APEX Model Upgrades, Data Inputs, and Parameter Settings for Use in CEAP Cropland Modeling

January 2011

Xiuying (Susan) Wang, Research Assistant Professor, Blackland Research & Extension Center
Jimmy Williams, Research Scientist, Blackland Research & Extension Center
Jay D. Atwood, Agricultural Economist; USDA, Natural Resources Conservation Service
M. Lee Norfleet, Soil Scientist; USDA, Natural Resources Conservation Service
Arnold D. King, Agronomist; Texas Agrilife (retired from USDA, NRCS)

Table of Contents

APEX Model Description

Summary

The Agricultural Policy/Environmental eXtender (APEX) model addresses the impacts of management on environmental and production issues for whole farms and small watershed. It is constructed to evaluate the wide array of management strategies applied to crop, pasture, and grazing lands and estimates long-term sustainability of land management in respect to erosion (wind, sheet, and channel), economics, water supply, water quality, soil quality, plant competition, weather and pests for crop land as well as grazing and pasture land. Management capabilities simulated include: irrigation; surface and subsurface drainage; furrow diking; buffer strips; terraces; waterways; windbreaks; fertilization and manure management, lagoons and water retention reservoirs, crop selection and rotation; fertilizer, nutrient and pesticide fate and application; grazing management; tillage timing and intensity; and harvest timing and methods. Furthermore, APEX can address strategic implications of global climate/CO_2 changes; confined animal feeding facilities, production systems for bioenergy; and other spin off applications. The model operates on a daily time step (some processes are simulated with hourly or less time steps) assimilating the changes in daily weather and with specific timing and application of management practices in context of our current knowledge of physical, biological and environmental processes. Simulations can examine one year or hundreds of years if necessary and results can be summarized and examined daily, monthly, yearly or with multi-year analyses. APEX's unique feature is the ability to subdivide farms or fields by soil type, landscape position, surface hydrology or management configuration represent crop diversity and landscape characteristics within a field or farm. Each subarea may be linked with each other according to the water routing direction in the farm or watershed, starting from the most distant subarea towards the watershed outlet.

Background

APEX is derived 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. EPIC can be used to compare management systems and their effects on nitrogen, phosphorus, carbon, pesticides and sediment. The full theoretical and technical documentation of APEX can be found at http://epicapex.brc.tamus.edu/downloads/user-manuals.aspx

The development of APEX began in 1996 using proven technology, rigorously tested in many countries throughout the world over the last 25 years (Gassman, et al., 2004). APEX extends EPIC's capabilities to whole farms, multiple fields, and small watersheds to examine implications of farm management within context of the natural landscape and cropping patterns. 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 (Figure 1). Routing mechanisms allow for evaluation of interactions between subareas for surface runoff, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow as well as the collective evaluation/analysis for all subareas. 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 or for all subareas at the watershed outlet.
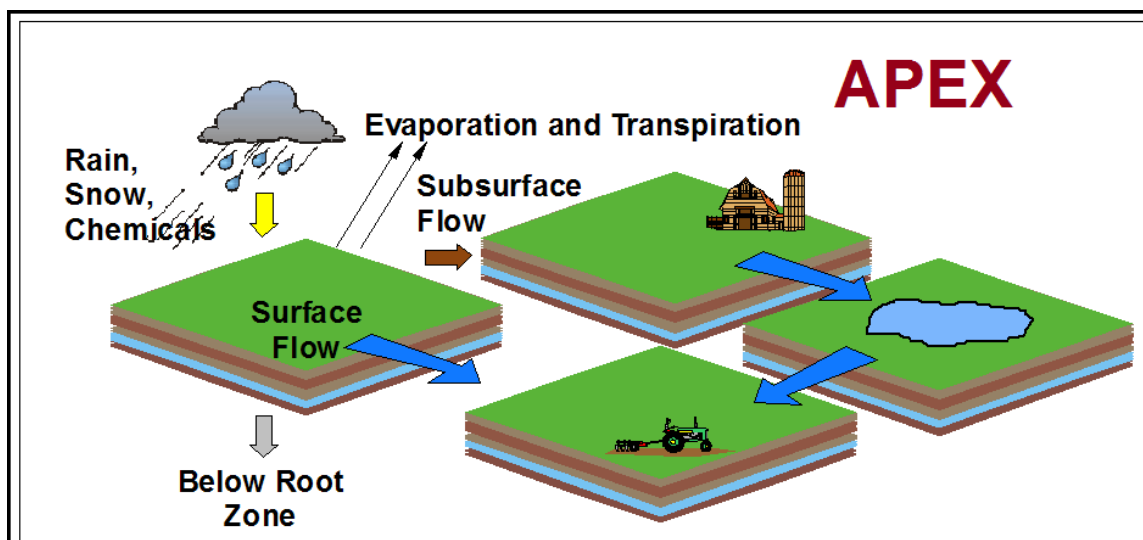

Figure 1. Illustration of water, nutrient, sediment routing between fields (subareas) defined for APEX simulations.

APEX uses major concepts and components that are well known and widely used in other models that have been published. These models include ALMANAC (Kiniry, et al., 1992), CENTURY (Parton, et al., 1994), CERES (Jones and Kiniry, 1986) , CLIGEN (Nicks and Lane, 1989), CREAMS (Knisel, 1980), GLEAMS (Leonard, et al., 1987), HYMO (Williams, 1975a), MUSLE (Williams, 1975b), RUSLE (Renard, et al., 1997), SWRRB (Williams, et al., 1985), SWAT (Arnold, et al., 1998), TR-55 (USDA-SCS, 1986), and WEQ (Woodruff and Siddoway, 1965).

History of EPIC/APEX Applications

The 1977 Resources and Conservation Act (RCA) charged the U.S. Department of Agriculture (USDA) with the responsibility to assess the status of the nation's soil and water resources on a regular basis. The first RCA appraisal conducted in 1980 revealed a significant need for improved technology for evaluating the impacts of soil erosion on soil productivity (Putnam et al., 1988). In response, the Erosion Productivity Impact Calculator (EPIC) model was developed by a USDA modeling team in the early 1980s to address this technology gap (Williams et al. 1984; Williams, 1990; Jones et al., 1991). The first major application of EPIC was for the 2nd RCA appraisal in 1985, in which the model was used to evaluate soil erosion impacts on the long term ability to meet food and fiber needs for 135 U.S. land resource regions (Putnam et al., 1988). Ongoing evolution of the model, including incorporation of additional functions related to water quality and atmospheric CO_2 change, resulted in the model name eventually being changed to Environmental Policy Integrated Climate. The latest version of EPIC features enhanced carbon cycling routines (Izaurralde et al., 2006) that are based on the approach used in the Century model (Parton et al., 1994).

Numerous applications of EPIC have been performed in the U.S. and in other regions of the world across a broad spectrum of environmental conditions. Example applications include assessment of sediment and nutrient losses as a function of different tillage systems, crop rotations, and fertilizer rates (Phillips et al., 1993; King et al., 1996), nutrient losses from livestock manure applications (Edwards et al. 1994; Pierson et al., 2001), nitrate-nitrogen (NO_3-N) losses via subsurface tile drainage (Chung et al., 2001; Chung et al., 2002), nutrient cycling as a function of cropping system (Cavero et al., 1999; Bernardos et al., 2001), soil loss due to wind erosion (Potter et al., 1998; Bernardos et al., 2001), climate change impacts on crop yield and/or soil erosion (Favis-Mortlock 1991; Brown and Rosenberg, 1999), losses from field applications of pesticides (Williams et al. 1992; Sabbagh et al., 1992), irrigation impacts on crop yields (Cabelgunne et al., 1995; Rinaldi, 2001), estimation of soil temperature (Potter and Williams, 1994; Roloff et al., 1998a), and soil carbon sequestration as a function of cropping and management systems (Lee et al., 1993; Apezteguía et al.,

2002). The flexibility of EPIC has also led to its adoption within several integrated economic and environmental modeling systems, that have been used to evaluate agricultural policies at the farm-, watershed-, and/or regional-scale (e.g., Taylor et al., 1992; Bernardo et al., 1993; Foltz et al., 1993; Babcock et al., 1997).

The APEX model (Williams and Izaurralde, 2005) was developed in the 1990s to facilitate multiple subarea scenarios and/or manure management strategies, such as automatic land application of liquid manure from waste storage ponds, which cannot be simulated in EPIC. The catalyst for creating APEX was the U.S. Environmental Protection Agency (USEPA) funded "Livestock and the Environment: A National Pilot Project (NPP)" that was initiated in 1992 to study livestock environmental problems on a watershed basis. The APEX model was used extensively for a wide range of livestock farm and nutrient management (manure and fertilizer) scenarios within the Comprehensive Economic Environmental Optimization Tool – Livestock and Poultry (CEEOT-LP), an economic-environmental modeling system developed for the NPP (Gassman et al., 2002; Osei et al., 2000a; Osei et al., 2000b; Osei et al., 2003a; Osei et al., 2003b). It has also been applied within a number of other studies. The APEX review report by Gassman, et al. (2009) provides a review of APEX applications reported in the peer-reviewed literature and other sources, including validation assessments versus measured data.

APEX and CEAP

APEX was selected to estimate the edge of field benefits of conservation practices for CEAP. To accommodate the CEAP assessment, several changes were made to strengthen the model's capability. The improvements include changes to the carbon cycle and organic matter decomposition; denitrification; manure erosion; irrigation, grazing component, surface runoff volume. The improvement also includes the development of delivery ratios for transporting sediment, nutrient, and pesticides from APEX sites to 8-digit watershed outputs (see Appendix G). Furthermore, an extensive assessment of APEX's performance for estimating impacts of conservation practices was conducted to verify the conceptual algorithms in APEX reliably estimated the edge-of-field effects of conservation practices applied to croplands was conducted (see Appendix E).

To extend the impacts of conservation practices beyond the field edge to the watershed, river basin and beyond, APEX's cropland results were fed to SWAT, the Soil and Water Assessment Tool, where SWAT aggregated the cropland impacts from APEX, aggregates impacts of other land uses (agricultural and urban) and quantifies the stream impacts on water quality (Figure 2). The cropping

practices reported on the Farm Survey formed the baseline practices for each NRI sampling point. APEX results from each point were analyzed to obtain the edge of field estimates and comparisons to the "no" (conservation) practice and "enhanced" conservation practice scenario. Offsite and Stream impacts were estimating by aggregating APEX results from each CEAP farm survey and applying the appropriate expansion factors to represent a four-digit HUC.
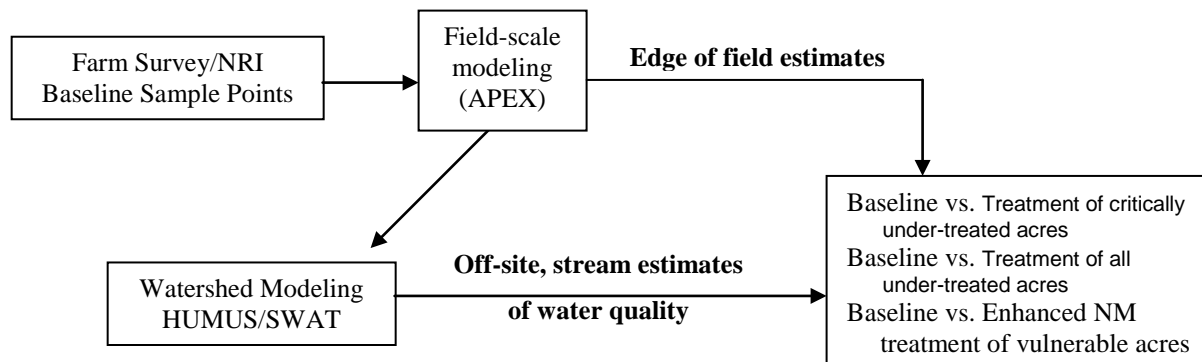

Figure 2. Schematic diagram illustrating the use of CEAP Farm Survey information to estimate the edge of field estimates with APEX and the off-site and stream estimates of water quality with HUMUS/SWAT.

