THE APEX MODEL

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INTRODUCTION

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_2 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 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 EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, crop growth, soil temperature, tillage, economics, and plant environment control. Although EPIC 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. EPIC can be used to compare management systems and their effects on nitrogen, phosphorus, carbon, pesticides and sediment. 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 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).

THE SUBAREA COMPONENT

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

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

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

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

$$R6 = RST(3,MO)/6. \qquad\qquad (1c)$$

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.

$$RF = (RST(1,MO)/ECF)*(-\ln(rnd))^{EXPK} \qquad\qquad (2)$$

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 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 ^{o}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:

$$PW = NWD/ND \qquad\qquad (3)$$

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.

$$P(W|D)=b1*PW \qquad\qquad (4)$$

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

$$P(W|W)=1.0-b1+P(W|D) \qquad\qquad (5)$$

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 4 and 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. A box is formed outside the watershed with dimensions set by the equations

$$XSL=3.*(XCU-XCS) \qquad\qquad (6)$$

where XSL is the x scale of the box, XCU is the maximum x coordinate of the subarea centroids, XCS is the minimum x coordinate of the subarea centroids. YSL the y scale is computed similarly. Thus, for a watershed with north-south length orientation the box extends east from XCU and west from XCS a distance equal the watershed width, and north from YCU and south from YCS a distance equal the watershed length. These large dimensions assure that generated storm centers are completely random with respect to all subareas (with smaller dimensions more storm centers occur in subareas near the center of the watershed). Storm centers are generated using the equation

$$x=rnd*XSL+2.*XCS-XCU \qquad\qquad (7)$$

where x is the x coordinate of the storm center and rnd is a uniform   random number. A similar equation is used to compute y. The storm center rainfall is simulated using Eqs 1 or 2. Monthly weather generator parameters for up to ten stations may be input along with the fraction of the watershed they represent. The fractions are used to form a cumulative probability distribution. Each time a storm occurs one set of weather parameters is chosen randomly from the cumulative distribution to generate the storm rainfall. Rainfall for each subarea is simulated using the equation

$$RF(j)=NSA*RF*ZTP(j)*TDST/SUM \qquad\qquad (8)$$

$$ZTP(j)=X2*(1.+BXCT*XCT(j))*(1.+BYCT*YCT(j)) \qquad\qquad (8a)$$

$$X2=1.0-DUR^{-.1478}*D/(D+exp(2.291+0.00117*D)) \qquad\qquad (8b)$$

$$D=sqrt((x-XCT(j))^2+(y-YCT(j))^2) \qquad\qquad (8c)$$

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where RF is the storm center rainfall in mm, NSA is the number of subareas in the watershed, XCT and YCT are the x and y coordinates of the subarea centroids, ZTP is the subarea rainfall weighting factor that accounts for rainfall duration, distance between subarea centroid and storm center and rainfall gradient, BXCT is the rate of change in annual rainfall from east to west in mm km^{-1}, BYCT is the rate of change in annual rainfall from south to north in mm km^{-1}, D is the distance between the subarea centroid and the storm center in km, DUR is the storm duration in h, TDST is a deviate drawn from a triangular distribution ranging between 0.8 and 1.2, SUM is the summation of ZTP for all subareas, and j is the subarea number. Eq 8 provides wider distributions for long duration storms, higher rainfall for subareas near the storm center, rainfall gradient correction, and a random component. NSA and SUM are used to normalize the ZTP 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

$$SDRA=0.25*(RAMX-RA) \qquad\qquad (9)$$

where SDRA is the standard deviation of daily solar radiation in MJ m^{-2}, 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:

$$TWMX=TDMX-b2*(TMX-TMN) \qquad\qquad (10)$$

where TWMX is the daily mean maximum temperature for wet days in ^{o}C, TDMX is the daily mean maximum temperature for dry days in ^{o}C, b2 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 b2=1.0 provides highest deviations on wet days and b2=0.0 ignores the wet day effect. Observed data indicate that b2 usually lies between 0.5 and 1.0.

Since Eq 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

$$TMX*ND=TWMX*NWD+TDMX*NDD \qquad (11)$$

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 10 into Eq 11 and solving for TDMX

$$TDMX=TMX+B2*(TMX-TMN)*NWD/ND \qquad (12)$$

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

$$RAW=b3*RAD \qquad (13)$$

where RAW is the daily mean solar radiation on wet days in
MJ m^{-2}, b3 is a scaling factor ranging from 0.0 to 1.0, and RAD is the daily mean solar radiation on dry days. A b3 value of 0.5 gives satisfactory results for many locations. The dry day equation is developed by replacing temperature with radiation in Eq 11 and substituting Eq 13 for RAW. Then,

$$RAD=RA*ND/(b3*NWD+NDD) \qquad (14)$$

where RA is the daily mean solar radiation in MJ m^{-2}.

The maximum possible solar radiation is computed with the equations

$$RAMX=30.*DD*(H*YLS*sin(SD)+YLC*cos(SD)*sin(H)) \qquad (15)$$

$$DD=1.+.0335*sin((IDA+88.2)/58.13) \qquad (15a)$$

$$SD=.4102*sin((IDA-80.25)/58.13) \qquad (15b)$$

$$CH=-tan(YLAT/57.296)*tan(SD) \qquad (15c)$$

$$H=acos(CH); \quad -1.0<CH<1.0 \qquad (15d)$$

$$H=0.0; \quad CH>1.0 \qquad (15e)$$

$$H=3.1416; \quad CH<-1.0 \qquad (15f)$$

$$YLS=\sin(YLAT/57.296) \tag{15g}$$

$$YLC=\cos(YLAT/57.296) \tag{15h}$$

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

$$HRLT=7.72*H \tag{16}$$

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

$$u10=a1*U10*(-\ln(f))^{a2} \tag{17}$$

where u10 is the wind speed at f fraction of the day, U10 is the mean wind speed for the day, and a1 and a2 are parameters. Eq 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 $0.1 < a2 < 0.6$. Values of a2 are generated daily from a triangular distribution with base ranging from 0.1 to 0.6 and peak at 0.35. The value of a1 can be closely approximated with the equation

$$a1=1.557*(a2)^{0.1508}*\exp(-0.4336*a2) \tag{18}$$

Eq 18 assures that the mean wind speed U10 is preserved.

Values of u10 are simulated with f starting with the threshold windspeed for erosion. The threshold f value (fo) is determined using the wind erosion Eq 135 and Eq 17 in the form

$$fo=\exp((-u'/(0.0408*U10))^{-a2}) \tag{19}$$

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

$$U10=bw1*U10(mo)*(-\ln(rnd))^{bw2} \tag{20}$$

where U10(mo) is the mean wind speed for month mo, rnd is a random number, bw2 is a parameter for month mo, and bw1 is calculated directly using an approach similar to that described in Eq 18. Experimental work with data from Bushland, TX and Temple, TX indicates that bw2 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

$$RHW=RHD+bh1*(1.0-RHD) \tag{21}$$

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

$$RHD=(RH(mo)-bh1*NWD/ND)/(1.0-bh1*NWD/ND) \tag{22}$$

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

$$RHU=RHP+(1.0-RHP)*exp(RHP-1.0) \tag{23}$$

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

$$RHL=RHP*(1.0-exp(-RHP)) \tag{24}$$

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

$$RHG'=RHG*RHP/RH \tag{25}$$

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 93i and 93j. If dew point temperature is not available APEX estimates monthly mean relative humidity using the equation

$$RH = 0.9 - 0.8*X1/(X1 + exp(5.12 - 0.127*X1)) \qquad (26)$$

$$X1 = TMX - TMN \qquad (26a)$$

where TMX and TMN are monthly means in ^{o}C. Equation 26 was derived assuming that relative humidity varies inversely with temperature variations (Hargreaves and Samani, 1985).

HYDROLOGY

Rainfall Interception

Rainfall interception by plant canopy is estimated with the equation

$$RFI = RIMX*(1.0 - exp(-bi*sqrt(TAGP*SMLA))) \qquad (27)$$

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 27 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.

$$RFV = RF - RFI \qquad (28)$$

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)

$$Q=(RFV-0.2*s)^2/(RFV+0.8*s); \quad RFV>0.2*s \qquad (29)$$

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

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)

$$s=254.*(100./CN-1.) \qquad\qquad (30)$$

The constant, 254, in Eq 30 gives s in mm. Thus, RFV and Q are also expressed in mm. CN_2--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_2 value is appropriate for a 5% slope, we developed the following equation for adjusting that value for other slopes.

$$s_{2S}=s_2*(1.1-STP/(STP+exp(3.7+0.02117*STP))) \qquad (31)$$

where s_{2S} is the retention parameter associated with CN_2 adjusted for slope and STP is the average slope of the watershed in %. CN_2
and CN_{2S} are calculated by substituting s_2 and s_{2S} into eq 30.   Values of CN_1, the curve number for moisture condition 1 (dry), and CN_3 (wet) corresponding to CN_2 are also tabulated in the handbook. For computing purposes, CN_1 and CN_3 were related to CN_2 with the equations

$$CN_1=CN_{2S}-20.*C2/(C2+exp(2.533-0.0636*C2)) \qquad (32)$$

$$CN_3=CN_{2S}*exp(0.00673*C2) \qquad\qquad (33)$$

$$C2=100.-CN_{2S} \qquad\qquad (33a)$$

Fluctuations in soil water content cause the retention parameter to change according to the equation

$$s=s_1*(1.0-FFC/(FFC+exp(w1-w2*FFC))) \qquad\qquad (34)$$

where s_1 is the value of s associated with CN_1, FFC is the fraction of field capacity, and w1 and w2 are shape parameters. FCC is computed with the equation

$$FFC=(ST-WP)/(FC-WP) \qquad\qquad (35)$$

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).

Values for w1 and w2 are obtained from a simultaneous solution of Eq 34 according to the assumptions that $s=s_2$ when FCC=0.6 and $s=s_3$, when (ST-FC)/(PO-FC)=0.5

$$w1=X1+60.*w2 \tag{36}$$

$$w2=(X1-X2)/(POFC-60.) \tag{37}$$

$$X1=\ln(60./(1.0-s_2/s_1)-60.) \tag{37a}$$

$$X2=\ln(POFC/(1.0-s_3/s_1)-POFC) \tag{37b}$$

$$POFC=100.+50.*X3/X4 \tag{37c}$$

$$X3=sum(PO(l)-WP(l)), l=1,M \tag{37d}$$

$$X4=sum(FC(l)-WP(l)), l=1,M \tag{37e}$$

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 36 and 37 assure that CN_1 corresponds with the wilting point and that the curve number cannot exceed 100.

The FFC value obtained in Eq 35 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

$$FFC'=X1/X2 \tag{38}$$

$$X1=sum(FFC(l)*X2) \tag{38a}$$
$$X2=sum((Z(l)-Z(l-1))/Z(l)); \quad l=1,M \tag{38b}$$

$$Z(l)<1.0m \tag{38c}$$

where FFC' is the depth weighted FFC value for use in Eq 34 and Z is the depth in m to the bottom of soil layer l. Eq 38 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.

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

$$s'=0.1*s \tag{39}$$

where s' is the retention parameter for frozen ground. Eq 39 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 30, 31, 34, 38, and 39. 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 30 to estimate runoff with Eq 29.

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

$$f = SATK*(s/(FT+1.)) \tag{40}$$

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

$$Q = sum(dt*(r-f)) \tag{41}$$

where dt is the time interval in h and r is the rainfall rate in mm h^{-1}.
Individual storm rainfall rates are generated from an exponential distribution taken from CLIGEN (Nicks, Lane, 1989).

$$r = r_p*(1.-(RTP-sum(r*dt))/XKP_1); \quad 0<t<t_p \tag{42}$$

$$r = r_p*(1.-(sum(r*dt)-RTP)/XKP_2); \quad t_p<t<DUR \tag{43}$$

where r_p is the peak rainfall rate in mm h^{-1}, t_p is the time to peak of the storm in h, RTP is the rainfall volume at t_p in mm, DUR is the rainfall duration in h, and XKP_1 and 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 XKP_1 and XKP_2 are determined by solving the dimensionless exponential equations between the limits $0.01<r/r_p<1.0$.

$$r = r_p*exp((t-t_{pu})/XK_1)); \quad 0<t<t_{pu} \tag{44}$$

$$r = r_p*exp((t_{pu}-t)/XK_2); \quad t_{pu}<t<DUR \tag{45}$$

$$XK_1 = t_{pu}/4.605 \tag{46}$$

$$XK_2 = (1.-t_{pu})/4.605 \tag{47}$$

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

$$DUR = RFV/(r_p*(XK_1+XK_2)) \tag{48}$$

Finally the storm parameters XKP_1 and XKP_2 are available.

$$XKP_1 = XK_1*DUR \tag{49}$$

$$XKP_2 = XK_2*DUR \tag{50}$$

The value of r_p is obtained as described in the water erosion section and RTP is the product of 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

$$q_p = bq*r*WSA/360. \tag{51}$$

where q_p is the peak runoff rate in $m^3 \ s^{-1}$, bq 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

$$bq = Q/RFV \tag{52}$$

Since RFV is input and Q is computed with Eqs 29 or 41, bq can be calculated directly. Rainfall intensity can be expressed with the relationship

$$r = RFV_{TC}/TC \tag{53}$$

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,

$$RFV_{TC} = alp*RFV_{24} \tag{54}$$

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

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The peak runoff equation is obtained by substituting Eqs 52, 53, and 54 into Eq 51.

$$q_p = alp*Q*WSA/(360.*TC) \tag{55}$$

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

$$TC = TC_C + TC_S \tag{56}$$

where TC 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

$$TC_C = L_C/VCH \tag{57}$$

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

$$L_C = sqrt(L*L_{CA}) \tag{58}$$

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

$$TC_C = sqrt(L*L_{CA}*n^{0.75}/(0.489*q_c^{0.25}*CHS^{0.375})) \tag{59}$$

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

$$TC_C = 1.75*L*n^{0.75}/(WSA^{0.125}*CHS^{0.375}) \tag{60}$$

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

$$q_c' = q_{c1}/sqrt(WSA) \tag{61}$$

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

$$q_{c1} = Q/DUR \tag{62}$$

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

$$DUR = -4.605/(2.*ln(1.-alp_{.5})) \tag{63}$$

where $alp_{.5}$ is computed with Eq 54 using $RFV_{.5}$ instead of RFV_{TC}. Eq 63 is derived assuming rainfall intensity is exponentially distributed. Details of the procedure for estimating $alp_{.5}$ and DUR are given in the water erosion section of this chapter.

