maximum 0.5-h rainfall amount in mm for a month.
RFV <sub>.5u</sub>	Maximum 0.5-h rainfall amount in mm for frequency F.
RFV <sub>24</sub>	24-h duration rainfall volume in mm.
RFV <sub>TC</sub>	Maximum rainfall volume during the watershed's time of concentration in mm.
RGF	Minimum root growth stress factor.
RH	Monthly long-term average relative humidity.
RHD	Daily mean relative humidity on dry days.
RHG	Generated relative humidity.
RHG'	Generated relative humidity adjusted to the mean of the triangular distribution.
RHL	Lower limit for generated relative humidity for the day.
RHP	Peak of the triangular relative humidity distribution (RHW or RHD).
RHT	Input ridge height for a tillage operation in m.
RHTT	Ridge height in mm.
RHU	Upper limit for generated relative humidity for a day.
RHW	Daily mean relative humidity on wet days.



RIF	Wind erosion ridge roughness factor.
RIMX	Maximum possible intercepted rainfall for an event in mm.
RINT	Ridge interval in m.
RLA	Lime required to neutralize Al in t ha <sup>-1</sup> .
RMP	Mineralization rate of fresh organic P in kg ha <sup>-1</sup> d <sup>-1</sup> .
RN	Net radiation in MJ m <sup>-2</sup> d <sup>-1</sup> .
Rnd	Uniform random number (0.0-1.0)
RNIT	Nitrification rate in kg ha <sup>-1</sup> d <sup>-1</sup> .
RNV	Combined nitrification and volatilization kg ha <sup>-1</sup> d <sup>-1</sup> .
ROK	Coarse fragment content of a soil layer in %.
ROKF	Coarse fragment factor in soil erosion equations.
R <sub>p</sub>	Peak rainfall rate in mm h <sup>-1</sup>
RR	Flow rate through the principal spillway in m <sup>3</sup> d <sup>-1</sup> .
RRF	Clod roughness factor.
RRUF	Soil surface random roughness in mm.
RSD	Flat crop residue in t ha <sup>-1</sup> .
RSDM	Manure on the soil surface in t ha <sup>-1</sup> .
RSFN	Groundwater return flow N rate in kg d <sup>-1</sup> .
RSHC	Hydraulic conductivity of the reservoir bottom in mm h <sup>-1</sup> .
RSON	Organic N content of a reservoir in kg.
RSON <sub>0</sub>	Organic N content of a reservoir in kg at the start of a day.
RSSA	Reservoir surface area in ha.
RSSF	Groundwater return flow rate in mm d <sup>-1</sup> .
RSSN	Soluble N content in a reservoir in kg.
RSSN <sub>0</sub>	Soluble N content in a reservoir at the start of a day in kg.
RSV	Reservoir water content in m <sup>3</sup> .
RSV <sub>0</sub>	Reservoir water content at the start of the day in m <sup>3</sup> .
RSV <sub>E</sub>	Reservoir storage volume in m <sup>3</sup> at the emergency spillway elevation.
RSV <sub>P</sub>	Reservoir storage volume in m <sup>3</sup> at the principal spillway elevation.
RSY	Reservoir sediment content in t.

RSY <sub>0</sub>	Reservoir sediment content in t at the start of the day.
RTP	The rainfall volume at t <sub>p</sub> in mm.
RUE	Radiation use efficiency factor for converting energy to biomass in (kg ha <sup>-1</sup> )/(MJ m <sup>-2</sup> ).
RVOL	Volatilization rate in kg ha <sup>-1</sup> d <sup>-1</sup> .
RW	Total root weight in t ha <sup>-1</sup>
RW <sub>0</sub>	Total root weight in t ha <sup>-1</sup> at the beginning of a day.
RWT	Root weight by soil layer in t ha <sup>-1</sup> .
RZ	Minimum of soil profile depth and RDMX in m.
RZLN	Root zone N leaching rate in kg d <sup>-1</sup> .
S	SCS runoff retention parameter.
S'	SCS runoff retention parameter adjusted for frozen soil.
S <sub>1</sub>	SCS runoff retention parameter associated with CN <sub>1</sub> .
S <sub>2</sub>	SCS runoff retention parameter associated with CN <sub>2</sub> .
S <sub>3</sub>	SCS runoff retention parameter associated with CN <sub>3</sub> .
SALB	Soil albedo.
SAN	Sand content of the soil in %.
SAT	Soil saturation factor.
SATK	Soil saturated conductivity in mm h <sup>-1</sup> .
SC	Saturated conductivity of a soil layer in mm h <sup>-1</sup> .
SD	Sun's declination angle in radians.
SDRA	Standard deviation of daily solar radiation in MJ m <sup>-2</sup> d <sup>-1</sup> .
SEP	Reservoir seepage loss in m <sup>3</sup> .
SEV	Potential soil evaporation for a soil layer in mm.
SEV'	Adjusted soil water evaporation in mm based on limited soil water content.
Sf	Fraction of the soil mineral N in NO <sub>3</sub> -N and NH <sub>3</sub> sorbed onto the litter N compartment: 0.05 for surface litter, 0.1 for belowground litter.
SFL	TR-55 shallow flow length in km.
SFV	Average shallow flow velocity in km h <sup>-1</sup>
SIA	Reach storage plus the inflow volume in m during DTHY.
SIL	Silt content of the soil in %.
SL	USLE slope length and steepness factor.