Testing and Evaluating the APEX Field-scale Model

Testing and evaluating the APEX model consists of verification and validation. Verification procedures aid in evaluating the reliability and accuracy of the model and inputs to ensure computational solutions are consistent with known solutions. Validation evaluates the accuracy of a computational simulation by comparison with independent experimental data. In validation, the relationship between computation and the real world, i.e., experimental data, is the issue." First the model must be solved correctly, i.e. verified, and then it can be validated.

Verification activities mainly take two forms: stability testing and screening model outcomes. Stability testing ensures the computer model runs across a wide range of management systems and environmental conditions. Screening model outcomes involves evaluating model solutions to ensure the model reliably portrays known physical processes, solutions are consistent with previous model solutions, and that geospatial biases or errors are identified.

The fundamental strategy of validation is to assess how accurately the computational results compare with experimental or observed data, with quantified error and uncertainty estimates for both. The

main issue is to provide evidence concerning how accurately the model simulates the real world. One component, calibration, assesses the sensitivity of model input parameters and adjusts the values so that simulation results closely match experimental results. Then the validation evaluates the accuracy of an APEX model simulation by comparison with independent experimental data. Appendix E describes our efforts to verify and validate APEX.

APEX Model Upgrades for CEAP

Carbon cycle routines

The current versions of EPIC/APEX incorporate carbon and nitrogen algorithms to estimate soil carbon sequestration as affected by climatic conditions, soil properties, and management practices (Izaurralde et al., 2006). The soil organic matter model follows the Century model (Parton et al., 1987, 1993, 1994; Vitousek et al., 1994). The following modifications were performed when implementing the Century model carbon cycling into EPIC/APEX: 1) organic materials' movement from surface litter to subsurface layers are estimated by the leaching equations currently in EPIC/APEX; 2) temperature and water controls affecting transformation rates are calculated with equations currently in EPIC/APEX; 3) the surface litter fraction in EPIC/APEX has a slow compartment but no passive compartment; and 4) the lignin concentration in EPIC/APEX is modeled as a sigmoidal function of plant age.

Denitrification routine

Denitrification consists on the sequential reduction of NO_3^- to NO_2^-, NO, N_2O, and N_2. The last three compounds can diffuse from the soil to the open atmosphere, representing a net loss of nitrogen from the soil. In practical terms, the factors affecting denitrification are: (1) NO_3^- availability, (2) oxygen concentration, (3) organic carbon availability for respiration, (4) temperature affecting microbial respiration. The minor effect of soil pH on denitrification is not considered here.

The two dominant components of denitrification are N_2 and N_2O. To simulate these two gaseous emissions in EPIC/APEX we followed the common rational of adjusting a maximum, empirically determined emission rate, by factors controlling total denitrification rate. The total denitrification rated is then partitioned into N_2 and N_2O fluxes. No attempt is made to estimate N_2O flux from the atmosphere to the soil. More comprehensive approaches to estimate CO_2, O_2, and N_2O fluxes in the soil-plant-atmosphere system with EPIC are under testing but are not presented here. The equation used to compute total denitrification is:

$$R_{dn} = (1/1000) \cdot \rho \cdot dz \cdot R_{max} \cdot f_{NO3} \cdot f_{resp} \cdot f_w \qquad (1)$$

where R_{dn} is the denitrification rate ($N_2O + N_2$) kg N m^{-2} day^{-1}), ρ is the soil bulk density (Mg m^{-3}) dz is the layer thickness (m), R_{max} is the maximum denitrification rate ($N_2O + N_2$) (32 x 10^{-6} kg N kg^{-1} soil day^{-1}), f_{NO3} is an adjustment factor for nitrate, f_{resp} is an adjustment factor for respiration – carbon availability, f_w is an adjustment factor for moisture 1/1000 converts Mg to kg.

The factors controlling denitrification were assumed to operate multiplicatively. The effect of carbon availability and temperature were lumped in the respiration factor, as respiration is controlled by soil temperature. The R_{max} of 32 x 10^{-6} kg N kg^{-1} soil day^{-1} is in broad agreement with rates reported in Rolston et al. (1978) and Del Grosso et al. (2000). The nitrate adjustment factor f_{NO3} follows a half saturation curve, as used in SOILN (Wu and McGechan, 1998), that we parameterized as follows:

$$f_{NO3} = NO_3^- / (NO_3^- + 60) \qquad (2)$$

where NO_3^- is in mg N kg^{-1} soil. This asymptotic equation assumes increasing saturation in the capacity of the denitrifiers to reduce any additional nitrate.

Soil moisture or the air filled volume is used as a surrogate for oxygen concentration in soils, as air volume is related to diffusivity of gases in soils. The ratio of soil to air diffusivity of gases has been associated to the soil air filled porosity (AFP), with a proportionality constant of about 0.66 (Penman, 1940) or 0.61 (Van Bavel, 1952). However, as the water content increases the continuity of the soil air-filled pore space decreases, further limiting gases diffusivity. In Wesseling (1962) formulation, gas diffusivity in soils is near 0 at a water filled porosity (WFP = 1 – AFP) of 0.9 (approximately 0.05 m^3 m^{-3} volumetric air content for many soils). Therefore, at AFP < 0.1 denitrification is likely near its maximum value. Rolston et al. (1978) found that denitrification responds dramatically to small changes in water content, with a threshold-like response to decreasing AFP (or WFP). Simulating denitrification requires therefore an accurate simulation of soil water content above field capacity. The following equation was used to represent the effect of soil volumetric air content (A_v, m^3 air m^{-3} soil) on denitrification rate:

$$f_w = 1 / [1 + ((1 - A_v)/(0.90 + 0.1 \cdot f_{clay}))^{-60}] \qquad (3)$$

where f_{clay} is the soil layer clay fraction. It is assumed that the threshold A_v triggering denitrification is a function of texture. Daily or sub-daily time steps may be needed to simulate denitrification appropriately.

Many factors affecting diffusivity and likely denitrification have not been included in this simple response to A_v. Soil structure has a role in defining diffusivity. Currie (1965) found that the intra and extra aggregate diffusivity determines the soil diffusivity and that the relationship can be

parameterized. Soils with poor structure tend to be poorly aerated and therefore develop anoxia earlier than well structured soils of the same texture, a feature that can be partially captured here through effects of organic matter on bulk density and soil hydraulic properties. The interaction between soil water content and respiration rate has not been explicitly addressed. Anoxia will develop faster in soils with high respiration rate. The soil thawing-freezing associated with small burst of N_2O emission from soils (R. Engel comm. pers.) has not been represented.

The effect of soil respiration is accounted for through a linear relationship as follows:

$$f_r = \min(1, C_{resp}\text{-}CO_2/50) \tag{4}$$

where C_{resp} is the CO_2 emissions per soil layer (mg $C\text{-}CO_2$ kg^{-1} soil). To partition the denitrification products in N_2 and N_2O we calculated the fraction of denitrification released as N_2O (f_{rN2O}) as follows:

$$f_{rN2O} = f_{NO3}\cdot(1 - f_w^{0.5})\cdot(1 - f_r^{0.33}) \tag{5}$$

This formulation renders a higher fraction of denitrification as N_2O when soils have more air filled space, less respiration, and high nitrate content. High denitrification rates are therefore associated to lower ratios of N_2O to total denitrification, unless the nitrate concentration in denitrifying layers is high.

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. 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.

$$YMNU=0.25*(Q*q_p)^{0.5}*PE*SL*RSDM^{0.5}*\exp(-.15*AGPM)) \tag{6}$$

where YMNU is the manure erosion (t ha^{-1}) Q is the runoff volume (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 (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.

The CEAP national cropland assessment includes both manure deposition from grazing animals and mechanical application of manure to cropland fields, but does not include any simulation of feeding areas as described in the previous two paragraphs. For application of manure to farm fields, the quantities of manure were adjusted to exclude materials other than N, P, K, and C. The exclusion of water and other materials was necessary due to the nature of some of the reported materials and the way manure is handled in APEX. For example, one CEAP sample reported a very dilute liquid animal waste material applied at a rate of 330 tons per acre per year with an irrigation system. In that case, the proportions of material as mineral N and organic N were only 0.00005 and 0.00003, resulting in an annual application rate of 52.8 lbs of N, and an "irrigation" rate of about 3 acre-inches. If that application were specified and simulated directly as reported with APEX, the simulation results would be incorrect for two reasons. First, the APEX model assigns a soil erosion reduction value to the inert material, without considering whether the inert material is water or other materials. Secondly, the portion of the inert material that is water is not considered in the APEX soil water balance accounting. Consequently, for the CEAP analysis, manure applications were specified in terms of elemental N, P, and C, with other portions of the composite manure materials ignored. In the entire national survey there were only a few manure application events where the implied irrigation water amounted to one-half inch or more, so water content of the manure was ignored. Also, in cases such as these, irrigation water applied with the manure is normally a minor component of the water budget. Additional information on the setup of manure for the CEAP cropland assessment can be found in the "Transforming Survey Data to APEX Model Input Files" document on the web site from which this document was obtained.

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.

Besides the general APEX complex grazing system options described above, another option was developed for the CEAP assessment, in which the herd type can be specified at the subarea level (grazing rate and manure type and quantity deposition per animal) and the herd size can be specified for each instance of grazing, allowing even different densities for pre- and post- harvest grazing of a single crop. This is set with a "start graze" field operation. Note that any grazing operation started in the fall automatically stops on December 31 and to restart grazing in the next year of the rotation, another "start graze" operation is required on January 1. Table 1 gives the grazing herd definition. Additional information on the setup of grazing for the CEAP cropland assessment can be found in the following document (website link): http://www.nrcs.usda.gov/technical/nri/ceap/umrbdocumentation/ "Transforming Survey Data to APEX Model Input Files"

Table 1. Grazing herd definition in APEX for CEAP.

Herd Number	Will be set at 1 – only 1 herd because only 1 main cropland subarea (if additional cropped subareas are replicated for representing practices, then the herd is also replicated with livestock number adjusted proportionately if acreage is different).
Number of animals	Density initially set at the average for the sample, but will be reset with each grazing start operation.
Fraction of herd in feeding area	0.0 since not modeling an associated feed yard
Grazing rate	Daily biomass per head in kg (assumed to be 3% of live weight)
Daily Manure Dump	Kg/head
Manure ID	Fertilizer table ID number for each livestock manure type
Urine Volume	0 since not concerned with moisture build up in feedlot situation

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 option include a signal to trigger applications (the three trigger choices include: plant water stress level, 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 day. 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, accounting for evaporation, runoff, and percolation losses.

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.

For CEAP we used the Variable mode Automatic Option, except for samples where the annual average number of days with plant growth limited by salt stress was more than five. For those samples, we used the Fixed mode Automatic Option of irrigation to move more of the salts below the root zone.