Substituting Eq 62 into Eq 60 gives the final equation for TC_C

$$TC_C=1.75*L*n^{0.75}/(q_{c1}^{0.25}*WSA^{0.125}*CHS^{0.375}) \qquad (64)$$

A similar approach is used to estimate TC_S:

$$TC_S=SPLG/OFV \qquad (65)$$

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

$$OFV=0.8375*d^{0.667}*STP^{0.5}/n \qquad (66)$$

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

$$d=(q_o*n)^{0.375}/(5.025*STP^{0.5}) \qquad (67)$$

where q_o is the average flow rate in m^3 s^{-1}. Substituting Eqs 66 and 67 into Eq 65 gives

$$TC_S=0.0216*(SPLG*n)^{0.75}/(q_{c1}^{0.25}*STP^{0.375}) \qquad (68)$$

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 54, an expression for the minimum value of alp, alpmn, is obtained

$$alpmn=TC/24. \qquad (69)$$

Thus, alp ranges within the limits

$$alpmn<alp<1. \qquad (69a)$$

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 (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

$$q_p = q_{p'} * RFV \qquad (70)$$

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

$$TC = TC_C + TC_S + TC_{SF} \qquad (71)$$

where TC is the watershed time of concentration in h and TC_C, TC_S, and TC_{SF} are the TC components attributed to channel flow, surface flow, and shallow channel flow. The channel component is computed with the equation

$$TC_C = (CHL-SPLG-SFL)*n/(3.6*d^{0.667}*CHS^{0.5}) \qquad (72)$$

where TC_C 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^{-1}. The shallow flow component of TC is estimated with the equation

$$TC_{SF} = SFL/SFV \qquad (73)$$

where SFV the average shallow flow velocity in km h^{-1} is estimated with the equation

$$SFV = 17.7*STP^{0.5}; \quad SFV < 2.19 \text{ km h}^{-1} \qquad (74)$$

where STP is surface flow slope in m m^{-1}. The length of shallow flow, SFL is estimated with the equations

$$SFL = 0.05; \quad L > 0.1 \text{ km} \qquad (75)$$

$$SFL = L-0.05; \quad 0.05 < L < 0.1 \text{ km} \qquad (75a)$$

$$SFL = 0.0; \quad L < 0.05 \text{ km} \qquad (75b)$$

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

$$TC_S = 0.0913*(SPLG*n)^{0.8}/(STP^{0.4}*RFV^{0.5}) \qquad (76)$$

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.

The storage routing technique 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

$$ST(l)=(STo(l)-FC(l))*exp(-dt/TT(l))+FC(l) \qquad (77)$$

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.

$$O(l)=(ST(l)-FC(l))*(1.-exp(-24./TT(l))) \qquad (78)$$

where O is the flow rate for layer l in mm d^{-1}.

Travel time through a layer is computed with the linear storage equation

$$TT(l)=(PO(l)-FC(l))/SC(l) \qquad (79)$$

where PO is the porosity in mm, FC is field capacity in mm, and SC is saturated conductivity in mm h^{-1}.

Vertical and horizontal flows are partitioned using the equation

$$QV(l)+QH(l)=(ST(l)-FC(l))*X3; \quad ST(l)>FC(l) \qquad (80)$$

$$X3=1.-exp(-24./TT_V(l))*exp(-24./TT_H(l)) \qquad (80a)$$

where QV is the vertical flow or percolation rate in mm d^{-1}, QH is the horizontal flow or lateral subsurface flow rate in mm d^{-1}, TT_V is the vertical travel time in h, TT_H is the horizontal travel time in h, and subscript l is the soil layer number. The vertical travel time is computed with Eq 79 and the horizontal travel time is computed with the equation

$$TT_H(l)=HST(l)/HCL(l) \qquad (81)$$

where HST is the soil water storage in mm and HCL is the horizontal saturated flow rate in mm h^{-1}. The horizontal saturated flow rate is computed with the equation

$$HCL(l)=SC(l)*STP \qquad (82)$$

where STP is the land slope in m m^{-1}. The horizontal storage is computed with the equation

$$ST(l)=(PO(l)-FC(l))*0.5*SPLG/DZ \qquad (83)$$

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 80 leads to the equation

$$QV(l)+QV(l)*X2/X1=(ST(l)-FC(l))*X3 \qquad (84)$$

$$X1=1.-exp(-24./TT_V(l)) \qquad (84a)$$

$$X2=1.-exp(-24./TT_H(l)) \qquad (84b)$$

Solving for QV gives the final percolation equation

$$QV(l)=(ST(l)-FC(l))*X3/(1.+X2/X1) \qquad (85)$$

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

$$SSF(l)=0.001*(ST(l)-FC(l)-QV(l))*SPLG/RCHL \qquad (86)$$

$$QRF(l)=ST(l)-FC(l)-QV(l)-SSF(l) \qquad (87)$$

where QRF is quick return flow rate in mm d^{-1}, SSF is the subsurface flow rate in mm d^{-1}, 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

$$CPVV(l)=CPRV(l)*QI(l) \qquad (88)$$

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

$$CPVH(l)=CPRH(l)*(I(l)-CPVV(l)) \qquad (89)$$

where CPVH is the horizontal pipe flow rate in mm d^{-1} and CPRH is the fraction of inflow partitioned to horizontal pipe flow. CPRH is added to quick return flow. The operating sequence is Eq 88, Eq 89, Eqs 80-87.

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

$$UF(l)=bu1*(0.8*T_2+0.2*T_1)^{bu2} \tag{90}$$

$$bu2=(WP2-FC2)/1.6576 \tag{90a}$$

$$bu1=10.^{(WP2-3.1761*bu2)} \tag{90b}$$

$$WP2=\log(WP(l)) \tag{90c}$$

$$FC2=\log(FC(l)) \tag{90d}$$

where UF is the upward flow from layer l to layer l-1 in mm and the water tension in layer l is T_2 and in layer l-1 is T1. Note that
T_2 receives a greater weighting than T_1 in simulating the process. Water tension for any water content is estimated using the equation

$$T_2=10.^{(3.1761-1.6576*(\log(ST(l)-WP2)/(FC2-WP2))} \tag{91}$$

The same equation with appropriate values is used to compute T_1.

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

$$SC(l)=12.7*X1*SS(l)/(X1+\exp(11.45-0.097*X1))+1.0 \tag{92}$$

$$X1=100.-CLA(l) \tag{92a}$$

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.

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

$$EO=(RN*DLT/HV+GMA*FWV*VPD)/(DLT+GMA) \tag{93}$$

$$RN=RA*(1.0-AB)-RBO*(0.9*RA/RAMX+0.1) \tag{93a}$$

$$DLT=EA*(6790.5/TK-5.029)/TK \tag{93b}$$

$$HV=2.501-0.0022*TX \tag{93c}$$

$$GMA=6.595E-4*PB \tag{93d}$$

$$PB=101.3-ELEV*(.01152-5.44E-7*ELEV) \tag{93e}$$
$$FWV=2.7+1.63*U10 \tag{93f}$$

$$RBO=(0.34-0.14*sqrt(ED))*4.9E-9*TK^4 \tag{93g}$$

$$VPD=EA-ED \tag{93h}$$

$$EA=.1*exp(54.879-5.029*ln(TK)-6790.5/TK) \tag{93i}$$

$$ED=EA*RH \tag{93j}$$

where EO is the potential evaporation in mm d^{-1}, DLT is the slope of the saturation vapor pressure curve in kPa $^oC^{-1}$, GMA is a psychrometer constant in kPa $^oC^{-1}$, RN is the net radiation in MJ m $^{-2}$ d^{-1}, HV is the latent heat of vaporization in MJ kg^{-1}, FWV is a wind speed function in mm d^{-1} 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 ^oC and ^oK, VPD is the vapor pressure deficit in kPa, U10 is the mean wind speed at 10 m height in m s^{-1}, RA is the solar radiation in MJ m $^{-2}$ d^{-1}, RAMX is the clear day radiation at the surface in MJ m^{-2} d^{-1}, RBO is the net outgoing long wave radiation in MJ m $^{-2}$ 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_2 changes (Stockle et al., 1992). The Penman-Monteith equation is expressed as

$$EO=(RN*DLT+86.66*AD*VPD*U10/350.)/(HV*(DLT+GMA)) \quad (94)$$

$$EP=(RN*DLT+86.66*AD*VPD/AR)/(HV*(DLT+GMA*(1.+CR/AR))) \quad (95)$$

$$AD=.01276*PB/(1.+.00367*TX) \qquad (95a)$$

$$AR=6.25*(\ln((ZZ-Z_D)/Z_0))^2/UZZ \qquad (95b)$$

$$UZZ=U10; \quad CPHT<8. \qquad (95c)$$
$$ZZ=10.$$

$$UZZ=U10*LN(ZZ/.0005)/9.9035; \quad CPHT>8. \qquad (95d)$$
$$ZZ=CHMX+2.$$

$$Z_0=0.131*CPHT^{0.997} \qquad (95e)$$

$$Z_D=0.702*CPHT^{0.979} \qquad (95f)$$

$$CR=p1/(SMLA*G1*exp(.00155*(330.-CO_2)) \qquad (95g)$$

$$G1=GSI*FVPD \qquad (95h)$$

$$FVPD=1.0-bx*(VPD-VPTH)); \quad 0.1<FVPD<1.0 \qquad (95i)$$

where AD is the air density in kg m^{-3}, EP is the potential plant evaporation in mm d^{-1}, CR is the canopy resistance for vapor transfer in s m^{-1}, AR is the aerodynamic resistance for heat and vapor transfer in s m^{-1}, CPHT is crop height in m, CHMX is maximum potential crop height in m, Z_D is the displacement height of the crop in m, Z_0 is the surface roughness parameter in m, UZZ is the daily mean wind speed adjusted for the crop height in m s^{-1}, 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^{-1}, VPTH is the threshold vapor pressure for the crop, bx is a crop coefficient, and CO_2 is the atmospheric carbon dioxide concentration in g m^{-3}.

Priestly-Taylor

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

$$EO=1.28*(RN*(1.0-AB)/HV)*DLT/(DLT+GMA) \qquad (96)$$

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

$$EO=0.0032*(RAMX/HV)*(TX+17.8)*(TMX-TMN)^{0.6} \qquad (97)$$

where TMX and TMN are the daily maximum and minimum air temperatures in $^{\circ}$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

$$EO=0.288*TMX-0.144*TMN+0.139*RAMX-4.931 \qquad (98)$$

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

$$AB=0.23*(1.-EAJ)+SALB*EAJ \qquad (99)$$

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

$$EAJ=exp(-X1) \qquad (100)$$

$$X1=max(0.4*SMLA,0.1*(CV+.1)) \qquad (100a)$$

where CV is the weight of all above ground plant material in t ha^{-1}.

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

$$EP=LAI*EO/3.; \quad 0.0<LAI<3.0 \qquad (101)$$

$$EP=EO; \qquad LAI>3.0 \qquad (101a)$$

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

$$EO'=EO-RFI; \quad RFI<EO \qquad (102)$$

$$EP'=min(EO',EP) \qquad (102a)$$

$$EO'=EO; \qquad RFI>EO \qquad (103)$$

$$SWLT=SWLT+RFI-EO \qquad (103a)$$

$$EP'=0.0 \qquad (103b)$$

$$ES=0.0 \qquad (103c)$$

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where EO' is the potential evaporation in mm d^{-1} 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 102) the excess EO can be used for plant or soil evaporation. If the reverse is true (Eq 103) 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

$$ES=EO'*EAJ \qquad\qquad\qquad (104)$$

$$ES'=min(ES,ES*EO'/(ES+EP')) \qquad\qquad (105)$$

where ES is the potential soil water evaporation rate in mm d^{-1}. Eq 105 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

$$EVZ=ESR*Z/(Z+exp(2.374-0.00713*Z)) \qquad\qquad (106)$$

EVZ is the total potential soil water evaporation in mm d^{-1} from soil of depth Z in mm and ESR is the potential soil evaporation remaining after snow and litter evaporation. The coefficients of Eq 106 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

$$SEV(l)=EVZ(l)-EVZ(l-1) \qquad\qquad\qquad (107)$$

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

$$SEV'(l)=SEV(l)*exp(2.5*(ST(l)-FC(l))/(FC(l)-WP(l))); \quad WP<ST<FC \quad (108)$$

$$SEV'(l)=SEV(l); \quad FC<ST \qquad\qquad\qquad (108a)$$

$$SEV'(l)=ST(l)-p5*WP(l); \quad (ST(l)-p5*WP(l))<SEV(l) \qquad (108b)$$

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 ^{o}C. Snow is melted as a function of the snow pack temperature using the equation

$$SML=AMAX1(0.,X1*(1.52+.54*F*SNPKT)); \quad 0.0<SML<SNO \qquad (109)$$

$$SNPKT=.3333*(2.*X2+TX) \qquad\qquad\qquad (109a)$$

$$X1 = sqrt(TMX*RA) \qquad \qquad \qquad (109b)$$

$$X2 = min(DST0,STMP(2)) \qquad \qquad (109c)$$

$$F = TSNO/(TSNO+exp(5.34-2.395*TSNO)) \qquad (109d)$$

where SML is the snowmelt rate in mm d^{-1}, SNO is the snow present in mm of water, STMP is the temperature in ^{o}C of soil layer 2, SNPKT is the snow pack temperature in ^{o}C, DST0 is the soil surface temperature in ^{o}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. The driving mechanism is the volume of groundwater storage relative to the maximum groundwater storage.

$$WTBL = WTMX+(WTMN-WTMX)*X1/(X1+exp(8.185-0.0809*X1)) \quad (110)$$

$$X1 = 100.*GWST/GWMX \qquad \qquad (110a)$$

where WTBL is the current depth in m from the surface to the water table, WTMX and WTMN are the maximum and minimum annual depths in m, GWST is the groundwater storage in mm, and GWMX is the maximum groundwater storage in mm. If the the water table is within 1m of the soil surface it can cause aeration stress (more stress as it approaches the surface). If it is below 1 m it provides needed water to reduce water stress.