SMB	Sum of the bases in $\text{cmol kg}^{-1}$ .
SML	Snowmelt rate in $\text{mm d}^{-1}$ .
SMLA	Leaf-area-index of the plant stand.
SMX <sub>0</sub>	Sum of the material in TLD before mixing in $\text{kg ha}^{-1}$ .
SN	N stress factor for a crop.
SNO	Snow present in mm of water.
SNOF	Snow cover factor used in soil temperature equations.
SNPKT	Snow pack temperature in $^{\circ}\text{C}$ .
SNS	Scaling factor for N stress.
SP	P stress factor for a crop.
SPLG	Upland slope length in m.
SPN	Total soil profile N supply in $\text{kg ha}^{-1} \text{d}^{-1}$ .
SPP	Total soil profile supply of P in $\text{kg ha}^{-1} \text{d}^{-1}$ .
SS	Root growth soil strength stress factor.
SSF	Subsurface flow rate in $\text{mm d}^{-1}$ .
ST	Soil water content in the root zone in mm.
ST <sub>1</sub>	Water content minus field capacity of the top 1 meter of soil in mm.
ST <sub>25</sub>	Water content at $\text{WP}+0.25(\text{FC}-\text{WP})$ in mm.
STD	Standing crop residue in $\text{t ha}^{-1}$ .
STD <sub>0</sub>	Standing crop residue before tillage in $\text{t ha}^{-1}$ .
STDL	Weight of lignin in STD in $\text{kg ha}^{-1}$ .
STDN	Weight of N in STD in $\text{kg ha}^{-1}$ .
STDNE	Standing dead N after enrichment with sorbed N in a soil layer in $\text{kg ha}^{-1}$ .
STH	Watershed storage volume in mm at the end of the time interval in h.
STH <sub>0</sub>	Watershed storage volume in mm at the start of the time interval in h.
STL	Standing live biomass of the crop in $\text{t ha}^{-1}$ .
STL'	Standing live biomass at the end of the day in $\text{t ha}^{-1}$ .
STMP	Soil layer temperature in $^{\circ}\text{C}$ .
STMP <sub>0</sub>	Soil layer temperature for previous day in $^{\circ}\text{C}$ .
STP	Average slope of the watershed in $\text{m m}^{-1}$ .

STS	Root growth temperature stress for a crop.
SWF	Nutrient cycling soil water factor.
SWH	Accumulated plant water use in mm between HUI values of 0.5 and 1.0.
SWLT	Water stored in the litter in mm.
SZ	Scaling factor in soil settling equation.
T <sub>1</sub>	Water tension in soil layer 1 in kPa.
T <sub>2</sub>	Water tension in soil layer 2 in kPa.
TAGP	Above ground plant material in t ha <sup>-1</sup> .
TBP	Tillage factor for biological processes.
TBSC	Crop-specific base temperature in °C.
TC	Watershed time of concentration in h.
TC <sub>C</sub>	Time of concentration for channel flow in h.
TC <sub>S</sub>	Time of concentration for surface flow in h.
TC <sub>SF</sub>	Time of concentration for shallow channel flow in h.
TDMX	Daily mean maximum temperature for dry days in °C.
TDP	Time required for reservoir to return to normal concentration in d.
TDST	Deviate drawn from a triangular distribution.
TFN	Nutrient cycling temperature factor.
THW	Wind direction clockwise from north in radians.
TK	Mean daily air temperature in °K.
TLAI	Leaf area index of mixed plant stand.
TLD	Tillage depth in m.
TMN	Daily minimum air temperature in °C.
TMX	Daily maximum air temperature in °C.
TNO3	NO <sub>3</sub> -N content in the soil root zone in kg ha <sup>-1</sup> .
TOPC	Optimal temperature for a crop in °C.
T <sub>p</sub>	Time to peak of the storm in h.
t <sub>pu</sub>	Time to peak of the dimensionless rainfall distribution.
TRT	Reach floodplain travel time in h.
TS	Plant temperature stress factor.