The enhanced irrigation component for CEAP includes:

1) adding a new variable, Irrigation Fraction Field Capacity (FIRG)

   For auto irrigation the user can now specify a proportion of the Field Capacity deficit that will be added (previously always added exactly the deficit). The purpose of this is to allow user to account for uneven with-in field distribution for gravity irrigated systems (FIRG > 1.) This parameter can also be increased to reflect the additional leaching required for salinity control.

2) specifying a variety of irrigation operations, each with own efficiency, that would be available for use by auto – irrigate. For each instance of auto-irrigate, the user can specify which operation to use. When one of those operations is included in the field operation schedule to trigger the start of auto-irrigation, the user can also now reset irrigation runoff proportion, FIRG, and the runoff Curve Number (for natural precipitation events). For CEAP we will do this for each separate crop in the rotation. This was important because some CEAP samples used different systems for different crops.

3) specifying the runoff proportion with the irrigation operation.

For CEAP, for each crop in the rotation, a separate Irrigation Operation was used to initiate auto-irrigation. And each of those operations had its own FIRG, efficiency, and runoff proportion, based on the collected irrigation data. More detail is given on the setup of the irrigation simulation in the following document (website link): http://www.nrcs.usda.gov/technical/nri/ceap/umrbdocumentation/ "Transforming Survey Data to APEX Model Input Files"

Surface runoff volume

The daily runoff volume is calculated using a modification of the NRCS curve number method (Mockus, 1969; USDA-NRCS, 2004). The modification to the curve number method includes:

adjusting the curve number value for moisture condition 2 (CN_2) considering slope factor, and linking the retention parameter, S, in the curve number method to a continuous soil moisture accounting procedure with this equation (Wang et al., 2008):

$$S = S_{prev} + PET \times \exp(-CNIC \times \frac{S_{prev}}{S_{max}}) - P_{prev} + Q_{prev} + Q_{return} + Q_{drainage} + SSF + PRK \tag{7}$$

where S is the retention parameter for a given day (mm), S_{prev} is the retention parameter on the previous day (mm), PET is the potential evapotranspiration for the day (mm d^{-1}), $CNIC$ is the weighting coefficient used to calculate the retention coefficient for daily curve number calculations dependent on plant evapotranspiration, S_{max} is the maximum value the retention parameter can achieve (mm) which is associated with CN_1 for moisture condition 1 (dry), P_{prev} is the rainfall after plant interception on the previous day (mm), and Q_{prev} is the runoff on the previous day (mm), $Q_{drainage}$ is drainage flow on the previous day (mm), SSF is the lateral subsurface flow on the previous day (mm), and PRK is percolation on the previous day (mm).

Once the daily retention parameter is calculated, the calculation of the daily adjusted curve number is then performed using the following equation:

$$CN = 25400/(S + 254), CN_1 \leq CN \leq CN_3 \tag{8}$$

where CN_1 and CN_3 are the curve numbers for moisture condition 1 (dry) and moisture condition 3 (wet), respectively. In APEX, the values of CN_1 and CN_3 are calculated based on the initial CN_2 for the moisture condition 2 curve number (or average curve number).

The CN_2 is a required input which can be obtained from standard USDA sources such as Mockus (1969) or USDA-NRCS (2004). In APEX, the CN2 input was previously started with a subarea default value and kept that value until reset by the first planting operation, then repeatedly reset by the following planting operations till the end of the rotation. Then, it is reverted to the subarea default value again until the first planting operation of the rotation. Refinement has made in the CEAP project, where the CN2 set by the last planting operation of the rotation will be kept until reset by a planting operation, and then by next planting operation, and so on. the CN2 never reverts to the subarea default (unless user neglects to input CN2 with all planting operations).

The standard CN_2 is assumed to represent conditions representative of a 5% slope (i.e., a typical slope) in the model. The CN_2 is adjusted in the model to account for slope effects that are not incorporated in the original curve number method using the following equation:

$$CN_{2S} = 100/(1 + (100/CN_2 - 1)(1.1 - STP/(STP + exp(3.7 + 0.02117 \times STP)))) \quad (9)$$

where CN_{2S} is the handbook CN_2 value adjusted for slope and STP is the average slope of the watershed in %. The values of CN_1 and CN_3 which correspond to CN_{2S}, are then calculated with the equations:

$$CN_1 = CN_{2S} - 20 \times (100 - CN_{2S})/(100 - CN_{2S} + exp(2.533 - 0.0636 \times (100 - CN_{2S}))) \quad (10)$$

$$CN_3 = CN_{2S} \times exp(0.00673 \times (100 - CN_{2S})) \quad (11)$$

Delivery ratio

There are typically 20 + NRI-CEAP points (APEX simulation sites) within a 8-digit watershed. Each NRI-CEAP point, simulated with the APEX model, represents a fraction of the total area which is randomly distributed throughout this watershed. Therefore, the APEX site locations are considered randomly distributed. Each NRI-CEAP point is assumed to be 16 ha; APEX is used to simulate the 16 ha sub-areas within a 8-digit watershed. Sediment yield from the APEX sites is routed to the outlet of the 8-digit watershed and becomes input to SWAT for further routing downstream. A delivery ratio procedure was developed to estimate sediment, nutrient, and pesticide transport from APEX sites to 8-digit watershed outlet. The detail was described in Appendix G.

Data Inputs and APEX Model Parameter Settings for CEAP

The APEX model requires inputs of daily weather, soil attributes by layer, field management, site information and watershed characteristics. Model parameters in the APEX database include the parameters for crops, tillage operations, fertilizers, and pesticide characteristics. There is also a parameter file, which contains many equation coefficients, definitions of s-curve, and miscellaneous parameters used in APEX. The input data sources are summarized in Table 2. The specific settings for many of the data variables listed in the following sections varied due to the varied complex nature of the farming systems found in the CEAP cropland survey. More information on the specific settings for those items can be found in one of the following documents (website link):

http://www.nrcs.usda.gov/technical/nri/ceap/umrbdocumentation/

"Transforming Survey Data to APEX Model Input Files"

"Modeling Structural Conservation Practices for the Cropland Component of the National Conservation Effects Assessment Project"

Table 2. CEAP APEX input data summary

File	Short Description	Source/Method
Weather		
*.txt	Daily precipitation and maximum and minimum air temperatures (all NRI-CEAP points within one 8-digit watershed use the same file)	Combine the specific daily station data from Eischeid, *et al.* (2000) and the monthly PRSIM[†] grids (Daly *et al.*,1997 and 2002) to produce a single weather data series for each of the USGS 8-digit watersheds, accounting for latitude, longitude, and elevation (Di Luzio *et al.*, 2008).
Iawind.dat	Lists monthly wind weather statistics, including average monthly wind speed, monthly % wind from 16 wind directions, which are crucial if the user analyzes issues of wind erosion as well as dust distribution and air quality from feedlots. Used to generate daily wind speed and direction.	Monthly weather data series were the weather station data associated with the climate clusters described in Goss et al. (2001) and Potter et al. (2006). Weather data are generated based on the monthly weather generator parameters imbedded in the APEX model (Nicks, 1974; Sharpley and Williams, 1990).
Iaweath.dat	Lists average monthly weather statistics, such as average monthly maximum and minimum temperatures and their standard deviations, monthly precipitation, monthly max 0.5 hour rainfall, solar radiation, relative humidity, monthly skew coef of daily rainfall, monthly probability of wet day after dry day and wet day after wet day, etc. These variables are used to generate weather when no daily weather data, such as daily solar radiation, are available. Examples of other uses include: the monthly temperatures for calculating PHU for tree crops; the max 0.5 h rainfall for estimating alph for use in computing peak runoff rate and rainfall energy.	
Soil attributes		
*.sol	Lists soil attributes, such as soil albedo, hydrologic soil group, and other soil attributes by layer, e.g., depth, bulk density, sand, silt, soil PH, orgianic carbon etc.	NRI data set NASIS soil map unit data contained in the NRCS Soil Data Mart (SDM) (USDA-NRCS, 2007).
Field management		
*.ops	Lists operation schedule by date, such as planting (crop ID, PHU, landuse number or CN2, plant population), harvesting, tillage, fertilizer application (fertilizer ID, application rate, depth), pesicide application (pesicide ID, application rate).	NRI-CEAP survey (Atwood, et al., 2009)
Site information and watershed characteristics		
iasit.dat	Lists site latitude, longitude, elevation etc.	NRI data set
iasub.dat	Contains subarea information, such as soils and operation schedules used for each subarea, catchment charactersitics and channel geometry of routing reaches, etc.	NRI data set Subarea setup are based on "structural" conservation practices reported in 2003, 2004, and 2005 CEAP surveys (Potter, et al.,

2009).

† PRSIM: Parameter-elevation Regressions on Independent Slopes Model

Data Inputs for CEAP Model Runs

Weather

The daily weather input data includes precipitation, maximum and minimum air temperatures, solar radiation, average relative humidity, and average wind speed. Two challenges were faced in choosing historical weather data sets for the simulations. First, since the APEX model output for cultivated cropland was being passed to the SWAT model at the 8-digit watershed level, it was necessary that both the APEX and SWAT model use the same daily weather data series within each 8-digit watershed. Second, since a typical watershed had varied elevation and other topographic characteristics, it was generally not possible to choose a single reporting station for each watershed that would adequately represent the weather for the entire watershed. To overcome these two challenges, the historical daily weather data from a large set of weather stations was used, along with a complex grid-based weighting system, to develop a single artificial daily weather data series for each 8-digit watershed. This was completed for the data series of daily precipitation and daily temperature minimum and maximums.

The available weather data series from across the U.S. are generally incomplete for some periods of times. However, Eischeid, et al. (2000) created a serially complete daily data set of weather station data from weather station records available from the NCDC (National Climatic Data Center), for the period of 1960 to 2006, including precipitation, temperature maximum, and temperature minimum. This dataset contained multiple reporting stations for most 8-digit watersheds. Di Luzio, et al., (2008) then developed a method to combine the specific daily station data from Eischeid and the monthly PRSIM grids (Parameter-elevation Regressions on Independent Slopes Model) (Daly, et al., 1997 and 2002) to produce a single weather data series for each of the USGS 8-digit watersheds, accounting for latitude, longitude, and elevation. The PRISM data were distributed at a resolution of approximately 4 km. The combination approach included an inverse distance weighting (IDW) approach, to combine daily ratios calculated from the point measurements (station records) and the monthly PRSIM grids to accomplish the distribution of the daily records with orthographic adjustments over each of the USGS 8-digit watersheds, for the period 1960-2006.

18

In both the APEX and SWAT simulations, daily solar radiation, wind speed and direction, relative humidity, and rainfall intensity data were simulated using the monthly weather generator parameters imbedded in the models (Nicks, 1974; Sharpley and Williams, 1990). The weather generators use monthly weather data series. The monthly weather data series used were the weather station data associated with the climate clusters described in Goss et al. (2001) and Potter et al. (2006).

Atmospheric nitrogen deposition

Atmospheric deposition can be a significant component of nitrogen balance and contribute to plant growth and nitrogen runoff concentrations especially in some of non-agricultural land. Hence, estimates of nitrogen deposition (nitrate and ammonium) were incorporated into SWAT and APEX models. Nitrogen deposition data (loads and concentration) were developed from the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) database (NADP/NTN, 2004) which consisted of yearly deposition grids available for the entire nation, for the period of 1994 to 2001.