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

$$Y=X*EK*CVF*PE*SL*ROKF \tag{111}$$

$$X=EI \qquad\qquad USLE, RUSLE \tag{111a}$$

$$X=0.646*EI+0.45*(Q*q_p)^{0.33} \quad Onstad\text{-}Foster \tag{111b}$$

$$X=1.586*(Q*q_p)^{0.56}*WSA^{0.12} \quad MUSLE \tag{111c}$$

$$X=2.5*(Q*q_p)^{0.5} \qquad MUST \tag{111d}$$

$$X=0.79*(Q*q_p)^{0.65}*WSA^{0.009} \quad MUSS \tag{111e}$$

$$X=by1*Q^{by2}*q_p^{~by3}*WSA^{by4} \quad MUSI \tag{111f}$$

where Y is the sediment yield in t ha^{-1}, 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_p is the peak runoff rate in mm h^{-1}, 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....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).

$$SL=(SPLG/22.127)^{XM}*(STP*(65.41*STP+4.56)+.065) \tag{112}$$

$$XM=0.3*STP/(STP+exp(-1.47-61.09*STP))+0.2 \tag{112a}$$

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

$$SL=RSF*RLF \tag{113}$$

$$RSF=10.8*STP+0.03; \quad SPLG>4.57; \quad STP<0.09 \tag{113a}$$

$$RSF=16.8*STP-0.5; \quad SPLG>4.57; \quad STP>0.09 \tag{113b}$$

$$RSF=X1; \quad SPLG<4.57 \tag{113c}$$

$$X1=3.*STP^{0.8}+.56 \tag{113d}$$

$$RLF=(SPLG/22.127)^{RXM} \tag{113e}$$

$$RXM=B/(1.+B) \tag{113f}$$

$$B=STP/(.0896*X1) \tag{113g}$$

The APEX user may choose Eq 112 or 113 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

$$CVF=FRSD*FBIO*FRUF \qquad (114)$$

$$FRSD=\exp(-0.75*CVRS) \qquad (114a)$$

$$FBIO=1.-FGC*\exp(-0.1*CPHT) \qquad (114b)$$

$$FRUF=\exp(-.026*(RRUF-6.1)) \qquad (114c)$$

$$FGC=STL/(STL+\exp(1.175-1.748*STL)) \qquad (114d)$$

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^{-1}, 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^{-1}, 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

$$EK=X1*X2*X3*X5 \qquad (115)$$

$$X1=0.2+0.3*\exp(-0.0256*SAN*(1.-.01*SIL)) \qquad (115a)$$

$$X2=(SIL/(CLA+SIL))^{0..3} \qquad (115b)$$

$$X3=1.0-0.25*WOC/(WOC+\exp(3.718-2.947*WOC)) \qquad (115c)$$

$$X5=1.0-0.7*SN1/(XX+\exp(-5.509+22.899*SN1)) \qquad (115d)$$

$$SN1=1.0-0.01*SAN \qquad (115e)$$

where SAN, SIL, and CLA, and WOC are the sand, silt, clay, and organic carbon contents of the soil in % . Eq 115 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_p. To estimate the daily rainfall energy in the absence of time-distributed rainfall, it is assumed that the rainfall rate is exponentially distributed:

$$r_t=r_p*\exp(-t/k) \qquad (116)$$

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where r_t is the rainfall rate at time t in mm h^{-1}, r_p is the peak rainfall rate in mm h^{-1}, and k is the decay constant in h. Eq 116 contains no assumption about the sequence of rainfall rates (time distribution). The USLE energy equation in metric units is

$$RE=dRFV*(12.1+8.9*\log(dRFV/dt)) \qquad (117)$$

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 116 for rainfall rate to yield the equation

$$RE=RFV*(12.1+8.9*(\log(r_p)-0.434)) \qquad (118)$$

The rainfall energy factor, EI, is obtained by multiplying Eq 118 by the maximum 0.5-h rainfall intensity $(r_{.5})$ and converting to the proper units:

$$EI=RFV*(12.1+8.9*(\log(r_p)-0.434))*r_{.5}/1000. \qquad (119)$$

To compute values for r_p, Eq 116 is integrated to give

$$RFV=r_p*k \qquad (120)$$

$$RFV_t=RFV*(1.0-\exp(-t/k)) \qquad (121)$$

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

$$RFV_{.5}=RFV*alp_{.5} \qquad (122)$$

To determine the value of r_p, Eqs 122 and 120 are substituted into Eq 121 to give

$$r_p=-2.0*RFV*\ln(1.0-alp_{.5}) \qquad (123)$$

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).

$$F=1.0/(2.0*NWD*NY) \qquad (124)$$

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

$$RFV_{.5a}=-RFV_{.5u}/\ln(F) \qquad (125)$$

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

$$alp_{.5}=RFV_{.5a}/RFV \qquad (126)$$

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^{-1} is generally near the upper limit of rainfall intensity) into Eq 121

$$alp_{.5u}=1.0-exp(125.0/RFV) \qquad (127)$$

where $alp_{.5u}$ is the upper limit of $alp_{.5}$. The peak of the .5 triangular distribution is $alp_{.5}$ from Eq 126.

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

$$ROKF=exp(-0.03*ROK) \qquad (128)$$

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

$$QPX=QXM/24. \qquad (129)$$

where QPX is the flow rate in mm h^{-1} and QXM is the application rate in mm d^{-1}. For furrow irrigation the flow rate is converted to m^3 s^{-1} to determine the flow velocity.

$$QPX'=2.778E-6*QPX*RINT*WSA/FW \qquad (130)$$

where QPX' is the flow rate in m^3 s^{-1}, 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

$$VX=R^{0.667}*WSX \qquad (131)$$

$$WSX=sqrt(STP)/n \qquad (131a)$$

$$R=AX/PX \qquad (131b)$$

$$AX=0.5*DX*X2 \qquad (131c)$$

$$X2=DX*X1 \qquad (131d)$$

X1=1000.*RINT/RHTT   (131e)

PX=2.0*sqrt(DX*DX+0.25*X2*X2)   (131f)

DX=(2.0*QPX/(WSX*X1*(1.0/(4.0+16.0/(X1*X1)))$^{0.333}$))$^{0.375}$ (131g)

where VX is the flow velocity in m s^{-1}, STP is the field slope in
m m^{-1}, n is Manning's roughness coefficient, AX is the cross sectional area in m^2, 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   (132)

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

CY=CY$_1$*VX^{p31} (133)

where CY$_1$ is the sediment concentration at a velocity at of 1.0
m s^{-1} and p31 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   (134)

Wind

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.

Basic Equation

The basic WECS wind erosion equation is

YW=FI1*FRF*FV*FD*YWR   (135)

where YW is the wind erosion in kg m^{-1}, FI1 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)$^{1.5}$ (136)

USTR=0.0408*DU10   (136a)

$$USTRT=0.0161*sqrt(DIAM) \hspace{3cm} (136b)$$

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 136 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

$$YWR'=0.255*(USTR^2-USTRT^2-0.5*(ST/WP)^2)^{1.5} \hspace{2cm} (137)$$

Soil Erodibility Factor

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

$$FI1=FI/695. \hspace{4cm} (138)$$

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.

Roughness Factor

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)

$$FR=1.0-exp(-(wn1/RFB)^{RFC}) \hspace{3cm} (139)$$

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

The coefficient RFC is calculated with the equation

$$RFC=0.77*1.002^{RHTT} \hspace{3cm} (140)$$

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

$$RFB=RRF+RIF \hspace{4cm} (141)$$

$$RRF=11.9*(1.-exp(-(RRUF/9.8)^{1.3})) \hspace{2.5cm} (141a)$$

$$RIF=abs(sin(wn2))*1.27*RHTT^{0.52} \hspace{2.5cm} (141b)$$

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.

Vegetative Cover Factor

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.

$$VGF=1.-X1/(X1+\exp(-0.331-1.055*X1)) \tag{142}$$

$$X1=bwn(1)*STL+bwn(2)*STD+bwn(3)*RSD \tag{142a}$$

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.

Unsheltered Distance Factor

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

$$FD=1.-\exp(-WL/wn3) \tag{143}$$

$$WL=FL*FW/(FL*abs(\cos(BT))+FW*abs(\sin(BT))) \tag{143a}$$

$$BT=1.571+THW-ANG \tag{143b}$$

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 137 and 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.

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 155 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.

$$YMNU=0.25*(Q*q_p)^{0.5}*PE*SL*RSDM^{0.5}*exp(-.15*AGPM)) \qquad (144)$$

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.

NUTRIENTS

Nitrogen

Nitrate Losses--Leaching, Surface Runoff, Lateral Subsurface Flow

The amount of NO3-N lost when water flows through a layer is estimated by considering the change in concentration. Thus, the equation

$$QNO3=QT*CNO3 \qquad (145)$$

where QNO3 is the amount of NO3-N lost from a soil layer and CN03 is the average concentration of NO3-N in the layer during the percolation of volume QT through the layer. At the end of the day, the amount of NO3-N left in the layer is

$$WNO3'=WNO3-QT*CNO3 \qquad (146)$$

where WNO3 and WNO3' are the weights of NO3-N contained in the layer at the beginning and ending of the day. The NO3-N concentration can be calculated by dividing the weight of NO3-N by the water storage volume:

$$CNO3'=CNO3-CNO3*QT/(bs1*PO) \qquad (147)$$

where CNO3' is the concentration of NO3-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 147 is a finite difference approximation for the exponential equation

$$CNO3'=CNO3*exp(-QT/(bs1*PO) \qquad (148)$$

Thus, QNO3 can be computed for any volume, QT, by integrating Eq 148

$$QNO3=WNO3*(1.0-exp(-QT/(bs1*PO)) \qquad (149)$$

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

$$CNO3=QNO3/QT \qquad (150)$$

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.

$$p14=CS/CO \qquad\qquad\qquad (151)$$

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

$$QNO3=CO*QV+CS*QH \qquad\qquad\qquad (152)$$

Substituting Eq 151 into Eq 152 and solving for CO gives

$$CO=QNO3/(QV+p14*QH) \qquad\qquad\qquad (153)$$

$$CS=p14*CO \qquad\qquad\qquad (153a)$$

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

$$ENO3=SEV(l)*CNO3(l) \qquad\qquad\qquad (154)$$

where ENO3 is the amount of NO3-N in kg ha^{-1} 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

$$YON=0.001*Y*CON*ER \qquad\qquad\qquad (155)$$

where YON is the organic N runoff loss in kg ha^{-1}, Y is the sediment yield in t ha^{-1}, CON is the concentration of organic N in the top soil layer in g t^{-1}, 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

$$DR=(q_p/rep)^{0.56} \tag{156}$$

where DR is the sediment delivery ratio (sediment yield divided by gross sheet erosion), q_p is the peak runoff rate in mm h^{-1}, and rep is the peak rainfall excess rate in mm h^{-1}. Eq 156 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

$$rep=r_p*(Q/RFV)^{0.1} \tag{157}$$

where r_p is the peak rainfall rate in mm h^{-1} 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

$$ER=be1*CY^{be2} \tag{158}$$

where CY is the sediment concentration in g m^{-3} 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 154 at the boundaries assuming that sediment concentrations range from 500 to 250,000 g m^{-3} gives

$$be2=log(DR)/2.699 \tag{159}$$

$$be1=1.0/0.1^{be2} \tag{160}$$

Denitrification

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

$$DN=WNO3*(1.-exp(-1.4*TFN*WOC)); \quad SWF>0.95 \tag{161}$$

$$DN=0.0; \quad SWF<0.95 \tag{161a}$$

where DN is the denitrification rate in kg $ha^{-1} d^{-1}$, 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

$$TFN=STMP/(STMP+exp(5.059-0.2504*STMP)) \tag{162}$$

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

$$SWF=0.1*(ST/WP)^2; \quad ST<WP \hspace{4cm} (163)$$

$$SWF=0.1+0.9*sqrt((ST-WP)/(FC-WP)); \quad ST>WP \hspace{2cm} (163a)$$

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 (Izaurralde et al., submitted). 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):

$$STDNE=STDN+Sf*(WNO3+WNH3); \quad CNR \geq 10 \hspace{2cm} (164)$$

$$STDNE=STDN; \quad CNR < 10 \hspace{4cm} (164a)$$

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):

$$LMF=0.85 – 0.018*STDL/STDNE; \quad STDL/STDNE < 47.22 \hspace{2cm} (165)$$

$$LMF=0.0; \quad STDL/STDNE = 47.22 \hspace{3cm} (165a)$$

LSF=1.0-LMF   (166)

LM=LMF*STD   (167)

LS=LSF*STD   (168)

Next, all of the lignin in the standing dead (STDL) is transferred to the structural litter (Parton et al., 1987):

LSL=STDL   (169)

LSLF=LSL/LS   (170)

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:

LSC=Cf*LSF*STD   (171)

LSN=LSC/150;   STDNE $\geq$ LSC/150   (172)

LSN=STDNE;   STDNE $<$ LSC/150   (172a)

LSNF=LSN/LS   (173)

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:

LMC=Cf*LM   (174)

LMN=STDNE – LSN   (175)

LMNF=LMN/LM   (176)

The potential transformation of C in structural litter (LSCTP) on the surface and subsurface is calculated with Eq 177 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_{LSLF}, Eq 178), and a combined factor (CS, Eq 179) expressing the effects of temperature (TFN, Eq 162), soil water content (SWF, Eq 163), oxygen (OX, Eq 179a), and tillage (TBP, Eq 179b) 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.