TSNO	Age of the snow pack in d.
TT	Travel time through a soil layer in h.
TT <sub>H</sub>	Horizontal travel time through a soil layer in h.
TT <sub>R</sub>	Travel time through a routing reach in h.
TT <sub>V</sub>	Vertical travel time through a soil layer in h.
TW	Water surface width at depth DH in m.
TW <sub>2</sub>	Water surface width in m at depth D <sub>2</sub> .
TW <sub>3</sub>	Water surface width in m at depth D <sub>3</sub> .
TWMX	Daily mean maximum temperature for wet days in °C.
TX	Mean daily air temperature in °C.
u'	Threshold friction velocity in m s <sup>-1</sup>
u10	Wind speed at f fraction of the day in m s <sup>-1</sup>
U10	Mean daily wind speed at 10 m height in m s <sup>-1</sup> .
UC	Soil layer plant water use compensation factor.
UF	Upward flow rate in a soil layer in mm d <sup>-1</sup>
UN	Rate of N supplied by the soil in kg ha <sup>-1</sup> d <sup>-1</sup> .
UN'	The actual plant N uptake rate in kg ha <sup>-1</sup> d <sup>-1</sup> .
UN1	Actual N content of the crop in kg ha <sup>-1</sup> .
UNM	Crop N uptake rate in kg ha <sup>-1</sup> d <sup>-1</sup> .
UNO	Optimal N content for the crop in kg ha <sup>-1</sup> .
UP	Rate of P supplied by the soil in kg ha <sup>-1</sup> d <sup>-1</sup> .
UP'	Actual plant P uptake rate from a soil layer in kg ha <sup>-1</sup> d <sup>-1</sup> .
UP1	Actual P content of the crop in kg ha <sup>-1</sup>
USTR	Friction velocity in m s <sup>-1</sup> .
USTRT	Threshold friction velocity in m s <sup>-1</sup> .
UW	Plant water use rate in a soil layer in mm d <sup>-1</sup> .
UX	Potential water use rate in mm d <sup>-1</sup>
UZZ	Daily mean wind speed adjusted for the crop height in m s <sup>-1</sup> .
V	Flow velocity in m s <sup>-1</sup>
VCH	Channel flow velocity in m s <sup>-1</sup> .

VFP	Floodplain flow velocity in $\text{m s}^{-1}$ .
VGf	Wind erosion vegetative cover equivalent factor.
VPD	Vapor pressure deficit in kPa.
VPTH	Threshold vapor pressure for the crop kPa.
VX	Furrow irrigation flow velocity in $\text{m s}^{-1}$
w1	Parameter in CN-soil water relationship.
W2	Parameter in CN-soil water relationship.
WAVP	Crop parameter relating RUE and VPD.
WDRM	Minimum day length for the location plus 1.0 in h.
WFX	Calculated N fixation rate considering growth stage, soil water content, and soil N content in $\text{kg ha}^{-1} \text{d}^{-1}$ .
WFX'	Final adjusted N fixation rate in $\text{kg ha}^{-1} \text{d}^{-1}$ .
WIP	P immobilization rate in $\text{kg ha}^{-1} \text{d}^{-1}$ .
WL	Unsheltered field length along the prevailing wind direction in km.
wn1	Descent angle of saltating sand grains in degrees.
Wn2	Angle of the wind relative to ridges in radians
wn3	Wind erosion distance of run parameter.
Wn4	Wind erosion rate parameter.
WNF	Nitrification-volatilization wind speed factor.
WNH3	Weight of $\text{NH}_3$ in a soil layer in $\text{kg ha}^{-1}$ .
WNO3	$\text{NO}_3\text{-N}$ content in a soil layer in $\text{kg ha}^{-1}$ .
WNO3'	$\text{NO}_3\text{-N}$ content at the end of a day in $\text{kg ha}^{-1}$ .
WO	Amount of pesticide washed off the plants by a rainstorm in $\text{g ha}^{-1}$ .
WOC	Organic carbon content of the soil in %.
WOF	Washoff fraction for the particular pesticide.
WP	Wilting point soil water content (1500 kPa for many soils) in mm.
WPMA	Soil layer active mineral P content in $\text{kg ha}^{-1}$ .
WPML	Soil layer labile P content in $\text{kg ha}^{-1}$ .
WPMS	Soil layer stable mineral P content in $\text{kg ha}^{-1}$ .
WPO	Soil layer organic P content in $\text{kg ha}^{-1}$ .
WS	Water stress factor for a crop.