The network is a cooperative effort between many different groups, including the State Agricultural Experiment Stations, U.S. Geological Survey, U.S. Department of Agriculture, and numerous other governmental and private entities. Final spatial records, for each of the 8-digit watersheds, were estimated with a GIS combination of the NADP concentration maps and the previously estimated daily precipitation records. These data were processed for creating nitrogen deposition records for each 8-digit watershed. The resulting daily nitrogen deposition records were cumulated at the yearly time step for incorporation into SWAT and APEX. Ammonia and nitrate amounts were estimated separately, converted to elemental and then converted to an average annual per-acre value for each 8-digit watershed.

Soil Attributes

The basic soils data for the APEX model simulations was obtained from the NASIS soil map unit data contained in the NRCS Soil Data Mart (SDM) (USDA-NRCS, 2007). The soil name and classification key interpretations for each NRI point were used to link to the appropriate soil attribute data in NASIS. Since the primary purpose behind the collection of the soil attribute data had been for soil taxonomy, rather than for use in simulation models to investigate management alternatives, in some cases the soil attribute data was insufficient for modeling adjustments or additions were required. In addition, for some NRI points, some soils were not linked to SDM and for some soils, some data elements were missing and these were filled in from other soils data sources such as the

pre-NASIS database of Soils_5 data. Other sources for missing data included pedon level data from the national Soil Survey laboratory and several National Cooperative Soil Survey laboratories and procedures similar to those described in the Map Use Unit File system (Baumer, et al., 1994).

The following procedures were applied to the soils data:
1) division of thick top layers into layers of 0.2 meters or less;
2) for soils without an apparent Ap horizon (non-cultivated soils) adjusting soil carbon content by region, texture, hydrologic group, and depth based on statistical analysis of similar soils that did have an Ap horizon;
3) checking that soil parameters such as bulk density, coarse fragment, electrical conductivity, pH, etc., were within possible limits rather than being obvious data recording errors; and
4) adjusting for various minor corrections such as sum of silt and sand percentage being greater than 100.

The soil layer splitting and soil carbon adjustment were particularly important for soils where the top layer was reported to be up to 1.5 meters deep while having a reported carbon content appropriate only for the top 0.2 meters. In those cases if uncorrected, the implied pool of soil carbon and nitrogen was so large that loss estimates were tremendous regardless of farming practices.

Landscape data

The NRI point attribute data included links to soil attribute data, slope length and angle, use indicates for some conservation practices, land-use history, and the factors for the Universal Soil Loss Equation and Wind Erosion Equation. These data were used for the APEX simulation. The CEAP point is simulated as a 400 x 400 meter subarea (16 hectares or about 40 acres), representing a homogenous field with respect to soil, climate, and management. Upland slope and slope length are assumed to be uniform and are set for each point to the values reported in the NRI. Modifications of the standard field configuration were developed to simulate specific practices or suites of practices in the baseline scenario or a priori conditions in the No Practice scenario. Whenever the baseline included any combination of grass filter strip, riparian buffer, grass waterway or grade stabilization structure, a modified field configuration was used in place the standard configuration for the baseline. Also, modified field configurations were required in the no practice scenario when a grass waterway or grade stabilization was reported. In total, fifteen field configurations, each identified by a unique field id, were developed. Model input values for each field configuration were developed and

imputed to CEAP points by linking each point with a baseline and no practice field configuration (See Potter, et al. (2009) for more details). The variables in the APEX subarea file are listed in Table 3.

Table 3. The APEX subarea file

Line, Var	Variable name	Value if global	Description
1	TITSA		Subarea ID number, Description of the subarea.
2, 1	INPS		Soil number from soil list indicating which soil is used for this subarea.
2, 2	IOPS		Operation schedule from operation schedule list indicating which operation schedule is used for this subarea.
2, 3	IOW	1	Owner ID #
2, 4	II		**Feeding area** =0: for non feeding area >0: Herd # for feeding area
2, 5	IAPL		Manure application area =0: non manure application area >0: Use the positive subarea ID of the feedlot to indicate solid manure application <0: Use the negative subarea ID of the feedlot (lagoon) to indicate liquid manure application.
2, 6	IFLS		**Filter Strip Code** 0: for normal subarea 1: for filter strip
2, 7	NVCN	0	**Non-varying CN-CN2 Used** 0: Used the NVCN0 setup in the APEX control file (Table 4), which means that the "Variable daily CN soil moisture index" is used.
2, 8	IWTH		Input daily weather station number
2, 9	IPTS	0	Point source number (no point source used)
3, 1	SNO	0	**Water content of snow on ground at start of simulation** The water content of snow on the ground at the beginning of the simulation is user specified. For long-term simulations used in decision making, SNO is usually not known, but in most cases the estimate is not very critical. Plus, there are 15-year pre-run for CEAP.
3, 2	STDO	2.5	**Standing dead crop residue** The STD variable allows input of initial, standing dead crop residue in t/ha. STD may be left at 0 if unknown; however, year one will not have standing dead residue prior to crop growth. Only after the first crop cycle will crop residue be present.
3, 3	XCT		**X Coordinate(Longitude) of subarea centroid** It needs to be entered if dust distribution and air quality is considered in the study or if the Spatially Generated Weather option is to be used. Spatially Generated Weather is set by entering 0 for the variable NGN in control table. Note: A minus degree designates western hemisphere.
3, 4	YCT		**Y Coordinate(Latitude) of subarea centroid** It needs to be entered if dust distribution and air quality is considered in the study. It also needs to be entered if the Spatially Generated Weather option is to be used. Spatially Generated Weather is set by entering 0 for the variable NGN in the control table. Note: A minus degree designates the southern hemisphere.
4, 1	WSA	0.4-16	**Watershed/subarea drainage area**

			Size is in (ha). If this is a second extreme and its flow joins the first extreme area flow but does not flow through the first extreme area a (-) sign is added to the front of the second extreme area WSA making it a negative number. This tells the program to add the second area WSA to the first extreme area when pertaining to water flow.
4, 2	CHL	0.02-0.45	**Distance from outlet to most distant point on watershed/subarea** The channel length is the distance along the channel from the outlet to the most distant point on the watershed. Often in small areas (approx. 1 ha) there is no defined channel. In such cases the length is measured along a concentrated flow path or it can simply be estimated from the length-width ratio of the watershed. Units are kilometers (metric) or miles (English). If this is an EXTREME subarea then Channel Length of Routing Reach MUST EQUAL Distance from Outlet. If this is a DOWNSTREAM subarea then Channel Length of Routing Reach can NOT BE EQUAL to Distance from Outlet.
4, 3	CHD		**Channel depth** Depth of the channel in meters. Estimated in APEX.
4, 4	CHS		**Mainstream channel slope** The average channel slope is computed by dividing the difference in elevation between the watershed outlet and the most distant point by CHL. For small areas this measurement is not critical because CHL and CHS are only used in estimating the watershed time of concentration. The dominant portion of the time of concentration is involved with overland rather than channel flow in small watersheds. Slope is expressed as units of drop per unit of distance. (m/m)
4, 5	CHN		**Manning's N for channel**. If the channel conducting runoff to the edge of the field is winding and/or contains obstructions, water flow rates will be reduced, and sediment will have an opportunity to settle. The channel roughness factor is referred to as the Manning's "n" value. The table contains suggested values of Manning's "n" for various condition channel flow (Chow 1959). Chow has a very extensive list of Manning's roughness coefficients. These values represent only a small potion of those listed in his book.
4, 6	STP		**Average Upland Slope** Slope is in m/m. Must be entered. The average watershed slope can be estimated from field measurement or by using the Grid-Contour Method (Williams and Berndt 1977).
4, 7	SPLG		**Average Upland Slope Length** Length in m. Must be entered. The watershed slope length can be estimated by field measurement as described by Wischmeier and Smith (1978) or from topographic maps using the Contour-Extreme Point Method (Williams and Berndt 1977).
4, 8	UPN		**Manning's N for Upland** The surface roughness factor is Manning's "n" values. This table contains suggested values and possible ranges of Manning's 'n' for various condition overland flow (Engman 1983).
4, 9	FFPQ		**Fraction of floodplain flow** Partitions flow through filter strips.
5, 1	RCHL		**Channel Length of Routing Reach** The length (distance) in km between where channel starts or enters the subarea and leaves the subarea. If this is an EXTREME subarea, then Routing Reach Length MUST EQUAL Longest Distance from Outlet (CHL). If this is a DOWNSTREAM subarea, then Routing Reach Length can not be equal to Longest Distance from Outlet.

5, 2	RCHD		**Channel Depth of Routing Reach**

5, 2   RCHD   **Channel Depth of Routing Reach**
Depth of the channel for the routing reach in meters.

5, 3   RCBW   **Bottom Width of Channel of Routing Reach**
Width in meters of the bottom of the channel of routing reach.

5, 4   RCTW   **Top Width of Channel of Routing Reach**
Width in meters of the top of the channel of routing reach.

5, 5   RCHS   **Channel Slope of Routing Reach**
Slope of the routing reach channel in m/m. Must be entered.

5, 6   RCHN   **Channel Manning's N of Routing Reach**
The table contains suggested values of Manning's "n" for various condition channel flow (Chow 1959). Chow has a very extensive list of Manning's roughness coefficients. These values represent only a small potion of those listed in his book.

5, 7   RCHC   **USLE Crop Management Channel Factor**
Must be entered. With bare channel condition, RCHC should be 0.1- 0.6, and if the channel has very good land cover, it should have a value of 0. 0001 (Range is 0.0001 - 0.6)

5, 8   RCHK   **USLE Erodibility Channel Factor**
Must be entered. With a rock condition, RCHK should be 0.0001; with loess (silt/mud) condition, it should be 0.30.(Range is 0.0001 - 0.5)

5, 9   RFPW   **Buffer/Floodplain width**
(Drainage Area(WSA) X 10000) / (Floodplain length (RFPL) X 1000) , in (m)

5, 10   RFPL   **Buffer/Floodplain length**
Length of buffer/ floodplain in km.

6, 1-10   **not used**   **Reservoir data**

7, 1-3   **not used**   **Reservoir data**

8, 1   NIRR, IRR   **Rigidity of Irrigation Code**
0 For flexible (variable) applications. Applies minimum of soil water field capcity (FC-SW) and maximum single irrigation application volume (ARMX).
1 For rigid (fixed) applications. Applies input amount or ARMX.
The irrigation code is used to specify the irrigation strategy. There are two modes of irrigating -- manual and automatic. The following details how the model handles the combination of rigid and flexible applications and manual and automatic irrigation.

    1.   Fixed/Rigid
         If MANUAL irrigation is used, irrigation is applied according to the amounts and dates specified by the user in the operation schedule. If AUTOMATIC irrigation is used, the amount applied per application is equal to the maximum single application amount (ARMX) which is set for each subarea and irrigation is applied when the irrigation trigger (BIR) is reached. If the amount of irrigation is greater than the amount of water needed to bring the soil to field capacity, the model will run off the fraction (EFI) and the remaining water will be percolated through the soil. This may cause leaching of nutrients, however.

    2.   Variable/Flexible
         If MANUAL irrigation is used, irrigation is applied on the date specified in the operation schedule in an amount to

bring the soil to field capacity. If AUTOMATIC irrigation is used, irrigation is applied based on the irrigation trigger (BIR) and according to the minimum (ARMN) and maximum (ARMX) single irrigation application rates as well as maximum annual irrigation amount (VIMX) and the irrigation interval (IRI) set for each subarea.