LSCTP=LSC*LSR*X_{LSLF}*CS   (177)

X_{LSLF}=exp(-3*LSLF)   (178)

CS=sqrt(TFN*SWF)*0.8*OX*TBA);   CS $<$ 10   (179)

OX=1.0-0.9*Z_5/(Z_5+exp(16.79-0.0196*Z_5))   (179a)

TBP=exp(6.0*(BD-BDP))   (179b)

The potential transformation of C in lignin of structural litter (LSLCTP) is computed with Eq 180 while the potential transformations of C (LSL_NCTP) and N (LSNTP) in non-lignin components of structural litter are calculated with Eqs 181 and 182.

$$LSLCTP= \quad LSCTP*LSLF \qquad\qquad (180)$$

$$LSL_NCTP= \quad LSCTP*(1 - LSLF) \qquad\qquad (181)$$

$$LSNTP=LSN*(LSCTP/LSC) \qquad\qquad (182)$$

The metabolic litter is transformed into microbes (Active) (surface =0.40; subsurface = 0.45) or CO_2 (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):

$$LMCTP=CS*LMR*LMC \qquad\qquad (183)$$

$$LMNTP=LMN*(LMCTP/LMC) \qquad\qquad (184)$$

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:

$$BMCTP=BMC*BMR*CS*X_{BMT} \qquad\qquad (185)$$

$$BMNTP=BMN*(BMCTP/BMC) \qquad\qquad (186)$$

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

$$HSCTP=HSC*HSR*CS \qquad\qquad (187)$$

$$HDNTP=HSN*(HSCTP/HSC) \qquad\qquad (188)$$

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

$$HPCTP=HPC*HPR*CS \qquad\qquad (189)$$

$$HPNTP=HPN*(HPCTP/HPC) \qquad\qquad (190)$$

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

$$ABL=BMC*(1.0-exp(-QV/(0.01*ST+0.1*KdBM*BD)) \qquad\qquad (191)$$

where BMC is the weight of C in soil microbial biomass and associated products in kg ha^{-1}, ABL is the amount of C leached in kg ha^{-1}, 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^{-3}.

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):

$$NCBM = 1.0/(-5.0251*Nf+20.05); \qquad 2.0 \geq Nf \geq 0.01 \qquad\qquad (192)$$

$$NCBM = 0.05; \quad Nf < 0.01 \qquad\qquad (192a)$$

$$CBM = 0.1; \quad Nf > 2.0 \qquad\qquad (192b)$$

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:

$$NCBM = 1/(b*MINT+a); \qquad MINT \leq 20 \text{ kg ha}^{-1} \qquad\qquad (193)$$

$$NCBM = 0.33; \qquad MINT > 20 \text{ kg ha}^{-1} \qquad\qquad (194)$$

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^{-1} 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.

PT_1: Structural litter → Biomass $PN_1 = LSL_N CTP*(1-ALSL_N CO2)*NCBM$ (195)

PT_2: Structural litter → Slow $PN_2 = LSLCTP*(1-ALSLCO2)*NCHS$ (196)

PT_3: Metabolic litter → Biomass $PN_3 = LMCTP*(1-ALMCO2)*NCBM$ (197)

PT_4: Biomass → Leaching $PN_4 = BMCTP*ABL*NCBM$ (198)

PT_5: Biomass → Passive $PN_5 = BCTP*ABP*NCHP$ (199)

PT_6: Biomass → Slow $PN_6 = BMCTP*(1-ABL-ABP- ABCO2)*NCHS$ (200)

PT_7: Slow → Biomass $PN_7 = HSCTP*(1 - ASCO2 - ASP)*NCBM$ (201)

PT_8: Slow → Passive $PN_8 = HSCTP*ASP*NCHP$ (202)

PT_9: Passive → Biomass $PN_9 = HPCTP*(1-APCO2)*NCBM$ (203)

PT_{10}: Plant Demand $PN_{10} = UNDP$ (UND, From Williams, 1995). (204)

Total Demand for Nitrogen (NP_T) $NP_T = \sum PN$ $_I$ (205)

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, $NMIN_1$) as the difference between the potential transformation of N in structural litter (LSNTP) and the potential net demand for that transformation (PN_1 and PN_2) upon the condition that $LSNTP \geq PN_1 + PN_2$ (Eq 206). Otherwise, the model calculates the amount of N that has to be competed against other transformations (CPN_1):

$$NMIN_1 = LSNTP - (PN1 + PN2); \qquad LSNTP \geq (PN_1 + PN_2) \qquad\qquad (206)$$

$$CPN_1 = PN_1 + PN_2 - LSNTP; \qquad LSNTP < (PN_1 + PN_2) \qquad\qquad (206a)$$

Similar calculations are made for the N transformations from metabolic litter to biomass ($NMIN_2$, CPN_2), biomass turnover ($NMIN_3$, CPN_3), slow turnover ($NMIN_4$, CPN_4), and passive turnover ($NMIN_5$, CPN_5):

$$NMIN_2 = LMNTP - PN_3; \qquad LMNTP \geq PN_3 \qquad\qquad (207)$$

$$CPN_2 = PN_3 - LMNTP; \qquad LMNTP < PN_3 \qquad\qquad (207a)$$

$$NMIN_3 = BMNTP - PN_4 + PN_5 + PN_6; \qquad BMNTP \geq PN_4 + PN_5 + PN_6 \qquad\qquad (208)$$

$$CPN_3 = PN_4 + PN_5 + PN_6 - BMNTP; \qquad BMNTP < PN_4 + PN_5 + PN_6 \qquad\qquad (208a)$$

$$NMIN_4 = HSNTP - PN_7 + PN_8; \qquad HSNTP \geq PN_7 + PN_8 \qquad\qquad (209)$$

$$CPN_4 = PN_7 + PN_8 - HSNTP; \qquad HSNTP < PN_7 + PN_8 \qquad\qquad (209a)$$

$$NMIN_5 = HPNTP - PN_9; \qquad HPNTP \geq PN_9 \qquad\qquad (210)$$

$$CPN_5 = PN_9 - HPNTP; \qquad HPNTP < PN_9 \qquad\qquad (210a)$$

Gross N mineralization (NMING) is calculated with Eq 211 as the sum of all partial N transformations ($NMIN_i$). The total net competitive demand for N (SUMP) is calculated as the sum of all demands for transformations, including plant uptake ($CPN_6 = PN_{10}$) that could not supply their own N (Eq 212).

$$NMING = \sum NMIN_i \qquad\qquad (211)$$

$$SUMP = \sum CPN_i \qquad\qquad (212)$$

This SUMP is then compared to the mineral N available (MINTEMP). 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 213).

$$CPNi = CPNi/SUMP*MINTMP \qquad\qquad (213)$$

The sum of all recalculated CPNi, except plant N uptake (CPN6), is termed N immobilization (NIMMOB) (Eq 214). Net N mineralization (NMINET) is calculated with Eq 215.

$$NIMMOB = \sum CPN_i \qquad\qquad (214)$$

$$NMINET = NMING - NIMMOB \qquad\qquad (215)$$

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 216-228.

$$LSCTA = LSCTP*CPN1/(PN1 + PN2 - LSNTP) \qquad\qquad (216)$$

$$LSLCTA=LSLCTP*LSCTA/LSCTP \qquad (217)$$

$$LSLNCTA= \quad LSLNCTP*LSCTA/LSCTP \qquad (218)$$

$$LSNTA=LSNTP*LSCTA/LSCTP \qquad (219)$$

$$LMCTA=LMCTP*CPN2/(PN3 – LMNTP) \qquad (220)$$

$$LMNTA=LMNTP*LMCTA/LMCTP \qquad (221)$$

$$BMCTA=BMCTP*CPN3/(PN4+PN5+PN6-BMNTP) \qquad (222)$$

$$BMNTA=BMCTA/BMCTP \qquad (223)$$

$$HSCTA=HSCTP*CPN4/(PN7+PN8-HSNTP) \qquad (224)$$

$$HSNTA=HSNTP*HSCTA/HSCTP \qquad (225)$$

$$HPCTA=HPCTP*CPN5/(PN9 – HPNTP) \qquad (226)$$

$$HPNTA=HPNTP*HPCTA/HPCTP \qquad (227)$$

$$UND=CPN6 \qquad (228)$$

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_2. 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 (Izaurralde et al., submitted), APEX calculates annual changes in BD due to changes in soil organic C (WOC) content using a modified version of the Adams equation (1973):

$$BD= 100/((WOC*1.724/0.244)+((100 – WOC*1.724) /BDM))); \qquad (229)$$
$$0 \le WOC < 58$$

$$BD=0.244; \qquad WOC > 58 \qquad (229a)$$

While the BD of soil organic matter is fairly constant (0.244 t m^{-3}), 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)

$$RNV=WNH3*(1.0-exp(-AKN-AKV)) \qquad (230)$$

$$AKN=TF*SWF'*PHF \qquad (230a)$$

$$TF=0.041*(STMP-5.0); \quad STMP>5.0 \qquad (230b)$$

$$SWF'=max(0.1,SWF,(ST-WP)/(ST_{25}-WP)); \quad ST<ST_{25} \qquad (230c)$$

$$SWF'=1.0; \quad ST_{25}<ST<FC \qquad (230d)$$

$$SWF'=max(0.1,1.0-(ST-FC)/(PO-FC)); \quad ST>FC \qquad (230e)$$

$$PHF=0.307*PH-1.269; \quad PH<7.0 \qquad (230f)$$

$$PHF=1.0; \quad 7.0<PH<7.4 \qquad (230g)$$

$$PHF=5.367-0.599*PH; \quad PH>7.4 \qquad (230h)$$

where RNV is the combined nitrification and volatilization
kg ha^{-1} d^{-1}, WNH3 is the weight of NH3 in kg ha^{-1}, AKN is the nitrification regulator, and AKV is the volatilization regulator, STMP is the soil temperature in ^{o}C, ST is the soil water content, WP is the wilting point soil water content, FC is the field capacity soil water content, ST_{25} 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 163.

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

$$AKV=TF*WNF; \quad surface \ soil \ layer \qquad (231)$$

$$WNF=0.335+0.16*ln(U10+0.2) \qquad (231a)$$

$$AKV=TF*FCEC*FZ; \quad all \ other \ layers \qquad (232)$$

$$FCEC=1.0-0.038*CEC; \quad FCEC>0.0 \qquad (232a)$$

$$FZ=1.0-Z_5/(Z_5+exp(4.55-0.00054*Z_5)) \qquad (232b)$$

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 230 is solved for each process separately and combined to give

$$RVOL=RNV*F1/(F1+F2) \qquad (233)$$

$$F1=1.0-\exp(-AKV) \hspace{4cm} (233a)$$

$$F2=1.0-\exp(-AKN) \hspace{4cm} (233b)$$

$$RNIT=RNV-RVOL \hspace{4cm} (233c)$$

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

$$YSP=0.01*CSP*Q/KD \hspace{3cm} (234)$$

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

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

$$YP=0.001*Y*CP*ER \hspace{3cm} (235)$$

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

$$RMP=DECR*FOP \hspace{3.5cm} (236)$$
$$DECR=0.05*CPRF*CS \hspace{3cm} (236a)$$

CPRF=exp(-.693*(CPR-200.)/200.) (236b)

CPR=580*RSD/(FOP+WPML) (236c)

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

HMP=CMP*CS*WPO (237)

where HMP is the humus P mineralization rate in kg ha^{-1} d^{-1}, CMP is the humus mineralization rate
constant (0.0003 d^{-1}), and WPO is the organic P content in 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

MPR=WPML-WPMA*PSP/(1.-PSP) (238)

where MPR is the mineral P flow rate in kg ha^{-1} d^{-1}, WPMA is the amount in the active mineral P pool
in 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 equation 238 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 WPMA*PSP/(1-PSP). Since reverse flow is much slower, equation 238 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

PSP=0.58-0.0061*CAC (239)

In noncalcareous, slightly weathered soils

PSP=0.02+0.014*WPML (240)

In noncalcareous, moderately weathered soils

PSP=0.0054*BSA+0.116*PH-0.73 (241)

In noncalcareous, highly weathered soils

43

$$PSP=0.46-0.0916\ln(CLA) \tag{242}$$

where PSP is the P sorption coefficient, CAC is the $CaCO_3$ concentration in g t^{-1}, PH is the soil pH, CLA is the soil clay content in %, and BSA is the base saturation by the ammonium acetate (NH_4OAc) 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

$$ASPR=bo*(4.0*WPMA-WPMS) \tag{243}$$

where ASPR is the flow rate between the active and stable mineral P pools in kg ha^{-1} d^{-1}, bo is the flow coefficient in d^{-1}, and WPMS is the amount of stable mineral P in kg ha^{-1}. The daily amount of P computed with equation 243 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, equation 243 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)

$$bo=\exp(-1.77*PSP-7.05) \tag{244}$$

for noncalcareous soils, and

$$bo=0.0076 \tag{245}$$

for calcareous soils.

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

$$PAPE=PAPR*PAEF \tag{247}$$

where PAPE is the effective amount of pesticide applied in g ha^{-1}, PAPR is the actual amount applied in g ha^{-1}, 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

$$GC=(1.0-\operatorname{erfc}(1.33*LAI-2.))/2.0 \tag{248}$$

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

$$FP=GC*PAPE \tag{249}$$

GP=PAPE-FP   (250)

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;   RFV>2.5mm   (251)

WO=0.0;   RFV<2.5mm   (251a)

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)   (252)

FP=FP$_0$*exp(-0.693/HLP)   (253)

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   (254)

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=0.01*PSQC*ST+0.1*PSYC*BD   (255)

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}, and BD is the soil bulk density in t m^{-3}. 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   (256)

where KD is the partitioning constant in m^3 t. The value of KD is computed from the equation

KD=0.01*KOC*WOC   (257)

where KOC is the linear adsorption coefficient for organic carbon and WOC is the organic carbon in the soil layer in %.