WSA	Watershed area in ha.
WSYF	Minimum harvest index for a crop.
WTBL	Depth in m from the soil surface to the water table.
WTMN	Minimum annual water table depth in m.
WTMX	Maximum annual water table depth in m.
X	Amount of the material in a soil layer after mixing in $\text{kg ha}^{-1}$ .
$X_0$	Amount of the material in a soil layer before mixing $\text{kg ha}^{-1}$ .
$X_{\text{BMT}}$	Microbial biomass transformation control by soil texture and structure. Its values: surface litter layer = 1; all other layers = $1 \hat{=} 0.0075 \times (\text{SIL} + \text{CLA})$
XCS	Minimum x coordinate of the subarea centroids in km.
XCT	x coordinates of the subarea centroids in km
XCU	Maximum x coordinate of the subarea centroids in km.
XKP <sub>1</sub>	Exponential parameter in simulated rainfall distribution in h.
XKP <sub>2</sub>	Exponential parameter in simulated rainfall distribution in h.
XLAI	Maximum leaf area index for a crop.
$X_{\text{LSLF}}$	Control on potential transformation of structural litter by lignin fraction of structural litter.
XSL	x scale of the box around the watershed for generating spatially distributed rainfall.
Y	Sediment yield in $\text{t ha}^{-1}$
YCS	Minimum y coordinate of the subarea centroids in km.
YCT	y coordinates of the subarea centroids in km.
YCU	Maximum y coordinate of the subarea centroids in km.
YI	Sediment inflow in $\text{t ha}^{-1}$ .
YLAT	Latitude of the site in degrees.
YLD	Amount of the crop removed from the field in $\text{t ha}^{-1}$ .
YMNU	Manure erosion in $\text{t ha}^{-1}$ .
YNO	Organic nutrient (N or P) outflow in $\text{kg ha}^{-1}$ .
YO	Sediment outflow in $\text{t ha}^{-1}$ .
YON	Organic N runoff loss in $\text{kg ha}^{-1}$ .
$YON_i$	Organic N reservoir inflow rate in $\text{kg d}^{-1}$ .
$YON_o$	Organic N reservoir outflow rate in $\text{kg d}^{-1}$ .
YP	Sediment phase P lost in runoff in $\text{kg ha}^{-1}$

YSL	y scale of the box around the watershed for generating spatially distributed rainfall in km.
YSP	Soluble P in $\text{kg ha}^{-1}$ lost in runoff.
YU	Potential change in sediment yield in $\text{t ha}^{-1}$ within a routing reach.
YW	Wind erosion in $\text{kg m}^{-1}$ .
YWR	Integral of the wind erosion rate over the duration of wind greater than threshold velocity.
YWR'	Wind erosion rate in $\text{kg m}^{-1} \text{ s}^{-1}$ .
Z	Soil depth in m.
Z <sub>0</sub>	Surface roughness parameter in m.
Z <sub>5</sub>	Depth to the center of a soil layer in mm.
Z <sub>CH</sub>	Channel depth in m.
Z <sub>D</sub>	Displacement height of the crop in m.
Z <sub>FP</sub>	Floodplain flow depth in m.
ZTP	Subarea rainfall weighting factor accounts for rainfall duration, distance between subarea centroid, and storm center and rainfall gradient.



# APPENDIX B

## APEX PUBLICATIONS

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- Benson, Verel W., D. Todd Rarrand, Robert E. Young III and Peter Zimmell. Estimated Nutrient Movement with Alternative Poultry Litter Application rates on various soils, using different management systems. 2000.
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# APPENDIX C

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