Irrigation Code
0 for dryland
1 for sprinkler irrigation
2 for furrow irrigation
3 for fertigation
4 for lagoon
5 for drip irrigation

The irrigation code is used to specify whether irrigation is used and the type of irrigation.
- If furrow/flood irrigation is specified, irrigation induced erosion is calculated.
- If fertigation is specified, IDFT identifies the type of fertilizer and FNP identifies the amount of fertilizer for each irrigation.

If lagoon is specified, the concentration in tons of soils per m^3 of effluent is specified by FNP and the nutrient fraction by creating a fertilizer in the Fert0604.DAT file with the appropriate nutrients and selecting it with IDFT.

8, 2	IRI	**Minimum application interval for automatic irrigation** This sets the number of days between automatic irrigation events. Irrigation will not occur until the minimum number of days has been met regardless if the BIR has already been met. If IRR = 0, then set IRI to 0. IRI will also affect manual irrigation. If manual irrigations are applied at a daily interval less than set in IRI, then manual irrigations will only be applied at the interval set in IRI.
8, 3	IFA	**Minimum fertilizer application interval for auto option** This sets the number of days between automatic fertilization events. Fertilization will not occur until the minimum number of days has been met regardless if the BFT has already been met.
8, 4	LM	**Liming Code** APEX enables the user to simulate application of agricultural limestone to increase soil pH and/or reduce soil aluminum saturation. For many soils and applications of APEX, this feature is not needed; therefore, it can be turned off by setting LM to 1. Long term simulations with noncalcareous soils and either nitrogen fertilizer or nitrogen-fixing legumes often require liming to prevent acidification of the soil and reduction of crop growth. 0 Lime applied automatically as needed to prevent acidification of the soil 1 No lime applied.
8, 5	IFD	**Furrow Dike Code** Furrow dikes (or tied ridges) are small dams constructed, usually by tillage equipment, in the furrows. They are designed to impede runoff and promote infiltration of rainfall and/or sprinkler irrigation. APEX simulates the construction, function, and destruction of furrow dikes. The furrow dike code IFD is used to determine whether dikes are simulated.

		0 Furrow dike system not simulated
		1 Furrow dike system simulated
8, 6	IDR	**Drainage code**

Artificial drainage systems (tiles, perforated pipes, open ditch drains, etc.) are often installed to remove excess water from fields.

		0 No drainage
		>0 Enter depth to drainage system in mm.
8, 7	IDF1	**Fertigation Fertilizer from Lagoon.**

Fertilizer identification number for fertigation or automatic fertilization from lagoon.

Enter 0 for no fertigation or automatic fertilization from a lagoon. To apply fertigation from a lagoon put in the number of fertilizer from lists provided (FERT0604.DAT). If no number is set, the model defaults to fertilizer #69. It is wise to set this number even if there are no current plans to use this function so that the selected fertilizer number matches the correct number in the fertilizer list which is being used. NOTES
    1.   MNUL in Control File MUST BE SET.
If no lagoon is present or turned on, then this function will not take effect even if a fertilizer number is set.

| 8, 8 | IDF2 | **Automatic Solid Manure Application from Feeding Area Stock Pile.** |

Fertilizer identification number for automatic fertilization using solid manure from the feeding area stock pile.

Enter 0 for no automatic fertilization using solid manure. To automatically apply solid manure from the feeding area stock pile put in the number of the fertilizer from lists provided (FERT0604.DAT). If no number is set, the model defaults to fertilizer #68. It is wise to set this number even if there are no current plans to use this function so that the selected fertilizer number matches the correct number in the fertilizer list which is being used.

NOTES
    1.   FNP2 in subarea file MUST BE SET
    2.   MNUL in Control File MUST BE SET

| 8, 9 | IDF4 | **Automatic Commercial Fertilizer Application.** |

Enter number of fertilizer from lists provided (FERT0604.DAT). If none is entered model defaults to Elemental N. If no number is set, the model defaults to fertilizer #52. It is wise to set this number even if there are no current plans to use this function so that the selected fertilizer number matches the correct number in the fertilizer list which is being used.

NOTES
    1.   BFT, FNP4 and IFA in subarea file MUST BE SET.

| 8, 10 | | |

| 8, 11 | IDF5 | **Automatic Solid Manure Application** |

To automatically apply solid manure (can come from an external source) enter the fertilizer number from the lists provided (FERT0604.DAT). If no number is set, the model defaults to fertilizer #68. It is wise to set this number even if there are no current plans to use this function so that the

selected fertilizer number matches the correct number in the fertilizer list which is being used.

NOTES
1. FNP5 and IFA from the subarea file MUST BE SET.
2. MNUL in the control table MUST BE SET.

9, 1	BIR	**Water stress factor to trigger automatic irrigation**.

To trigger automatic irrigation, the water stress factor is set:

0	manual irrigation
0 – 1.0	Plant water stress factor. (1 – BIR) equals the fraction of plant
	water stress allowed
1.0	Does not allow water stress
< 0.0	Plant available water deficit in root zone (number is in mm and
	must be negative)
> 1.0	Soil water tension in top 200mm (Absolute number is in kilopascals)
-1000	Sets water deficit high enough that only manual irrigations will occur. Effectively turns auto irrigation off.

NOTES
1. When BIR is set and used with a cropping system that includes more than one crop in rotation, the BIR will apply to all crops in the rotation.

When using a BIR based on anything other than plant water stress (0-1), be aware that irrigation will be applied outside of the growing season if the soil water deficit or soil water tension reaches BIR. This will reduce the amount of water available for irrigation during the growing season.

9, 2	EFI	**Runoff Vol/Vol Irrigation Water Applied**.

The irrigation runoff ratio specifies the fraction of each irrigation application that is lost to runoff.

9, 3	VIMX	**Maximum annual irrigation volume**

This is the maximum irrigation volume allowed each year in mm. If several crops are grown in one year, the first crop's needs will be supplied as needed and any remaining water will be applied as needed to the next crop. If all of the water allocated by VIMX is used on the first crop, the second crop will not receive any irrigation. This also applies to manual irrigation. Once the amount of irrigation applied equals VIMX, then no additional irrigation will be applied, regardless if it's manually or automatically applied.

9, 4	ARMN	**Minimum single application volume**

This is the minimum amount of irrigation allowed for each auto irrigation application in mm.

9, 5	ARMX	**Maximum single application volume**

This is the maximum amount of irrigation allowed for each auto irrigation application in mm. This is the amount applied if rigid automatic irrigation is selected.

| 9, 6 | BFT | **N stress factor to trigger auto fertilization.** |

The automatic fertilizer trigger functions much like BIR for irrigation. When the plant nitrogen stress level reaches BFT, nitrogen fertilizer may be applied automatically.

If this value is greater than 0, IDFT must be the Number of the Fertilizer application.

0.00   For manual fertilizer

0 – 1   Allows percentage of plant nitrogen stress (1 – BFT) equals the fraction

of N stress allowed.

1.00   No N stress, auto-fertilization when needed.

5.00   If BFT is greater than 1, BFT is the PPM(g/t) N in soil at which automatic fertilizer is triggered

| 9, 7 | FNP4 | **Auto Fertilization Appli**cation Rate (N) |

Variable rate of automatic commercial application (amount of fertilizer applied as needed to lower N stress); fixed rate of automatic commercial application (set amount of fertilizer applied each time N stress is reached). The units for this parameter are in kg.

NOTES

1. BFT (Auto Fertilizer Trigger) must be set
2. IDF0 (Auto Fertilizer Type) must be set to 4
3. IDF4 (Automatic commercial Fertilizer Application) can not be 0 for this variable to work.

| 9, 8 | FMX | **Maximum annual N fertilizer applied** |

Maximum amount of nitrogen fertilizer available for application per year in kg/ha. If more than one crop is grown per year, nitrogen will be applied to the first crop as specified. Nitrogen fertilizer will be applied to successive crops up to the maximum annual value. After the annual value has been met, no additional fertilizer will be applied. This variable can be overridden in the operation schedule where it can be set per crop. Refer to section 2.6 for further information on setting the maximum annual amount per crop.

NOTE

If this variable is set either in the subarea file or in the operation schedule and manual fertilization is applied, the model will only apply up this maximum amount regardless of the amount specified in the manual fertilization operation.

| 9, 9 | DRT | **Time requirement for drainage system to end plant stress in days.** |

Artificial drainage systems may be very efficient and quickly reduce water tables or it may take several days for the water level to decline sufficiently to eliminate aeration stress. The variable DRT is used to specify the time needed for the drainage system to eliminate stress. In this case time is measured in days. If drainage is not considered, enter 0.

| 9,10 | FDSF | **Furrow Dike Safety Factor** |

Fraction of furrow dike volume available for water storage. This value ranges from 0 to 1. FDSF controls the volume of water that can be stored in the dike before water tops over the dike. This variable is used to account for uncertainty in the volume of the furrow dike. The volume is calculated from the height of the row, row interval (width of row), length of dike and height of dike. If these values are not very certain, it may be wise to set FDSF to a low number which indicates that the

certainty of dike design in not very high. This will cause the dikes to overflow much quicker, however, which will affect runoff and erosion. If the certainty of design of the dike is great, FDSF can be set to 0.9 or higher, which will lessen dike overflow as well as runoff and erosion.

10, 1	PEC	**Erosion control practice factor.**

The erosion-control-practice factor normally ranges from about 0.1 to 0.9 depending upon the effectiveness of the conservation practice. Default = 1.0 for non-contoured fields. However, PEC can be set to 0.0 to eliminate water erosion entirely. When this is done, the soil profile remains relatively static because it is reset to initial conditions at the end of each year. This feature is very convenient for a given soil profile. At the other extreme, (PEC=10.) erosion rates are increased 10 times to improve log-term simulation efficiency. This feature is a big time saver in estimating water erosion effects on soil properties over periods of up to 1000 years. Obviously, the 1000-year period can be approximated with a 100-year simulation using PEC=10.

10, 2	DALG	**Fraction of Subarea controlled by lagoon.**

This is only needed when IRR = 4

10, 3	VLGN	**Lagoon Volume Ratio**

Normal Lagoon Volume as a fraction of Maximum Lagoon Volume. (Normal Lagoon Volume/Maximum lagoon volume) (fraction). Needed only when IRR = 4.

NOTE
1.   If Fraction of Subarea controlled by lagoon (DALG) = 0 then VLGN must = 0

10, 4	COWW	**Lagoon Input From Wash Water**

Needed only when IRR = 4 and owner has at least one head of livestock. (Average Normal is 0.015)

NOTE
1.   If Fraction of Subarea controlled by lagoon (DALG) = 0 then COWW must = 0 (m^3/animal unit/day).

10, 5	DDLG	**Time to Reduce Lagoon Storage From Maximum to Normal**

Needed only when IRR = 4.

NOTE
1.   If Fraction of Subarea controlled by lagoon (DALG) = 0 then DDLG must = 0 (days).

10, 6	SOLQ	**Ratio Liquid/Total Manure Applied in this Feedlot Subarea.**

Fraction of total manure produced that goes into a lagoon as liquid. Needed only when IRR = 4

NOTE
If Fraction of Subarea controlled by lagoon (DALG)   = 0 then SOLQ must = 0

10, 7	FNP5	**Automatic Manure application rate**

Activated only if IDF5 > 0. This function allows manure to be applied as needed in kg/ha. The manure applied can come from an external source.