Substituting Eq 257 into Eq 255 gives

GP=0.01*PSQC*ST+0.1*PSQC*KD*BD   (258)

Solving Eq 258 for PSQC gives

PSQC=GP/(0.01*ST+0.1*KD*BD)   (259)

Substituting PSQC from Eq 259 into Eq 254 yields

dGP/dt=GP*q/(0.01*ST+0.1*KD*BD)   (260)

Rearranging Eq 260 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(-QT/(0.01*ST+0.1*KD*BD))   (261)

where GP_0 is the initial amount of pesticide in the soil layer in
g ha^{-1}, 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_0 using the equation

PSTL=GP_0*(1.0-exp(-QT/(0.01*ST+0.1*KD*BD)))   (262)

where PSTL is the amount of pesticide leached by QT. The average concentration during the percolation of QT is

PSTC=PSTL/QT   (263)

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   (264)

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   (265)

Substituting Eq 264 into Eq 265 and solving for PCV gives

PCV=PSTL/(QV+p24*QH)   (266)

PCH=p24*PCV   (266a)

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 262-266 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=0.001*Y*PSYC*ER   (267)

where PSTY is the pesticide yield adsorbed to the sediment in
g ha^{-1}, Y is the sediment yield in t 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 158. The pesticide concentration in the soil is calculated by substituting Eq 257 into Eq 259 and solving for PSYC.

   PSYC=KD*GP/(0.01*ST+0.1*KD*BD)   (268)

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.

SOIL TEMPERATURE

Daily average soil temperature at the center of each soil layer is simulated for use in nutrient cycling and hydrology. The basic soil temperature equation is

   STMP=LAG*STMP$_0$+(1.0-LAG)*(FZ*(AVT-DST0)+DST0)   (269)

   FZ=X1/(X1+exp(-0.8669-2.0775*X1))   (269a)

   X1=0.5*(Z(l)+Z(l-1))/DD   (269b)

where STMP is the soil temperature at the center of a soil layer in
^{o}C, Z is the depth from the surface to the bottom of the soil layer l in m, LAG is a coefficient ranging from 0.0 to 1.0 that allows proper weighting of yesterday's temperature STMP$_0$, AVT is the long-term average annual air temperature at the site, DST0 is the soil surface temperature, and DD is the damping depth in m. Thus, given yesterday's temperature, Eq 269 estimates today's temperature as a function of soil surface temperature, depth, and a lag coefficient. It is assumed that the temperature remains almost constant at the damping depth and is approximately AVT. Obviously, Eq 269 makes near surface temperatures a strong function of DST0. As depth increases, AVT has more influence until finally at the damping depth, the temperature is within 5% of AVT.

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)   (270)

DP=1.+2.5*ABD/(ABD+exp(6.53-5.63*ABD))   (270a)

WC=0.001*ST/(Z(n)*(0.356-0.144*ABD)   (270b)

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.

To complete the solution of Eq 269, the soil surface temperature must be estimated. The first step is to estimate the bare soil surface temperature.

DST=0.5*(TMX+TMN)+(TMX-TMN)*(RA*(1.0-AB)-14.)/20.)   (271)

The first term in Eq 271 estimates bare soil temperature to equal average daily air temperature. The second term adjusts the basic estimate using the net radiation as a driver and half the temperature difference as a range. The adjustment changes signs at a net radiation value of 14 MJ m^{-2} d^{-1}. If the soil surface is not bare, the surface temperature can be affected considerably by the amount of cover (crop residue or snow). This effect can be simulated
by combining the estimated bare surface temperature for the day with the previous day's temperature in the second soil layer (the top 10 mm layer is considered too thin for this purpose).

DST0=(1.-BCV)*DST+BCV*STMP(2))   (272)

where DST0 is the final estimate of soil surface temperature in ^{o}C and BCV is a lagging factor for simulating residue and snow cover effects on surface temperature. The value of BCV is 0.0 for bare soil and approaches 1.0 as cover increases, as expressed in the equation

BCV=max(SNOF,BCV')   (273)

BCV'=CV/(CV+exp(5.34-2.40*CV))   (273a)

SNOF=SNO/(SNO+exp(2.30-0.220*SNO))   (273b)

where CV is the sum of above ground biomass and crop residue in t ha^{-1} and SNO is the water content of the snow cover in mm.

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

$$HU=0.5*(TMX+TMN)-TBSC; \quad HU>0.0 \qquad (274)$$

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 ^{o}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),

$$DDM=0.001*PAR*(RUE-WAVP*X1) \qquad (275)$$

$$PAR=0.5*RA*(1.0-exp(-0.65*LAI)) \qquad (275a)$$

$$X1=max(VPD-1.,-.5) \qquad (275b)$$

$$RUE=100.*CO_2/(CO_2+exp(bc1-bc2*CO_2)) \qquad (275c)$$

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

$$LAI(i)=LAI_0(i)+dHUF(i)*XLAI(i)*sqrt(REG(i))*LAI_0(i)/TLAI \qquad (276)$$

$$HUF(i)=HUI(i)/(HUI(i)+exp(ah(1,i)-ah(2,i)*HUI(i))) \qquad (276a)$$

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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

$$LAI(i)=LAI_0(i)*((1.0-HUI(i))/(1.0-HUI_D))^{ad} \qquad (277)$$

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

$$CHT(i)=HMX(i)*sqrt(HUF(i)) \qquad (278)$$

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

$$RWT(l,i)=RWT(l,i)+DRW*UTO \qquad (279)$$

$$DRW=RW(i)-RW_0(i) \qquad (279a)$$

$$RW(i)=DM(i)*(ar1(i)*(1.-HUI(i))+ar2(i)*HUI(i)) \qquad (279b)$$

$$UTO=UW(l)/AEP(i); \quad DRW>0.0 \qquad (279c)$$

$$UTO=RWT(l,i)/RW_0(i); \quad DRW<0.0 \qquad (279d)$$

where RW_0 and RW are the total root weight in t ha^{-1} at the beginning and end of the day, RWT is the root weight by soil layer in t ha^{-1}, DM is the total biomass, UW is the daily water use rate by soil layer in mm d^{-1}, AEP is the total water use rate in 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:

$$RD(i)=min(2.5*RDMX(i)*HUI(i),RDMX,RZ) \qquad (280)$$

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:

$$YLD(i)=HI(i)*STL(i) \qquad (281)$$

where YLD is the amount of the crop removed from the field in
t ha^{-1}, HI is the harvest index, and STL is the above-ground biomass in t 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

$$HI(i)=F*(HIT(i)-HIMN(i))+HIMN(i) \qquad (282)$$

$$F=SWH(i)/(SWH(i)+exp(5.563-0.03155*SWH(i))) \qquad (282a)$$

$$SWH(i)=sum(AEP(i)); \quad 0.5<HUI(i)<1.0 \qquad (282b)$$

$$HIT(i)=HIP(i)*X2/(X2+exp(11.11-0.1*X2)) \qquad (282c)$$

$$X2=100.*HUI(i) \qquad (282d)$$

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 282c 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

$$UW(l)=(UX(l)-CU*AEP(i)-(1.-CU)*UX(l-1))*F*RGF \qquad (283)$$

$$UX(l)=EP(i)*(1.-exp(-5.0*RZ*Z(l)/RD(i)))/(1.-exp(-5.0*RZ)) \qquad (283a)$$

$$F=min(1.0,4.0*(ST(l)-WP(l))/(FC(l)-WP(l))) \qquad (283b)$$

where UW is the water use rate in layer l in mm d^{-1}, UX is the potential water use rate in mm d^{-1} 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 283 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 NO3-N to the roots

$$UN(l)=WNO3(l)*UW(l)/ST(l) \tag{284}$$

where UN is the rate of N supplied by the soil in kg ha^{-1} d^{-1}, WNO3 is the amount of NO3-N in layer l in kg ha^{-1}, ST is the soil water content in mm, and UW is water use rate in mm d^{-1}. The mass flow rates obtained in Eq 284 are constrained by considering N supply and demand using the equations

$$UN'(l)=UN(l)*DMN/SPN; \quad DMN<SPN \tag{285}$$

$$UN'(l)=UN(l)+DMN-SPN; \quad DMN>SPN \tag{286}$$

where UN' is the actual plant uptake of N from soil layer l in kg ha^{-1}, 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 284 is reduced in Eq 285 using the ratio DMN/SPN. If the demand is greater than supply Eq 286 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

$$DMN=UNO-UN1 \tag{287}$$

$$UNO=DM(i)*(bn1+bn2*exp(-bn3*HUI(i))) \tag{287a}$$

where DMN is the N demand rate of crop i in kg ha^{-1} d^{-1}, UN1 is the actual N content of the crop in kg ha^{-1}, UNO is the optimal N content for the crop in kg ha^{-1}, DM is the accumulated biomass in t ha^{-1}, 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:

$$WFX'=p7*WFX+(1.-p7)*UNM \tag{288}$$

$$WFX=FIXR*UNM; \quad ASW3>0.25; \text{ and } FXN>0.0 \tag{288a}$$

$$WFX=0.0; \quad ASW3<0.25; \text{ or } FXN<0.0 \tag{288b}$$

$$FIXR=min(FXW,FXN,1.)*FXP \tag{288c}$$

$$FXP=min(FXG,FXS,1.) \tag{288d}$$

$$FXS=4.0-5.0*HUI(i) \tag{288e}$$

$$FXG=(HUI(i)-0.1)*5.0 \tag{288f}$$

FXW=1.333*ASW3-0.333   (288g)

FXN=1.5-0.005*TNO3/RD(i)   (288h)

ASW3=sum(ST(l)-WP(l))/(FC(l)-WP(l));   Z<0.3 m   (288i)

where WFX' is the final adjusted N fixation rate in kg ha^{-1} d^{-1}, 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^{-1} d^{-1}, p7 is a weighting factor ranging from 0.0 to 1.0, and TNO3 is the NO3-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 NO3 in the root zone can affect N fixation (Harper, 1976). This approach reduces N fixation when the NO3-N content of the root zone is greater than 100 kg ha^{-1} m^{-1} and prohibits N fixation at N contents greater than 300 kg ha^{-1} m^{-1}.

        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)   (289)

LPF=CSP(l)/(CSP(l)+exp(8.01-0.3604*CSP(l)));   0.0<CSP<30.0   (289a)

LPF=1.0;   CSP>30.0   (289b)

where UP is the rate of P supplied by the soil in kg ha^{-1} d^{-1}, DMP is the plant P demand for the day, CSP is the concentration of labile P in soil layer l in g t^{-1}, RW is the root weight in layer l in kg ha^{-1}, and RWT is the total root weight in kg ha^{-1}. 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 289 are constrained by considering P supply and demand using the equations

UP'(l)=UP(l);   DMP<SPP   (290)

UP'(l)=UP(l)+DMP-SPP;   DMP>SPP   (291)

where UP' is the actual plant P uptake rate from soil layer l in kg ha^{-1} d^{-1}, and SPP is the total soil profile supply of P for the day. If the demand is greater than supply Eq 291 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

$$DMP=DM(i)*(bp1+bp2*exp(-bp3*HUI(i)))-UP1 \qquad (292)$$

where DMP is the P demand rate of crop i in kg ha^{-1} d^{-1}, DM is the accumulated biomass in t ha^{-1}, 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^{-1}. 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.

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 275 is adjusted daily if any of the five plant stress factors is less than 1.0 using the equation

$$DDM'=DDM*REG \qquad (293)$$

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

$$WS(i)=AEP(i)/EP(i) \qquad (294)$$

where WS is the water stress factor for crop i, AEP is the plant water use rate in mm d^{-1}, and EP is the potential plant water use rate in mm d^{-1}. 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

$$TS(i)=sin(1.5707*RTO); \quad 0.0<RTO<2.0 \qquad (295)$$

$$TS(i)=0.0; \quad RTO<0.0 \text{ or } RTO>2.0 \qquad (295a)$$

RTO=(TX-TBSC(i))/(TOPC(i)-TBSC(i))   (295b)

where TS is the plant temperature stress factor, TX is the average daily air temperature in ^{o}C, TBSC is the base temperature for crop i, and TOPC is the optimal temperature for crop i. Equation 295 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)))   (296)

SNS(i)=200.*(UN1/UNO)   (296a)

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^{-1}, and UNO is the optimal N content for the crop in kg ha^{-1} (calculated in Eq 287).

The P stress factor, SP, is computed with Eq 296 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)); SAT>0.0   (297)

AS(i)=1.0; SAT<0.0   (297a)

SAT=100.*(ST_1/PO_1-CAF(i))/(1.0-CAF(i))   (297b)

where AS is the aeration stress factor for crop i,SAT is the saturation factor, ST_1 is the water content minus field capacity of the top 1 m of soil in mm, PO_1 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 279, 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 283. 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.

$$STS(l,i)=sqrt(2.0*STMP(l)/(TOPC(i)+TBSC(i)));\quad STMP>0.0 \qquad (298)$$

$$STS(l,i)=0.0;\quad STMP<0.0 \qquad (298a)$$

where STS is the temperature stress for crop i in soil layer l, STMP is the soil temperature in $^{\circ}$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:

$$SS(l)=BD(l)/(BD(l)+exp(br1+br2*BD(l))) \qquad (299)$$

$$br2=(ln(0.01124*BDL)-ln(8.0*BDU))/(BDL-BDU) \qquad (299a)$$

$$br1=ln(0.01124*BDL)-br2*BDL \qquad (299b)$$

$$BDL=p2+0.00445*SAN(l) \qquad (299c)$$

$$BDU=p2+0.35+0.005*SAN(l) \qquad (299d)$$

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 (given in the PARM File: PARM(2)), and br1 and br2 are parameters dependent upon soil texture. The values of br1 and br2 are obtained from a simultaneous solution of Eq 299 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)

$$BD(l)=BD3(l)+(BDD(l)-BD3(l))*RTO \qquad (300)$$

$$RTO=(FC(l)-ST(l))/(FC(l)-S15(l)*(4.083-3.33*BDD(l)^{0.333})) \qquad (300a)$$

where BD is the water-content-adjusted bulk density for soil layer l, 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 l 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

$$ATS(l,i)=(100.-ALS(l))/(100.-AL0(i)) \qquad (301)$$

$$AL0(i)=10.+(ALT(i)-1.0)*20.0 \qquad (301a)$$

where ATS is the Al toxicity stress factor (0-1) for soil layer l, ALS is the Al saturation in %, ALO 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

$$YLD(i)=HIA(i)*HE*PSTF(i)*STL(i) \tag{302}$$

$$HIA(i)=F*(AJHI(i)-WSYF(i))+WSYF(i) \tag{302a}$$

$$F=SWH(i)/(SWH(i)+exp(5.563-0.0315*SWH(i))) \tag{302b}$$

$$AJHI(i)=HI(i)*X2/(X2+exp(11.11-0.1*X2)) \tag{302c}$$

$$X2=100.*HUI(i) \tag{302d}$$

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 302c 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 302b 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.

$$STL'(i)=STL(i)*(1.0-F) \tag{303}$$

$$LAI'(i)=LAI(i)*(1.0-F) \tag{303a}$$

$$F=\max(FTM,FHR) \tag{303b}$$

$$FTM=ATMN/(ATMN+\exp(bf1(i)-bf2(i)*ATMN)); \quad TMN<-1.0\ °C \tag{303c}$$

$$FTM=0.0; \quad TMN>-1.0\ °C \tag{303d}$$

$$FHR=1.-HRLT/WDRM; \quad HRLT<WDRM \tag{303e}$$

$$FHR=0.0; \quad HRLT>WDRM \tag{303f}$$

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 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 calculated in Eq 273b.

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

$$X(l)=(1.0-EF)*X_0(l)+EF*SMXo*(Z(l)-Z(l-1))/TLD \tag{304}$$

where X is the amount of the material in layer l after mixing in
kg ha^{-1}, X_0 is the amount of the material before mixing 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 kg ha^{-1}, and Z is the depth to the bottom of the plow layer in m. In Eq 304 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

$$BDP(l)=BDPo(l)-(BDPo(l)-0.667*BD(l))*EF \qquad (305)$$

where BDP is the bulk density after tillage, BDPo 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

$$BDP(l)=BDPo(l)+F*(BD(l)-BDPo(l)) \qquad (306)$$

$$F=SZ(l)/(SZ(l)+exp(3.92-0.0226*SZ(l))) \qquad (306a)$$

$$SZ(l)=0.2*XX*(1.0+2.0*SAN(l)/(SAN(l)+exp(8.597-0.075*SAN(l))))/Z(l)^{0.6}$$
$$(306b)$$

where SZ is a scaling factor for soil layer l, XX is the inflow rate into the layer in mm d^{-1} (RFV-Q for the top layer), and SAN is the percentage of sand in the layer. The exponential parameters of equation 306a 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 306b 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 long-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

$$STD=STD_0*exp(-56.9*TLD*EF) \qquad (307)$$

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

$$RHTT=RHT(k)+(RHT(k-1)-RHT(k))*exp(-TLD(k)/TLD(k-1)); \qquad (308)$$

$$RHT(k)<RHT(k-1) \qquad (308a)$$

$$RHTT=RHT(k); \quad RHT(k)>RHT(k-1) \qquad (308b)$$

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.

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 80 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^{-1}; 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)

$$ALS(l)=154.2-1.017*BSA(l)-3.173*WOC(l)-14.23*PH(l); \quad PH<5.6 \qquad (309)$$

$$ALS(l)=0.0; \quad PH>5.6 \qquad (310)$$

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_4OAc (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

$$RLA=0.1*ALS*ECEC*BD*TLD \qquad (311)$$

where RLA is the lime required to neutralize Al in t ha^{-1}, ECEC is the effective cation exchange capacity in cmol(p+) kg^{-1}, BD is the soil bulk density in t m^{-3}, and TLD is the tillage depth in m.

ECEC is calculated as SMB/ALS (Soil Survey Staff, 1982), where SMB in cmol kg^{-1} is the sum of the bases extracted by NH_4OAc (pH=7.0). The constant 0.1 converts cmol(p+) kg^{-1} extractable aluminum to equivalent $CaCO_3$ in t ha^{-1}, assuming 2 cmol(p+) $CaCO_3$ 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^{-1} 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 $CaCO_3$ equivalent of fertilizer or fixed N is assumed to be 1.8 kg $CaCO_3$ kg^{-1} N (Pesek 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

$$DSB=0.036*(FN+WFX)/(BD*TLD*CEC) \qquad (312)$$

where FN is the amount of N fertilizer added during the year in kg ha^{-1} and WFX is the amount of N fixation by legumes in kg ha^{-1}. The PH value is reduced by using the equation

$$PH=PHo-0.05*DSB \qquad (313)$$

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

$$RLA=0.01*BD*TLD*CEC*DSB \qquad (314)$$

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 $CaCO_3$ in t ha^{-1}, assuming that applied $CaCO_3$ reacts with equivalent unsaturated CEC. The DSB is estimated with the relation

$$DSB=min((.5-PH)/0.023;90.0-BSA) \qquad (315)$$

For soils that are not highly weathered, lime is applied at the end of the year if RLA>2.0 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.

$$PSTF=1.0-(1.-PST(i))*Z1/(Z1+exp(2.696-0.499*Z1)); \quad PSTS>0.0 \qquad (316)$$

$$Z1=PSTX*PSTS/IPST \qquad (316a)$$

$$PSTF=1.0; \quad PSTS<0.0 \qquad (316b)$$

$$PSTD=TMN*(0.01*(ADRF-p9)+1.0); \quad TMN>0.0; \quad CV<p10 \qquad (316c)$$

$$PSTD=TMN; \quad TMN<0.0 \qquad (316d)$$

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 ^oC, 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 t ha^{-1}, and p10 is the threshold cover value in 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

$$PSTS=PSTS-1000.0*PSTE \tag{317}$$

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

$$DVOL=FDSF*(A_2*DH+0.5*(A_2+A_3)*(DI-4.*DH)+A_3*D_3)/(RINT*DKIN) \tag{318}$$

$$DVOL=FDSF*A_2*(DH+.5*(DH/STP-2.0*DH))/(RINT*DKIN) \tag{319}$$

$$A_2=.5*D_2*(TW_2+BW)$$

$$A_3=.5*D_3*(TW_3+BW)$$

$$TW=RINT-DH$$

$$BW=max(TW-4.0*DH,0.1*TW)$$

$$DI=DKIN-DH$$

$$D_2=DH*(1.0-2.0*STP)$$

$$D_3=DH-STP*(DI-2.0*DH)$$

$$TW_2=BW+D_2*(TW-BW)/DH$$

$$TW_3=BW+D_3*(TW-BW)/DH$$

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 318 and 319 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 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 318 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 319. Thus, the average dike volume of a field is estimated with equation 318 or 319 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

$$DH=DH_0*exp(-0.1*YW-Y) \qquad\qquad (320)$$

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 equation 320. The dikes are rebuilt automatically when $DH/DH_0<0.7$.

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 (preharvest) 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.

THE APEX ROUTING COMPONENT

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

$$q=Q*WSA/(360.*(DUR+TC)) \quad\quad\quad\quad\quad (321)$$

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

$$CSS=0.5*(CTW-CBW)/Z_{CH} \qquad\qquad (322)$$

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

$$q_{cp}=CHXA^{1.667}*sqrt(CHS/CHN)/CHP^{0.667} \qquad\qquad (323)$$

$$CHXA=0.5*Z_{CH}*(CBW+CTW) \qquad\qquad (323a)$$

$$CHP=CBW+2.0*Z_{CH}*sqrt(CSS*CSS+1.0) \qquad\qquad (323b)$$

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<qcp 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

$$VCH=q/(Z_{CH}'*(CBW+Z_{CH}'*CSS)) \qquad\qquad (324)$$

where VCH 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

$$q_{fp}=q-q_{cp} \qquad\qquad (325)$$

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

$$Z_{FP}=(q_{fp}*FPN/(FPW*sqrt(FPS)))^{0.6} \qquad\qquad (326)$$

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

$$VFP=q_{fp}/(Z_{FP}*FPW) \qquad\qquad (327)$$

where VFP 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

$$TRT=FPL/(3.6*VFP) \qquad\qquad (328)$$

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

$$q_{fp'}=q_{fp}-SC*TRT \qquad\qquad (329)$$

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}.

   Variable Storage Coefficient Flood Routing 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 42 and 43. Rainfall excess is estimated by applying Eq 29 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.

$$STH = STH_0 + DQ \qquad (330)$$

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.

$$STH = STH_0 * \exp(-p73 * DTHY/TC) \qquad (331)$$

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 330 and 331, subtracting the ending storage from the beginning storage, and converting from volume to rate.

$$q_{hy} = (STH_0 * (1.0 - \exp(p73 * DTHY/TC)) + DQ) * WSA/(DTHY * 360.) \qquad (332)$$

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 same basic equations are used in continuous simulation but there are additional application problems like maintaining ending daily storage and flow rates for all hydrographs in the watershed. Only the essential equations are presented here. The routing problem involves four flow rates (q_{i1}, q_{i2}, q_{o1}, and q_{o2}). The inflow hydrograph provides known values of q_{i1} and q_{i2}. q_{o1} is known initially (previous time step outflow rate). Thus, q_{o2} must be determined at each time step as follows.

1. Newton's method for solving nonlinear equations is used to solve Manning's equation for normal flow depth (D_{i2}) given the inflow rate (q_{i2}) and the channel and floodplain geometry.

2. A successive approximations solution is used to calculate q_{o2}.
   The model makes a first estimate (gs) of gs=q_{o1}.

A. Step 1 is repeated solving for D_{o2} given gs.

B. The flow velocity is estimated with the equation

$$V=(q_{i2}+gs)*sqrt(X1)/(A_{i2}+A_{o2})) \qquad (333)$$

$$X1=(RFPL*RFPS+D_{i2}-D_{o2})/(RFPL*RFPS) \qquad (333a)$$

C. Reach travel time is calculated with the equation

$$TT_R=RFPL/(3.6*V) \qquad (334)$$

D. The VSV routing coefficient is calculated with the equation

$$CVSC=2.0*DTHY/(2.*TT_R+DTHY)) \qquad (335)$$

E. The flow rate is computed using the equation

$$q_{o2}=CVSC*SIA/(3600.*DTHY) \qquad (336)$$

$$SIA=1800.*DTHY*(q_{i1}+q_{i2})+STH \qquad (336a)$$

F. Convergence is determined using the ratio

$$DF=abs(q_{o2}-GS)/q_{o2}<0.001 \qquad (337)$$

G. If DF>0.001 steps A/F are repeated setting gs=q_{o2}.

H. Upon convergence the reach storage is updated and the process (steps 1/2) is repeated for each time step.

$$STH=SIA-q_{o2} \qquad (338)$$

where q_{i1} and q_{i2} are the reach inflow rates in $m^3 s^{-1}$ at the start and end of the time interval DTHY, q_{o1} and q_{o2} are the associated outflow rates in $m^3 s^{-1}$, D_{i2} and D_{o2} are the inflow and outflow depths in m, A_{i2} and A_{o2} are the inflow and outflow areas in m^2, RFPL is the reach floodplain length in m, RFPS is the reach floodplain slope in $m\, m^{-1}$, V is the flow velocity in $m\, s^{-1}$, TT is the travel time through the reach in h, CVSC is the VSC routing coefficient, STH is the reach storage in m^3, and SIA is the reach storage plus the inflow volume in m during DTHY. Note that the VSC method accounts for changes in water surface slope as the hydrograph passes through the reach (Eq 333).

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.

$$CY_U = CY_1 * VCH^{p18} \tag{339}$$

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.

$$YU = 10.*QCH*(CY_U - CIN) \tag{340}$$

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.

$$DEP_{ch} = -YU \tag{341}$$

where DEP_{ch} is sediment deposition in the channel in t ha^{-1}. If YU is positive channel degradation is calculated with the equation

$$DEG_{ch} = YU*EK*CVF \tag{342}$$

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.

$$YO = YI - DEP_{ch} + DEG_{ch} - DEP_{fp} + DEG_{fp} \tag{343}$$

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 um. Deposition of particles of a certain size is estimated with the equation (Williams and Hann, 1978)

$$YO(i) = YI(i)*PCT(i)*exp(-B1*sqrt(PSZ(i))) \tag{344}$$

where PCT is the percent of particle size PSZ in um in the inflow, B1 is a coefficient, and subscript i refers to sand, silt, and clay. The coefficient B1 is determined by solving Eq 344 using the mean particle size (20um) of Houston Black Clay (a very fine textured soil).

$$B1 = ln(YO/YI)/4.47 \tag{345}$$

Thus, the outflow particle size can be estimated using Eq 344 in the form

$$PCTO(i)=PCT(i)*exp(-B1*sqrt(PSZ(i)))$$ (346)

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 346 (i=1,3). This simply assures that the sum of PCTO equals one.

NUTRIENTS

The organic forms of N and P are transported by sediment and are routed using an enrichment ratio approach.

$$YNO=0.001*CNI*ER*YO$$ (347)

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.

$$ER=PSZM_I/PSZM_O$$ (348)

where $PSZM_I$ and $PSZM_O$ 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.

PESTICIDES

The pesticide routing approach is the same as described for nutrients. The adsorbed pesticide phase is transported with sediment using the enrichment ratio (equations 347 and 348) and the soluble phase is transported with flow in a conservative manner.

THE RESERVOIR COMPONENT

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

$$RSV=RSV_0+QI+RFRA-EV-SEP-QO$$ (349)

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, SEP is the seepage loss rate, and QO is the outflow rate (all rates expressed in m^3 d^{-1}). To estimate RFRA, EV, and SEP reservoir volume is related to surface area using the equation

$$RSSA=bv1*RSV^{bv2}$$ (350)

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 SEP are estimated using the equations

$$RFRA=10.*RFV*RSSA \qquad (351)$$

$$EV=10.*CLE*EO*RSSA \qquad (352)$$

$$SEP=10.*DT*RSHC*RSSA \qquad (353)$$

where RFV is rainfall rate in mm d^{-1}, CLE is a lake evaporation coefficient (0.6), EO is the potential evapotranspiration in mm d^{-1}, DT is the time interval (24 h), and RSHC is the hydraulic conductivity of the reservoir bottom in mm h^{-1}. The outflow is controlled by the two spillways.

$$QO=RSV-RSV_E; \quad RSV>RSV_E \qquad (354)$$

$$QO=RR*DT; \quad RSV_P<RSV<RSV_E \qquad (354a)$$

$$QO=0.0; \quad RSV<RSV_P \qquad (354b)$$

where RSV_E and RSV_P are the reservoir storage volumes in m^3 at the emergency and principal spillway elevations and RR is the flow rate through the principal spillway in $m^3 \, d^{-1}$.