10, 8	SFLG	**Safety factor for Lagoon Spillover**

This number is expressed as a fraction (0-1). It is needed only when IRR = 4.
VLG = VLG0/(1-SFLG) where VLG equals the lagoon volume and VLG0 is the initial lagoon volume.

11	NY		**Herd(s) Eligible for Grazing this Crop**

Select none (0) if no herd is used in this subarea or select herd number(s) (NCOW from site file) eligible to feed in area.

12	XTP	2.0 (for grazing area)	**Grazing limit for each herd**

This is the minimum amount of plant material (t/ha) that must be present for grazing to occur. When herd grazes down to this limit, grazing is stopped and herd is placed on supplementary feed.

APEX Model Parameter Settings for CEAP

The APEX control file

The APEX model general setup, which determines the simulation length, starting date, type of output, simulation methods for potential evapotranspiration, driving water erosion equation, runoff estimation methodology, etc., is included in the APEX control file (Table 4).   Most of the variables in this file will be constant as given in Table 4 for all the CEAP runs.

Table 4. APEXCONT.DAT

Line, Var	Variable name	Value	Description (Option selected to use for CEAP)
1, 1	NBYR	62	**Number of Years for Simulation Duration**
1, 2	IYR	1945	**Beginning Year of Simulation** (including 15 years of pre-run not included in the analysis of output)
1, 3	IMO	1	**Beginning Month of Simulation**
1, 4	IDA	1	**Beginning Day of Simulation**
1, 5	IPD	13	**Print Code for Type of Output** (For annual and monthly printout in *.out)
1, 6	NGN	12	**Input Code for Weather Variables** (Daily total Precipitation and daily maximum and minimum temperatures.)
1, 7	IGN	0	**Number of Times Random Number Generator Cycles Before Simulations Starts.** (Default random number) The random number generator is used to generate stochastically a series of daily weather data for input into other components of APEX. By changing IGN, the user can alter the sequence of generated weather data without changing its long-term statistical properties. By setting IGN to a different number rather than 0 will activate a random number generator, which will replace the default set of random numbers with a new set. The value to which IGN is set determines the number of times the random number generator is cycled before the simulation begins. The seeds produced by the random number generator are then used by the weather generator instead of the default values. Historical weather data read into the model is not affected by this variable. However, if the historical weather data contains missing data, the weather generator will be used to generate data to replace the missing data. The generated data used to replace the missing data is affected by this variable.
1, 8	IGSD	0	**Day Weather Generator Stops Generating Daily Weather** (Normal operation of weather model)
1, 9	LPYR	0	**If Leap Year Considered** (Leap year is considered)

1, 10	IET	4	**Potential Evapotranspiration Equation Code** (Hargreaves)
1, 11	ISCN	0	**Stochastic CN Estimator Code** (default, stochastic curve number estimator) The final step in APEX's estimation of runoff volume is an attempt to account for uncertainty. The runoff retention parameter or curve number is based on land use, management, hydrologic soil group, land slope, soil water content and distribution. It is also adjusted for frozen soil. However, many natural processes and management factors that can affect runoff are not accounted for in the model. APEX enables the user to use either a deterministic or a stochastic method of estimating CN. If the deterministic method is chosen, the curve number is adjusted daily for soil water content (and frozen soil). If the stochastic method is chosen, the deterministic value is varied stochastically on a daily basis using a triangular distribution. The extremes of the distribution are +/- 5 curve numbers from the mean.
1, 12	ITYP	0	**Peak Rate Estimate Code** (Modified Rational EQ Peak Rate Estimate)
1, 13	ISTA	0	**Static Soil Code** (Normal erosion of soil profile)
1, 14	IHUS	0	**Automatic Heat Unit Scheduling** (Normal operation)
1, 15	NVCN	4	**Non-varying CN-CN2 Used** (Variable daily CN soil moisture index)
1, 16	INFL	0	**Runoff (Q) Estimation Methodology** (CN estimate of Q)
1, 17	MASP	0	**Pesticide Output in Mass and Concentration** (Mass only in .OUT file)
1, 18	IERT	0	**Enrichment Ratio Method** (EPIC enrichment ratio method)
1, 19	LBP	0	**Soluble Phosphorus Runoff Estimate Equation** (Soluble Phosphorus runoff estimate using GLEAMS pesticide equation)
1, 20	NUPC	0 or 1	**N and P plant uptake concentration code** =0: Smith Curve >0: S curve (for CRP, needed because of excess N stress in CRP situations)
2, 1	MNUL	0	**Manure application code** (Auto application to subarea with minimal labile P concentration)
2, 2	LPD	0	**Lagoon pumping** (Does not trigger extra pumping)
2, 3	MSCP	0	**Solid manure scraping** (Does not scrape extra manure from feeding area)
2, 4	ISLF	0	**Slope length/steepness factor** (RUSLE slope length / steepness factor)
2, 5	NAQ	0	**Air Quality Analysis** (No air quality analysis)
2, 6	IHY	0	**Flood Routing** (No flood routing)
2, 7	ICO2	1	**Atmospheric CO_2** (Dynamic atmospheric CO_2)
2, 8	ISW	0	**Field Capacity/Wilting Point Estimation** (Field capacity/wilting point estimated using the Rawls method (dynamic))
2, 9	IDNT	1	**Denitrification option** (for Armen Kemanian denitrification subprogram)
2, 10	ISAP	0	Enter subarea number (NBSA) to print monthly .OUT for 1 subarea
3, 1	RFN0	site-specific	**Average concentration of nitrogen in rainfall in ppm**
3, 2	CO2	360.0	**Carbon dioxide concentration in atmosphere in ppm**
3, 3	CQN	0.0	**Concentration of NO3-N in irrigation water in ppm** Non zero value of CQNX in *.sit file overrides this one.

3, 4	PSTX	0	**Pest damage scaling factor** The factor scales the growth of pests (insects and diseases only) in terms of population growth. It ranges from 0 (no pest growth-pest damage, function is shut off) to 10 (maximum pest growth). Under default conditions this parameter is set to 1.00 which produces only minimal pest growth and does not affect yield. This parameter works in conjunction with Parm 9 and 10.
3, 5	YWI	0	**Number years of maximum monthly 0.5 hour rainfall available**
3, 6	BTA	0	**COEF (0-1) governing wet-dry probabilities given days of rain** (zero if daily rainfall is inputted)
3, 7	EXPK	0	**Parameter used to modify exponential rainfall amount distribution** (May be left 0.0 if unknown or if standard deviation of rainfall and skew coefficient for daily precipitation is input.) The modified exponential distribution is used to generate rainfall amounts if the standard deviation and skew coefficient are not available. An EXPK value of 1.3 gives satisfactory results in many locations.
3, 8	QG	0	2 year frequency 24-h rainfall. Estimates reach channel geometry in mm/h. If unknown, BLANK if channel geometry is input by Channel bottom width/depth (BWD).
3, 9	QCF	0.5	**Exponent in watershed area flow rate equation.**
3, 10	CHS0	site-specific	**Average upland slope (m/m) in watershed**
4, 1	BWD	1.0	**Channel bottom width/depth in m/m; Channel flow rate (QG) > 0.**
4, 2	FCW	1.0	**Floodplain width/channel width in m/m**
4, 3	FPSC	0	**Floodplain saturated hydraulic conductivity in mm/h**
4, 4	GWS0	50.0	**Maximum ground water storage in mm**
4, 5	RFT0	10 - 50	**Ground water residence time in days** If 0, use default 50.
4, 6	RFP0	0.05-0.95	**Return Flow / (Return Flow + Deep Percolation)**
4, 7	SAT0	Not used	**Saturated Conductivity adjustment factor** (use with Green & Ampt).
4, 8	FL	Normally set at 0.4, but for wind erosion control, reduced to 0.01, 0.02, 0.03, 0.04, or 0.06 depending on vegetative strips, windbreaks, etc.	**Field length in km (if wind erosion is to be considered)** If the normal wind erosion calculation is to be utilized (Wind Erosion Adjustment Factor (ACW) = 1.), field dimensions and orientation must be specified. This variable refers to the length of the field that is exposed to the wind. Without trees, FL = length of the field. With trees, FL < length of the field. If wind erosion is simulated for specific sites, FL, FW and ANG can be measured easily. However, hypothetical sites are often used in long-term simulations associated with large-scale decision making. In such cases, values of FL, FW and ANG should be chosen to represent typical field configurations of the area. Efforts to match field dimensions and drainage area are not necessary. The field dimensions are used only to estimate wind erosion, with the exception that FL is used to estimate water erosion from furrow irrigation. Thus, the simulation site may be a small area (1 ha) in a field of 1.0 by 0.5 km. It should be noted that the change in simulated wind erosion is not large for any FL > 0. 3 km. Therefore, estimations of FL and FW are not usually critical for fields with areas greater than about 10 ha. When fields larger than 10 ha are strip cropped, however, the estimation of FW becomes more important. To evaluate the effect of strip cropping, FW is estimated as the average

			width of the strips. FL may be left at 0.0 if unknown, and it will be estimated.
4, 9	FW	Same as above for FL	**Field width in km (if wind erosion is to be considered)** See variable FL for further information. FW may be left at 0.0 if unknown, and it will be estimated.
4, 10	ANG0	90.0	**Clockwise angle of field length from north (if wind erosion is to be considered)** See variable FL for further information. ANG may be left at 0.0 if unknown, and it will be estimated. If ANG is known, enter the value in degrees.
5, 1	UXP	0.3-0.8 (see Table 4a below)	**Power Parameter of Modified Exponential Distribution of Wind Speed** (in regions with wind erosion as a Conservation Concern, this parameter was used to produce fewer higher velocity wind events, while preserving mean wind speed, as a means of calibrating the APEX wind erosion estimates to values comparable to NRI reported values. Table 4.a shows the values used.)
5, 2	DIAM	500.0	**Soil Particle Diameter in um** (if wind erosion is to be considered) If value is known enter it in micron. Normally this value ranges from 300 – 500 um (sands). Used only in wind erosion. If 0, a default 500 um will be used.
5, 3	ACW	1.0	**Wind Erosion Adjustment Factor** The wind erosion adjustment factor is used along with PEC values to shut off or accelerate erosion. As with water erosion, wind erosion can be shut off by setting ACW = 0. If normal wind erosion calculation is desired, set ACW = 1. Also, AWC can be increased to a high level ACW=[10.00]) as a short cut in estimating wind erosion effects on the soil profile. Since ACW is related linearly to wind erosion, 1000 years' simulation can be approximated by 100 years' simulation using ACW=10.
5, 4	GZL0	0.0	**Grazing limit for each herd-minimum plant material** **Optional** - If > 0, overrides all herd minimum grazing limits in owner's table. This is the minimum amount of plant material (t/ha) that must be present in order to allow grazing. Grazing will not be initiated until this limit has been reached. The grazing limit for each herd is 2.0 mt/ha which is set in the *.sub file for individual subarea which is grazed.
5, 5	RTN0	100.0	**Number of years of cultivation at start of simulation** This parameter affects the partitioning of nitrogen and carbon into the passive and slow humus pools. The number of years of cultivation before the simulation starts is used to estimate the fraction of the organic N pool that is mineralizable. Mineralization is more rapid from soil recently in sod. Also increasing the number of years the field has been in cultivation increases the amount of C and N in the passive pool. This means it will take longer for the carbon and nitrogen to become available.
5, 6	BXCT	0.0	**Linear coefficient of change in rainfall from east to west (PI/PO/KM)** PI = Average Annual precipitation on East side of watershed PO = Average Annual precipitation on West side of watershed
5, 7	BYCT	0.0	**Linear coefficient of change in rainfall from south to north (PI/PO/KM)** PI = Average Annual precipitation on South side of watershed PO = Average Annual precipitation on North side of watershed

5, 8	DTHY	0.0	**Time interval for flood routing**
5, 9	QTH	0.0	**Routing Threshold (mm) – VSC routing used on QVOL>QTH** VSC = Variable Storage coefficient QVOL = Daily volume of runoff QTH = Routing Threshold
5, 10	STND	0.0	**VSC Routing used when reach storage > STND** VSC = Variable Storage coefficient STND = Storage in reach daily
6, 1	DRV	0.0	**Equation for Water Erosion** (MUST: Modified MUSLE theoretical based equation)
6, 2	BUS(1-4)		**First through Fourth Parameter Estimates for MUSI Erosion Equation** These parameters are for those who feel they have more appropriate coefficients available for their particular geographical region, than those supplied with the other MUSLE equations. This enables one to input values into the MUSLE equation. The equation is as follows:
	BUS(1)	0.22	$YSD(6) = BUS(1) \times QD^{BUS(2)} \times QP^{BUS(3)} \times WSA^{BUS(4)} \times KCPLS$ **MUSI input according to equation above**
6, 3	BUS(2)	0.68	**MUSI input according to equation above**
6, 4	BUS(3)	0.95	**MUSI input according to equation above**
6, 5	BUS(4)	0.61	**MUSI input according to equation above**

Table 4a. Setting of Power Parameter by 4-digit part of HUC 2 river basins.