Sediment content is calculated each day using the mass balance equation

$$RSY=RSY_0+YI-YO-DEP \qquad (355)$$

where RSY_0 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

$$CY=(CY_0-CY_N)*exp(-bv3*DT)+CY_N \qquad (356)$$

where CY_0 and CY are the reservoir sediment concentrations in $t \, m^{-3}$ at the start and end of a day, CY_N 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.

$$bv3=ln((CY-CY_N)/(CY_0-CY_N))/TDP \qquad (357)$$

where TDP is the time required to return to normal concentration in d and $(CY-CY_N)/(CY_0-CY_N)=0.01$. Deposition is determined from the change in concentration using the equation

$$DEP=RSV*(CY-CY_0) \qquad (358)$$

Reservoir sediment outflow is computed with the equation

$$YO=CY*QO \qquad (359)$$

Organic N and P are transported in the reservoir by sediment particles. The organic nutrient content is calculated each day using the equation

$$RSON=RSON_0+YON_I-YON_O-DPON \qquad (360)$$

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

$$DPON=CON*DEP \qquad (361)$$

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.

$$CON=(RSON_0+YONI)/(RSY_0+YI) \qquad (362)$$

The organic N outflow rate is computed as in Eq 361

$$YON_O=CON*YO \qquad (363)$$

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

$$RSSN=RSSN_0+QNI-QNO \qquad (364)$$

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.

$$QNO=CSN*QO \qquad (365)$$

where CSN the soluble N concentration in the reservoir in kg m^3 is estimated assuming complete mixing.

$$CSN=(RSSN+QNI)/RSV \qquad (366)$$

Similar calculations are performed for soluble P.

THE GROUNDWATER COMPONENT

The groundwater mass balance equation is

$$GWST=GWST_0+QV+SEP-DPRK-RSSF \qquad (367)$$

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 mm d^{-1}, SEP is the reservoir seepage rate in mm d^{-1}, DPRK is the percolation rate from the groundwater storage in mm d^{-1}, and RSSF is the return flow rate in mm d^{-1}.

The DPRK and RSSF losses are estimated using the groundwater storage residence time and a partitioning coefficient.

$$\text{DPRK+RSSF=GWST*(1.0-exp(-1.0/RFTT))} \qquad (368)$$

where RFTT is the groundwater storage residence time in d. Partitioning of DPRK and RSSF is accomplished with the equation

$$\text{RSSF=RFPK*(DPRK+RSSF)} \qquad (369)$$

where RFPK is the partitioning coefficient. Substituting Eq 368 into Eq 369 gives

$$\text{RSSF=RFPK*GWST*(1.0-exp(-1.0/RFTT));} \quad \text{GWST>GWSTH} \qquad (370)$$

$$\text{RSSF=0.0;} \quad \text{GWST<GWSTH} \qquad (370a)$$

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

$$\text{GWSN=GWSN}_0\text{+RZLN-RSFN-GWLN} \qquad (371)$$

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.

$$\text{RSFN=CGWN*RSSF} \qquad (372)$$

$$\text{GWLN=CGWN*DPRK} \qquad (373)$$

where CGWN is the concentration of N in the groundwater in
kg mm^{-1}.

THE GRAZING COMPONENT

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 kg head^{-1} d^{-1}, grazing efficiency (accounts for waste by trampling, etc.), manure production rate in kg head^{-1} d^{-1}, urine production in l head^{-1} 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 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 subareas 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.

MANURE MANAGEMENT

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^{-1} d^{-1} and it's 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.

NOTATIONS

a1   = coefficient in wind speed equation.

a2   = exponent in wind speed equation.

A_2 = cross sectional area in m^2 at the toe of the downstream dike.

A_3 = cross sectional area in m^2 at the toe of the upstream dike.

AB   = soil albedo.

ABCO2   = allocation from biomass to CO_2; 0.6 (surface layer), 0.85-0068*(CLA+SIL)(all other layers)

ABD   = average soil bulk density of the profile in t m^{-3}.

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^{-3}.

ADRF   = accumulated 30 day rainfall in mm.

AEP   = total plant water use rate in mm d^{-1}.

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 qi2.

AJHI = simulated potential harvest index.

AKN = nitrification regulator.

AKV = volatilization regulator.

ALO = maximum ALS value a crop tolerate without stress in %.

ALMCO2 = allocation from metabolic litter to CO_2; 0.6 (surface layer), 0.55 (all other layers).

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}.

APCO2 = 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 x 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 ^{o}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 = parameter relating mean maximum air   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_2.

BCV = lagging factor for simulating residue and snow cover affects on surface temperature.

BD = soil layer bulk density in t m^{-3}.

BD3 = bulk density for 33 kPa water content in t m^{-3}.

BDD = bulk density of the oven dry soil in t m^{-3}.

BDP = soil layer tillage/compaction affected bulk density in t m^{-3}.

BDPo = bulk density in a soil layer before tillage in t m^{-3}.

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$^{-1.}$

BMCTP = potential C transformation rate in microbial biomass in kg ha^{-1} d$^{-1.}$

BMN = weight of N in soil microbial biomass and associated products in kg ha$^{-1.}$

BMNTP = potential N transformation rate in microbial biomass in kg ha^{-1} d$^{-1.}$

BMR = transformation rate of microbial biomass and associated products under optimal conditions surface = 0.0164 d^{-1}; all other layers = 0.02 d^{-1}) (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.

bsl = a fraction of the storage PO occupied by percolating water.

bsa = mineral P flow coefficient.

BSA = soil layer base saturation in %.

bv1,2 = parameters in reservoir volume-surface area equation.

bv3 = parameter in reservoir sediment deposition equation.

bw1 = parameter in mean wind speed equation.

bw2 = parameter in mean wind speed equation.

BW = furrow bottom width in m.

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 mm km^{-1}.

BYCT = rate of change in annual rainfall from south to north in mm km^{-1}.

CAC = soil layer CaCO$_3$ concentration in 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 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 m m^{-1}.

CHT = crop height in m.

CHXA = channel cross sectional area at top bank in m^2.

CIN = inflow sediment concentration in t m^{-3}.

CLA = clay content in soil layer in %.

CLE = lake evaporation coefficient.

CLP = concentration of labile P in the soil layer in g t^{-1}.

CMP = humus mineralization rate constant in d^{-1}.

CN$_1$ = SCS runoff curve number for moisture condition 1 (dry).

CN$_2$ = SCS runoff curve number for moisture condition 2 (average).

CN$_{2S}$ = CN2 value adjusted for watershed slope.

CN$_3$ = SCS runoff curve number for moisture condition 3 (wet).

CNI = inflow organic nutrient concentration in g t^{-1}.

CNO3 = concentration of NO3-N in kg mm^{-1}.

CNR = C/N ratio of standing dead crop residue.

CON = concentration of organic N in g t^{-1}.

CO$_2$ = atmospheric carbon dioxide concentration in g m^{-3}.

CP = concentration of P in the top soil layer in g t^{-1}.

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^{-1}.

CPVV = vertical pipe flow rate in mm d^{-1}.

CR = canopy resistance for vapor transfer in s m^{-1}.

CS = factor controlling biological processes.

CSN = soluble N concentration in the reservoir in kg m^{-3}.

CSP = soil layer concentration of labile P in g t^{-1}.

CSS = channel side slope in m m^{-1}.

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^{-1}.

CVF = USLE crop management factor.

CVRS = above ground crop residue in t ha^{-1}.

CVSC = VSC routing coefficient.

CY = sediment concentration in t m^{-3}.

CY_1 = potential sediment concentration for 1.0 m s^{-1} velocity.

CY_N = normal sediment concentration in a reservoir in t m^{-3}.

CY_0 = reservoir sediment concentration in t m^{-3} at the start of a day.

CY_U = potential sediment concentration in t m^{-3} for the flow velocity VCH.

d = flow depth in m.

D   = distance between the subarea centroid and the storm center in km.

D_2 = water depth in m at the toe of the downstream dike.

D_3 = water depth in m at the toe of the upstream dike.

DECR   = decay rate constant for fresh organic P in d^{-1}.

DD   = soil temperature damping depth in m.

DDM   = daily potential increase in biomass in $t\ ha^{-1}$.

DEG_{ch} = channel degradation in $t\ ha^{-1}$.

DEG_{fp} = floodplain degradation in $t\ ha^{-1}$.

DEP   = sediment deposition in a reservoir in t.

DEP_{ch} = sediment deposition in the channel in $t\ ha^{-1}$.

DEP_{fp} = sediment deposition in the floodplain in $t\ ha^{-1}$.

DH   = furrow dike height in m.

DH_0 = dike height in m before settling.

dHUF   = daily change in HUF.

DI   = water surface distance between dikes in m.

D_{i2} = 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 $kPa\ ^oC^{-1}$.

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_{o2} = 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 ^{o}C.

dt = time interval in h.

DT = reservoir routing time interval in h.

DTHY = routing time interval in h.

DU10 = wind speed in 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 cmol(p+) 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 NO3-N in kg ha^{-1} moved upward by soil water evaporation.

EO = potential evaporation in mm d^{-1}.

EO' = potential evaporation rate in mm d^{-1} adjusted for rainfall interception.

EP = potential plant evaporation rate in mm d^{-1}.

ER = enrichment ratio (organic N concentration in sediment to that of the top soil).

ES = potential soil water evaporation rate in mm d^{-1}.

ESR = potential soil evaporation remaining after snow and litter evaporation in mm.

EV = evaporation from the reservoir in m^3.

EVZ = total potential soil water evaporation in mm.

EXPK = power parameter in modified exponential rainfall distribution

f = infiltration rate in 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}.

FP_0 = 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 = psychrometer constant in kPa $^{\circ}C^{-1}$.

GP = amount of pesticide that reaches the ground in g ha^{-1}.

GP_0 = 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.

$GWSN_0$ = soluble N content of groundwater at the start of a day in kg.

GWST = groundwater storage volume in mm.

GWSTH = groundwater threshold storage in mm.

$GWST_0$ = groundwater volume at the start of a day 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 ^{o}C.
HUF	= heat unit factor.
HUI	= heat unit index (accumulated HU/PHU).
HUI_D	= value of HUI when LAI starts declining.
HV	= latent heat of vaporization in MJ kg^{-1}.
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^3 t^{-1}.
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_0	= 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$^{-1.}$

LMC   = weight of C in metabolic litter in kg ha$^{-1.}$

LMCTP   = potential transformation of C in metabolic litter in kg ha^{-1} d$^{-1.}$

LMF   = fraction of the litter that is metabolic.

LMN   = mass of N in metabolic litter in kg ha$^{-1.}$

LMNF   = fraction of metabolic litter that is N in kg kg$^{-1.}$

LMNTP   = potential transformation of N in metabolic litter in kg ha^{-1} d$^{-1.}$

LMR   = metabolic litter transformation rate under optimal conditions (surface = 0.0405 d^{-1}; all other layers = 0.0507 d^{-1}) (Parton et al., 1994)

LPF   = labile P uptake factor--allows optimum uptake rates when CSP is above 20 g t^{-1}.

LS   = weight of structural litter in kg ha$^{-1.}$

LSC   = weight of C in structural litter in kg ha$^{-1.}$

LSCTP   = potential transformation of C in structural litter in kg ha^{-1} d$^{-1.}$

LSF   = fraction of the litter that is structural.

LSL   = weight of lignin in structural litter in kg ha$^{-1.}$

LSLCTP   = potential transformation of C in lignin of structural litter in kg ha^{-1} d$^{-1.}$

LSLF   = fraction of structural litter that is lignin in kg kg$^{-1.}$

LSL$_N$CTP = potential transformation of C in non-lignin structural litter in kg ha^{-1} d$^{-1.}$

LSN   = weight of N in structural litter in kg ha$^{-1.}$

LSNF   = fraction of structural litter that is N in kg kg$^{-1.}$

LSNTP = potential transformation of N in structural litter in kg ha^{-1} d$^{-1.}$

LSR = structural litter potential transformation rate under optimal conditions (surface = 0.0107 d^{-1}; all other layers = 0.0132 d^{-1}) (Parton et al., 1994)

WPMA = soil layer active mineral P content in kg ha^{-1}.

WPML = soil layer labile P content in kg ha^{-1}.

MPR = mineral P flow rate in kg ha^{-1} d^{-1}.

WPMS = soil layer stable mineral P content in kg ha^{-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 mm d^{-1}.

OFV = overland flow velocity in m s^{-1}.

OX = oxygen factor controlling biological processes as a function of depth.

p1 = parameter in Penman-Monteith PET equation.

p2 = threshold bulk density for root stress for a soil of zero sand content.

p5 = fraction of wilting point--lower limit of plant water use.

p7 = weights N fixation between basic estimate and plant N demand.

p9   = threshold 30-day rainfall amount for pest damage in mm.

p14   = ratio of NO3-N runoff concentration to that of percolate.

p18   = exponential parameter in Bagnold's sediment transport equation.

p24   = ratio of pesticide concentration in runoff to that of percolate.

p31   = sediment routing exponent ranging from 1.0 to 1.5.

p73   = parameter in hydrograph development equation.

PAEF   = pesticide application efficiency.

PAPE   = effective amount of pesticide applied in kg ha^{-1}.

PAPR   = actual amount of pesticide applied in kg ha^{-1}.

PAR   = intercepted photosynthetic active radiation in MJ m^{-2} d^{-1} .

PB   = barometric pressure in kPa.

PCH   = pesticide concentration in horizontal flow in g t^{-1}.

PCT   = sediment particle size distribution in %.

PCTO   = outflow sediment particle size distribution in %.

PCV   = pesticide concentration in vertical flow in g t^{-1}.

PE   = USLE erosion control practice factor.

PH   = soil layer pH.

PO   = soil porosity volume in mm.

PO_1 = porosity minus field capacity of the top 1 m of soil in mm,

PSP = P sorption coefficient.

$PSQC$ = pesticide concentration in the water in $g\ t^{-1}$.

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 $g\ ha^{-1}$.

$PSTS$ = accumulated daily pest index.

$PSTX$ = pest damage scaling factor.