HUC 4 part of HUC 2:	HUC 2's where wind erosion was simulated:									
	04	09	11	12	13	14	15	16	17	18
01		0.75	0.40	0.35	0.75		0.75	0.75	0.65	0.75
02		0.75	0.80	0.40	0.55	0.75	0.75	0.75	0.77	
03	0.50		0.50	0.35	0.75	0.75	0.75	0.75	0.78	
04	0.60		0.67	0.35	0.75		0.60		0.76	
05	0.75		0.50	0.62		0.75	0.75		0.70	0.30
06	0.75		0.45	0.50	0.75				0.70	
07	0.75		0.40	0.40		0.75	0.75		0.70	
08	0.75		0.77	0.75	0.75	0.75				
09	0.75		0.75	0.55	0.71					
10	0.70		0.60	0.35						
11			0.40	0.73						
12			0.65							
13			0.55							
14			0.40							

The APEX parameter file

The APEX parameter file (Tables 5 and 6) contains definitions of s-curve, miscellaneous parameters, and many coefficients of equations used in the CEAP APEX model.

S-CURVE PARAMETERS

An S-shaped curve is used to describe the behavior of many processes in APEX. The y-axis is scaled from 0-1 to express the effect of a range in the x-axis variable on the process being simulated. The S-curve may be described adequately by two points contained in this file. It is convenient to represent the x and y coordinates of the two points with two numbers contained in this file. The numbers are split by APEX (the x-value is left of the decimal and the y-value is right of the decimal). The two points are contained in an array called SCRP. To illustrate the procedure, consider the two SCRP values in the first line of the PARM2110.DAT file (90.05,99.95). SCRP (1,1)=90.05, SCRP (1,2)=99.95. When split we have x1=90, y1=0.05, x2=99, and y2=0.95. APEX uses these two points to solve the exponential equation for two parameters that guarantee the curve originates at zero, passes through the two given points, and y approaches 1.0 as x increases beyond the second point. The form of the equation is

$$Y = x/[x+\exp (b_1-b_2*x)] \tag{12}$$

where b_1 and b_2 are the APEX determined parameters.

Table 5. S-Curve parameter definitions

SCRP1(1) 90.050	SCRP2(1) 99.950	**Root growth restriction by rock or coarse soil fragments** expresses the effect of soil course fragment content on plant root growth restriction. The number to the left of the decimal is the % coarse fragments, and the number to the right of the decimal is the fraction of root growth restriction.
SCRP1(2) 10.5	SCRP2(2) 100.95	**Soil evaporation – depth** governs soil evaporation as a function of soil depth. The number to the left of decimal is depth (mm), and the number to the right is fraction of soil evaporation between soil surface and specified depth.
SCRP1(3) 50.1	SCRP2(3) 95.95	**Potential harvest index** drives harvest index development as a function of crop maturity. The number to the left of decimal is % of growing season, and the number to the right is fraction of harvest index (drives potential harvest index development as a function of crop maturity).
SCRP1(4) 0	SCRP2(4) 0	**NRCS runoff curve number soil water relationship**. This is an exception to normal s-curve procedures. The number to the left of the decimal is soil water content, and the number to the right is curve number. Soil water fraction taken from SCRP(25,n) to match CN2 and CN3 (average and wet condition runoff curve numbers) *THIS IS ALWAYS LEFT AT 0.0, 0.0. SCRP (4) IS CALCULATED BASED ON SCRP (25).*
SCRP1(5) 25.05	SCRP2(5) 75.9	**% Groundwater storage table** drives water table between maximum and minimum limits as a function of ground water storage. The # to the left of decimal is percent of groundwater storage and the number to the right is water table depth (meters).
SCRP1(6) 5.1	SCRP2(6) 100.95	**Soil settling rainfall** settles after tillage soil bulk density to normal value as a function of rainfall amount, soil texture, and soil depth. The # to the left of decimal is rainfall-runoff adjusted for soil texture and depth (mm), and the number to the right of the decimal is soil settling fraction caused by rainfall.
SCRP1(7)	SCRP2(7)	**Aeration stress – root growth** determines the root growth aeration stress factor

5.25	50.95	as a function of soil water content and the critical aeration factor for the crop. The # to the left of decimal is % of soil water storage volume between critical aeration factor and saturation, and the number to the right is % reduction in root growth caused by aeration stress.
SCRP1(8) 20.5	SCRP2(8) 80.99	**N or P deficiency stress – based on plant N or P content** determines the plant stress caused by n or p deficiency. The # to the left of decimal is % of difference between plant N or P content ratios (ratio of actual potential N or P content). The number to the right is the N or P stress factor (=0.0 when N or P ratio = 0.5; = 1.0 when N or P ratio = 1).
SCRP1(9) 1.1	SCRP2(9) 10.99	**Pest damage – temp, water, cover**, calculates the pest damage factor as a function of temperature, considering thresholds for 30-day rainfall and above ground plant material. The # to the left of the decimal is average daily minimum temperature adjusted for soil cover and 30 day antecedent rainfall minus runoff. The number to the right is crop yield reduction by pests expressed as a fraction of the difference between 1.0 and the minimum pest factor (PST crop parameter). One of several parameters used to regulate pest growth. See also parm 9 and 10, PSTX in the control file, and PST in the crop file.
SCRP1(10) 10.05	SCRP2(10) 100.9	**Harvest Index – Plant Water Use** calculates the effect of water stress on harvest index as a function of plant water use.. The number to the left of the decimal is the % of actual to potential plant water use during the growing season. The # to the right is the fraction of actual to potential harvest index.
SCRP1(11) 5.01	SCRP2(11) 20.9	**P plant use – Soil P concentration** governs P use by plants as a function of soil P concentration. The # to the left of the decimal is the soil labile P concentration (PPM) and the number to the right is the P available in (kg/ha).
SCRP1(12) 5.05	SCRP2(12) 100.5	**N volatilization,** as a function of NH3 depth in soil. The # to the left of the decimal is depth at the center of soil layer (mm) and the number to the right is the N volatilization in (kg/ha). Governs n volatilization as a function of soil depth.
SCRP1(13) 1.8	SCRP2(13) 3.99	Calculates **wind erosion vegetative cover factor** as a function of above ground plant material. X = vegetative equivalent (C1*BIOM+C2*STD+C3*RSD). Where C1, C2, and C3 are coefficients, BIOM is above ground biomass, STD is standing dead plant residue, and RSD is flat residue. The # to the left of decimal is vegetative equivalent in (T/ha) and the number to the right is wind erosion cover factor (fraction).
SCRP1(14) 5.1	SCRP2(14) 20.95	Calculates **soil temperature factor used in regulating microbial processes**. X = soil temperature(C). The # to the left of the decimal is soil temperature and the number to the right is factor (fraction).
SCRP1(15) 10.1	SCRP2(15) 100.95	**Plant population in water erosion C-factor,** used for estimating plant population effect on USLE C-factor. The # to the left is plant population in plants per m^2 or plants per ha for trees and the number to the right is the water erosion cover factor (fraction) or the fraction of erosion control.
SCRP1(16) 3.1	SCRP2(16) 20.99	Increases snow melt as a function of time since the last snowfall. x = time since the last snowfall(d)
SCRP1(17) 20.1	SCRP2(17) 50.95	Component of the **plant water stress factor** based on soil water content. The number to the left of the decimal is the ratio of root zone soil water content to plant available water storage volume, and the number to the right of the decimal is the fraction of plant stress due to water stress. If Parm 38 = 1 then plant water stress is strictly a function of ET.

SCRP1(18) 5.1	SCRP2(18) 50.3	**Adjusts CN2 as a function of upland slope steepness**. The number to the left of the decimal is the upland slope (%), and the number to the right of the decimal is the fraction that the curve number is adjusted.
SCRP1(19) 10.01	SCRP2(19) 25.95	Regulates **feedlot dust emission** based on moisture content of litter. The number to the left of the decimal is the water in liter/weight of litter, and the number to the right of the decimal is the fraction of dust emission control
SCRP1(20) 400.05	SCRP2(20) 600.9	Simulates **oxygen content of soil** as a function of depth. Used in microbial processes of residue decay. The number to the left of the decimal is the depth to center of each soil layer (m) and the number to the right of the decimal is the adjustment to the oxygen content. This parameter works in conjunction with Parm 53. (1 – Parm 53) x SCRP20
SCRP1(21) 10.5	SCRP2(21) 100.9	**Distance factor in spatial rainfall generator**. The number to the left of the decimal is the distance from storm center to subarea centroid (km) and the number to the right of the decimal is the fraction of rainfall received at the storm center given distance X.
SCRP1(22) 100.01	SCRP2(22) 1000.90	**G**overns plant water stress as a function of soil water tension. x = gravimetric + osmotic tension.
SCRP1(23) 1.5	SCRP2(23) 3.99	Estimates **plant ground cover as a function of leaf area**. The number to the left of the decimal is the leaf area, and the number to the right of the decimal is the fraction of ground cover.
SCRP1(24) 3.25	SCRP2(24) 15.95	Estimates **plant ground cover as a function of standing live biomass**. The number to the left of the decimal is the standing live biomass (t/ha), and the number to the right of the decimal is the fraction of ground cover.
SCRP1(25) 0.0	SCRP2(25) 0.0	Not used.
SCRP1(26) 0.0	SCRP2(26) 0.0	Not used.
SCRP1(27) 0.0	SCRP2(27) 0.0	Not used.
SCRP1(28) 0.0	SCRP2(28) 0.0	Not used.
SCRP1(29) 0.0	SCRP2(29) 0.0	Not used.
SCRP1(30) 50.0	SCRP2(30) 10.0	This parameter does not follow the same X,Y format as the other parameters. In this case Y is always 0. **Exception** to normal S-Curve procedure – **sets soil water contents** coinciding with CN2 and CN3. X1 = soil water content as % of field capacity – wilting point; X2 = soil water content as % of saturation – field capacity. X1 = 50.00; this indicates that CN2 is 50% of the volume between field capacity and wilting point → (0.50*(FC-WP) + WP). X2 = 10.00; this indicates that CN3 is 10% of the volume between saturation and field capacity → (0.10*(SAT-FC) + FC).