$PSTY$ = pesticide yield adsorbed to the sediment in $kg\ ha^{-1}$.

$PSYC$ = concentration of adsorbed pesticide in $g\ t^{-1}$.

$PSZM_I$ = mean sediment particle size of the inflow in um.

$PSZM_O$ = mean sediment particle size of the outflow in um.

PW = probability of a wet day.

$P(W|D)$ = probability of a wet day following a dry day.

$P(W|W)$ = probability of a wet day after a wet day.

PX = furrow wetted perimeter in m.

Q = runoff volume in mm.

q = flow rate in $m^3\ s^{-1}$.

q_c = average flow rate in $m^3\ s^{-1}$.

$q_{c'}$ = average flow rate in $mm\ h^{-1}$.

q_{c1} = average flow rate from a 1 ha area in mm h^{-1}.

QCH = volume of flow through a reach channel in mm.

q_{cp} = channel capacity in $m^3 s^{-1}$.

q_{fp} = floodplain flow rate in $m^3 s^{-1}$.

QH = horizontal flow rate in soil layer in mm d^{-1}.

q_{hy} = subarea hydrograph outflow rate in $m^3 s^{-1}$.

QI = inflow rate in mm d^{-1} or $m^3 d^{-1}$.

q_{i1} = reach inflow rate in $m^3 s^{-1}$ at the start of the routing interval.

q_{i2} = reach inflow rate in $m^3 s^{-1}$ at the end of the routing interval.

QNI = soluble N reservoir inflow rate in kg d^{-1}.

QNO = soluble N reservoir outflow rate in kg d^{-1}.

QNO3 = amount of NO3-N lost from a soil layer by runoff and leaching kg ha^{-1}.

QO = outflow from reservoir in m^3.

q_{o1} = reach outflow rates in $m^3 s^{-1}$ at the start of the routing interval.

q_{o2} = reach outflow rates in $m^3 s^{-1}$ at the end of the routing interval.

q_p = peak runoff rate in $m^3 s^{-1}$.

$q_{p'}$ = TR-55 peak rate per unit of rainfall in h^{-1}.

QPX = furrow irrigation flow rate in mm h^{-1}.

QPX' = furrow irrigation flow rate in $m^3 s^{-1}$.

QRF = quick return flow rate in mm d^{-1}.

QT = percolation volume in mm.

QV   = vertical flow rate in soil layer in mm d^{-1}.

QXM   = irrigation application volume in mm.

r   = rainfall rate in mm h^{-1}.

RA   = mean daily solar radiation in MJ $m^{-2} d^{-1}$.

RAD   = daily mean solar radiation on dry days in
              MJ $m^{-2} d^{-1}$.

RAMX   = maximum daily solar radiation in MJ $m^{-2} d^{-1}$.

RAW   = daily mean solar radiation on wet days in
              MJ $m^{-2} d^{-1}$.

RBO   = net outgoing long wave radiation in
              MJ $m^{-2} d^{-1}$.

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 mm h^{-1}.

RFI   = intercepted rainfall in mm.

RFPK   = groundwater flow partitioning coefficient.

RFPL   = reach floodplain length in m.

RFPS   = reach floodplain slope in m m^{-1}.

RFRA   = rainfall on the reservoir in m^3.

RFTT   = groundwater storage residence time in d.

RFV   = rainfall that arrives on the soil surface in
              mm.

$RFV_{.5}$ = maximum storm rainfall in mm occurring in
              0.5 h.

$RFV_{.5a}$ = mean maximum 0.5-h rainfall amount in mm for

a month.

RFV$_{.5u}$ = maximum 0.5-h rainfall amount in mm for frequency F.

RFV$_{24}$ = 24-h duration rainfall volume in mm.

RFV$_{TC}$ = 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^{-1}.

RMP = mineralization rate of fresh organic P in kg ha^{-1} d^{-1}.

RN $\quad$ = net radiation in MJ m^{-2} d^{-1}.

rnd $\quad$ = uniform random number (0.0-1.0)

RNIT $\quad$ = nitrification rate in kg ha^{-1} d^{-1}.

RNV $\quad$ = combined nitrification and volatilization kg ha^{-1} d^{-1}.

ROK $\quad$ = coarse fragment content of a soil layer in %.

ROKF $\quad$ = coarse fragment factor in soil erosion equations.

r_p $\quad$ = peak rainfall rate in mm h^{-1}.

RR $\quad$ = flow rate through the principal spillway in m^3 d^{-1}.

RRF $\quad$ = clod roughness factor.

RRUF $\quad$ = soil surface random roughness in mm.

RSD $\quad$ = flat crop residue in t ha^{-1}.

RSDM $\quad$ = manure on the soil surface in t ha^{-1}.

RSFN $\quad$ = groundwater return flow N rate in kg d^{-1}.

RSHC $\quad$ = hydraulic conductivity of the reservoir bottom in mm h^{-1}.

RSON $\quad$ = organic N content of a reservoir in kg.

RSON$_0$ $\quad$ = organic N content of a reservoir in kg at the start of a day.

RSSA $\quad$ = reservoir surface area in ha.

RSSF $\quad$ = groundwater return flow rate in mm d^{-1}.

RSSN $\quad$ = soluble N content in a reservoir in kg.

RSSN$_0$ $\quad$ = soluble N content in a reservoir at the start of a day in kg.

RSV $\quad$ = reservoir water content in m^3.

RSV_0 = reservoir water content at the start of the day in m^3.

RSV_E = reservoir storage volume in m^3 at the emergency spillway elevation.

RSV_P = reservoir storage volume in m^3 at the principal spillway elevation.

RSY = reservoir sediment content in t.

RSY_0 = reservoir sediment content in t at the start of the day.

RTP = is the rainfall volume at t_p in mm.

RUE = radiation use efficiency factor for converting energy to biomass in $(kg\ ha^{-1})/(MJ\ m^{-2})$.

RVOL = volatilization rate in $kg\ ha^{-1}\ d^{-1}$.

RW = total root weight in $t\ ha^{-1}$.

RW_0 = total root weight in $t\ ha^{-1}$ at the beginning of a day.

RWT = root weight by soil layer in $t\ ha^{-1}$.

RZ = minimum of soil profile depth and RDMX in m.

RZLN = root zone N leaching rate in $kg\ d^{-1}$.

s = SCS runoff retention parameter.

s' = SCS runoff retention parameter adjusted for frozen soil.

s_1 = SCS runoff retention parameter associated with CN_1.

s_2 = SCS runoff retention parameter associated with CN_2.

s_3 = SCS runoff retention parameter associated with CN_3.

SALB = soil albedo.

SAN = sand content of the soil in %.

SAT = soil saturation factor.

SATK = soil saturated conductivity in mm h^{-1}.

SC = saturated conductivity of a soil layer in mm h^{-1}.

SD = sun's declination angle in radians.

SDRA = standard deviation of daily solar radiation in Mj $m^{-2} d^{-1}$.

SEP = reservoir seepage loss in m^3.

SEV = potential soil evaporation for a soil layer in mm.

SEV' = adjusted soil water evaporation in mm based on limited soil water content.

SFL = TR-55 shallow flow length in km.

Sf = fraction of mineral N sorbed to litter: 0.05 for surface litter, 0.1 for belowground litter.

SFV = average shallow flow velocity in km h^{-1}.

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 cmol kg^{-1}.

SML = snowmelt rate in mm d^{-1}.

SMLA = leaf-area-index of the plant stand.

SMX_0 = sum of the material in TLD before mixing in 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 ^{o}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 kg ha^{-1} d^{-1}.

SPP   = total soil profile supply of P in kg ha^{-1} d^{-1}.

SS   = root growth soil strength stress factor.

SSF   = subsurface flow rate in mm d^{-1}.

ST   = soil water content in the root zone in mm.

ST_1 = water content minus field capacity of the top 1 m of soil in mm.

ST_{25} = water content at WP+0.25(FC-WP) in mm.

STD   = standing crop residue in t ha^{-1}.

STD_0 = standing crop residue before tillage in t ha^{-1}.

STDL   = weight of lignin in STD in kg ha$^{-1.}$

STDN   = weight of N in STD in kg ha$^{-1.}$

STDNE   = standing dead N after enrichment with sorbed N in a soil layer in kg ha^{-1}.

STH   = watershed storage volume in mm at the end of the time interval in h.

STH_0 = watershed storage volume in mm at the start of the time interval in h.

STL   = standing live biomass of the crop in t ha^{-1}.

STL'   = standing live biomass at the end of the day in t ha^{-1}.

STMP   = soil layer temperature in ^{o}C.

$STMP_0$ = soil layer temperature for previous day
              in ^{o}C.

STP   = average slope of the watershed in 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.

TAGP   = above ground plant material in t ha^{-1}.

TBP   = tillage factor for biological processes.

TBSC   = crop-specific base temperature in ^{o}C.

TC   = watershed time of concentration in h.

TC_C = time of concentration for channel flow in h.

TC_S = time of concentration for surface flow in h.

TC_{SF} = time of concentration for shallow channel flow
              in h.

TDMX   = daily mean maximum temperature for dry
              days in ^{o}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 ^{o}K.

TLAI = leaf area index of mixed plant stand.

TLD = tillage depth in m.

TMN = daily minimum air temperature in ^{o}C.

TMX = daily maximum air temperature in ^{o}C.

TNO3 = NO3-N content in the soil root zone in kg ha^{-1}.

TOPC = optimal temperature for a crop in ^{o}C.

t_p = time to peak of the storm in h.

t_{pu} = 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_H = horizontal travel time through a soil layer in h.

TT_R = travel time through a routing reach in h.

TT_V = vertical travel time through a soil layer in h.

TW = water surface width at depth DH in m.

TW_2 = water surface width in m at depth D_2.

TW_3 = water surface width in m at depth D_3.

TWMX = daily mean maximum temperature for wet days in ^{o}C.

TX = mean daily air temperature in ^{o}C.

T_1 = water tension in soil layer 1 in kPa.

T_2 = water tension in soil layer 2 in kPa.

u'   = threshold friction velocity in m s^{-1}.

u10   = wind speed at f fraction of the day in m s^{-1}.

U10   = mean daily wind speed at 10 m height in m s^{-1}.

UC   = soil layer plant water use compensation factor.

UF   = upward flow rate in a soil layer in mm d^{-1}.

UN   = rate of N supplied by the soil in kg ha^{-1} d^{-1}.

UN'   = is the actual plant N uptake rate in kg ha^{-1} d^{-1}.

UN1   = actual N content of the crop in kg ha^{-1}.

UNM   = crop N uptake rate in kg ha^{-1} d^{-1}.

UNO   = optimal N content for the crop in kg ha^{-1}.

UP   = rate of P supplied by the soil in kg ha^{-1} d^{-1}.

UP'   = actual plant P uptake rate from a soil layer in kg ha^{-1} d^{-1}.

UP1   = actual P content of the crop in kg ha^{-1}.

USTR   = friction velocity in m s^{-1}.

USTRT   = threshold friction velocity in m s^{-1}.

UZZ   = daily mean wind speed adjusted for the crop height in m s^{-1}.

UW   = plant water use rate in a soil layer in mm d^{-1}.

UX   = potential water use rate in mm d^{-1}.

V   = flow velocity in m s^{-1}.

VCH   = channel flow velocity in m s^{-1}.

VFP   = floodplain flow velocity in 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 m s^{-1}.
w1	= parameter in CN-soil water relationship.
w2	= parameter in CN-soil water relationship.
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 kg ha^{-1} d^{-1}.
WFX'	= final adjusted N fixation rate in kg ha^{-1} d^{-1}.
WAVP	= crop parameter relating RUE and VPD.
WIP	= P immobilization rate in kg ha^{-1} d^{-1}.
WL	= unsheltered field length along the prevailing wind direction in km.
wn1	= descent angle of saltating sand grains in ^{o}.
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 NH3 in a soil layer in kg ha^{-1}.
WNO3	= NO3-N content in a soil layer in kg ha^{-1}.
WNO3'	= NO3-N content at the end of a day in kg ha^{-1}.
WO	= amount of pesticide washed off the plants by a rainstorm in 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.

WPO = soil layer organic P content in 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 kg ha^{-1}.

X_0 = amount of the material in a soil layer before mixing kg ha^{-1}.

X_{BMT} = microbial biomass transformation control by soil texture and structure. Its values: surface litter layer = 1; all other layers = $1 - 0.0075$ x (SIL+CLA)

X_{LSLF} = control on potential transformation of structural litter by lignin fraction of structural litter.

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_1 = exponential parameter in simulated rainfall distribution in h.

XKP$_2$ = exponential parameter in simulated rainfall distribution in h.

XLAI = maximum leaf area index for a crop.

XSL = x scale of the box around the watershed for generating spatially distributed rainfall.

Y = sediment yield in 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 t ha^{-1} .

YLAT = latitude of the site in degrees.

YLD = amount of the crop removed from the field in t ha^{-1}.

YMNU = manure erosion in t ha^{-1}.

YNO = organic nutrient (N or P) outflow in kg ha^{-1}.

YO = sediment outflow in t ha^{-1} .

YON = organic N runoff loss in kg ha^{-1}.

YON$_I$ = organic N reservoir inflow rate in kg d^{-1}.

YON$_O$ = organic N reservoir outflow rate in kg d^{-1}.

YP = sediment phase P lost in runoff in kg ha^{-1}.

YSL = y scale of the box around the watershed for generating spatially distributed rainfall in km.

YSP = soluble P in kg ha^{-1} lost in runoff.

YU = potential change in sediment yield in t ha^{-1} within a routing reach.

YW = wind erosion in kg m^{-1}.

YWR   = integral of the wind erosion rate over the
                 duration of wind greater than threshold
                 velocity.

YWR'   = wind erosion rate in kg m^{-1} s^{-1}.

Z   = soil depth in m.

Z_0 = surface roughness parameter in m.

Z_5 = depth to the center of a soil layer in mm.

Z_{CH} = channel depth in m.

Z_D = displacement height of the crop in m.

Z_{FP} = floodplain flow depth in m.

ZTP   = subarea rainfall weighting factor accounts
                 for rainfall duration, distance between subarea
                 centroid and storm center and rainfall gradient.

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