Table 6. APEX PARM definitions

PARM(n)	Value	Definition, units and/or range.
1	Not used	**Crop canopy-PET** (Range is from 1 - 2) factor used to adjust crop canopy resistance in the Penman-Monteith PET equation. Hargreaves method used in CEAP.
2	1.15-1.2	**Root growth-soil strength** (Range is from 1 - 2). Normally 1.15<parm(2)<1.2. Set to 1.5 to minimize various soil factor constraint on root growth. Setting Parm(2)>2 eliminates all root growth stress. Adjustments required for crop yield calibration by region, including accounting for effects of pH, aluminum toxicity, bulk density, and soil salt buildup.
3	0.5	**Water stress-harvest index** (Range is from 0 - 1) sets fraction of growing season when water stress starts reducing harvest index.
4	0.45	**Water storage N leaching** (Range is from 0 - 1) fraction of soil porosity that interacts with percolating water as nitrogen leaching occurs.
5	0.5	**Soil water lower limit** (Range is from 0 - 1) lower limit of water content in the top 0.5 m soil depth expressed as a fraction of the wilting point water content. Was reduced to as low as 0.2 in a few western regions for wind erosion calibration.
6	0.5	**Winter dormancy (h)** (Range is from 0 - 1) causes dormancy in winter grown crops. Growth does not occur when day length is less than annual minimum day length + parm(6).
7	0.25-0.9	**N fixation** (Range is from 0 - 1) at 1, fixation is limited by soil water or nitrate content or by crop growth stage. At 0 fixation meets crop nitrogen uptake demand. A combination of the two previously described scenarios is obtained by setting 0 < parm(7) < 1. Reduced to as low as 0.3 for western rotations with alfalfa hay; otherwise a rotation of e.g., 4 years of alfalfa and 1 year of corn silage would show low alfalfa yields due to N stress.
8	15.0	**Soluble phosphorus runoff coefficient.** ($0.1 m^3/t$), (Range is from 10 - 20). P concentration in sediment divided by that of the water.
9	20.0	**Pest damage moisture threshold**, (mm), (Range is from 25 - 150), previous 30_day rainfall minus runoff. One of several parameters used to regulate pest growth. See also parm 10, PSTX in the control file, PST in the crop file and SCRP (9).
10	20.0	**Pest damage cover threshold**, (t/ha), (Range is from 1 - 10), crop residue + above ground biomass. This is the amount of cover required for pests to begin to grow. Setting parm 10 at a large number (50) will result in little or no pest growth because it will be impossible to reach such high levels of cover. One of several parameters used to regulate pest growth. See also parm 9, PSTX in the control file, PST in the crop file and SCRP (9).
11	-100.0	**Moisture required for seed germination** (mm), (Range is from 10 - 30), soil water stored minus wilting point storage in the plow depth (plow layer depth = parm(43)). If the amount of moisture in the plow layer is not equal to or greater than Parm 11, germination will not occur. The value of -100.0 will turn this function off.
12	1.5	**Soil evaporation coefficient**, (Range is from 1.5 - 2.5), governs rate of soil evaporation from top 0.2 m of soil.
13	2.0	**Wind erodibility coefficient**, (Range is from 0 - 3), adjusts wind soil erodibility factor downward as loose material is eroded.
14	0.2	**Nitrate leaching ratio**, (Range is from 0.1 - 1), Ratio of nitrate concentration in surface runoff to nitrate concentration in percolate.
15	0.0	**Runoff CN weighting factor** (Range is from 0.0 - 1.0). Weights current and previous day's CN. If 1.0, uses current estimate; if 0.0 uses previous day's CN.

16	1.0	**Expands CN retention parameter** (Range is from 1.0 - 1.5). Values > 1.0 expand CN retention and reduce runoff.
17	0.1	**Soil evaporation – plant cover factor** (Range is from 0.0 - 0.5). Reduces effect of plant cover as related to LAI in regulating soil evaporation.
18	1.5	**Sediment routing exponent** (Range is from 1 - 1.5) exponent of water velocity function for estimating potential sediment concentration.
19	0.05	**Sediment routing coefficient**, (t/m^3)(Range is from 0.01 - 0.05) potential sediment concentration when flow velocity = 1.0 (m/s).
20	0.2	**Runoff curve number initial abstraction** (Range is from 0.05 - 0.4)
21	10.0	**Soluble Carbon adsorption Coefficient** $(0.1m^3/t)$ (Range is from 10 - 20). Carbon concentration in sediment divided by that in water
22	0.05	**Reduces NRCS Runoff CN Retention Parameter for Frozen Soil.** (Range is from 0.05 – 0.6) Fraction of S (Retention Parameter) Frozen Soil
23	0.0032	**Hargreaves PET equation coefficient** (Range is from 0.0023 - 0.0032), original value = 0.0023, current value = 0.0032.
24	0.1	**Pesticide leaching ratio** (Range is from 0.1 - 1) Ration of pesticide concentration in surface runoff to pesticide concentration in percolation.
25	5.0	Root sloughing coef(0._10.) for tree, large values increase root decay rate.
26	0.05	**Fraction of maturity at spring growth initiation** (Range is from 0 - 1) allows fall growing crops to reset heat unit index to a value greater than 0 when passing through the minimum temperature month.
27	0.3	**CEC effect on nitrification & volatilization** (Range is from 0 - 1) sets lower limit of CEC correction factor in nit/vol function. At 0 CEC should prevent nit/vol process. At 1 CEC has no effect on nit/vol.
28	Not used	Not used
29	0.1	**Biological mixing efficiency** (Range is from 0.1 - 0.5) simulates mixing in top soil by earth worms etc. Parm (31) sets depth for this action.
30	1.3	**Soluble phosphorus runoff exponent** (Range is from 1 - 1.5) provides nonlinear effect for soluble phosphorus-runoff eq.
31	0.3	**Maximum depth for biological mixing**, (m), (Range is from 0.1 - 0.3)
32	1.0	Organic p loss exponent(1_1.2) provides nonlinear effect for organic p loss eq.
33	2.5	**Coefficient in MUST EQ** (Range is from 2.0 – 3.0). Original value = 2.5.
34	0.5 or 0.6	**Hargreaves PET equation exponent** (Range is from 0.5 - 0.6) original value=0.5.
35	0.99	**Denitrification soil-water threshold** (Range is from 0.9 - 1.1), fraction of field capacity soil water storage to trigger denitrification.
36	0.7	**Denitrification rate constant** controls denitrification rate.
37	0.05	**Lower limit of daily mineralization rate coef(.01_.1) adjusts the temperature/moisture rate function.**
38	1.0	**Water stress weighting coefficient** (Range is from 0 - 1) at 0 plant water stress is strictly a function of soil water content; at 1 plant water stress is strictly a function of actual ET divided by potential ET. 0<parm 38<1 considers both approaches. See also SCRP 17.
39	0.2	Exponent in delivery ratio for swat output(.1_.6) transforms apex small watershed sediment yield to 8 digit basin sediment yield for swat input. normally 0.5—lower values increase sediment delivered to swat.
40	0.05-0.5	**Groundwater storage threshold** (Range is from 0.001 - 1.) fraction of groundwater storage that initiates return flow.

41	0.5	**Plant root temperature stress exponent** (Range is from 0.1 - 2.) exponent of ratio of soil layer temperature to average of plant optimal and base temperatures.
42	0.5-1.5	**SCS curve number index coefficient** (Range is from 0.3 -2.5) regulates the effect of PET in driving the SCS curve number retention parameter.
43	0.15	**Plow layer depth** (m) used to track soluble phosphorus concentration or weight.
44	1.5	**Upper Limit of Curve Number Retention Parameter S**(Range is from 1.0 - 2.0) SUL=PARM(44)*S1. Allows CN to go below CN1.
45	3.0	**Sediment routing travel time coefficient**, (Range is from 0.5 - 10.) brings inflow sediment concentration to transport capacity concentration as a function of travel time and mean particle size.
46	0.5	**RUSLE C-factor coefficient** (Range is from 0.5 - 1.5) coefficient in exponential residue function in residue factor.
47	1.0 0.01 (for CRP trees)	**RUSLE C-factor coefficient** (Range is from 0.5 - 1.5) coefficient in exponential crop height function in biomass factor.
48	0.0	**Adjusts climatic stress factor** (Range is from 50 - 80) ((Average annual precipitation/Average annual temperature) / Parm 48). Setting parm 48 to 0.0 gives a Climatic factor = 1.0 which has no effect on crop yield
49	0.0	**Maximum rainfall interception by plant canopy** (mm) (Range is from 0 - 15.0)
50	0.1	**Rainfall interception coefficient**, (Range is from 0.05 - 0.3)
51	0.0	**Water stored in litter (residue) coefficient** (Range is from 0.1 - 0.9). Fraction of litter weight.
52	10.0	**Exponential coefficient in EQUATION expressing tillage effect on residue decay rate** (Range is from 5 - 15)
53	0.9	**Coefficient in oxygen EQUATION used in modifying microbial activity with soil depth** (Range is from 0.8 - 0.95) See also SCRP 20.
54	Not used in EPIC enrichment ratio method	
55		
56		
57		
58		
59	1	**P upward movement by evaporation coefficient** (Range is from 1 - 20)
60	7.0	**Maximum number of days a pasture is grazed before rotation** (Range is from 1 - 365)
61	0.8	**Soil water tension weighting factor** (Range is from 0. - 1.) regulates upward water flow as a function of soil water tension in the layer of interest and the one above it. 0.0 only considers above layer tension. 1.0 only considers layer of interest's tension.
62	0.25	**Manure erosion equation coefficient**, (Range is from 0.1 - 0.5) larger values increase manure erosion.
63	0.1	**Pesticide loss coefficient**, (Range is from 0.1 - 1.0) fraction of porosity interacting with pesticides as water flows through a soil layer.
64	1.0	**Dust distribution coefficient**, (Range is from 0.5 - 1.5) affects downwind travel time.
65	1.1	N enrichment ratio for delivery to swat(.8_1.2) enrichment ratio for application to 8 digit sediment yield supplied to swat.

| 66	0.8	P enrichment ratio for delivery to swat(.8_1.2) enrichment ratio for application to 8 digit sediment yield supplied to swat.
67	10.0	**Dust distribution dispersion exponent** (Range is from 5.0 - 15.0) modifies the effect of the angle between the wind direction and the centroid of downwind subareas.
68	0.5-0.75	**Manure erosion exponent t** (Range is from 0.1 - 1.0) modifies equation based on weight of manure on soil surface.
69	0.5-0.75	Coefficient adjusts microbial activity function in top soil layer (0.1_1.0)
70	1.0	**Microbial decay rate coefficient** (Range is from 0.5 - 1.5). Adjusts soil water-temperature-oxygen equation.
71	1.15	**Manure erosion coefficient** (Range is from 1.0 -1.5). Modifies erosion estimate based on above ground plant material. Plant material (live and dead) reduces manure erosion.
72	0.15	**Volatilization/nitrification partitioning coefficient** (Range is from 0.05 - 0.5). Fraction of process allocated to volatilization.
73	0.5	**Hydrograph development parameter** (Range is from 0.1 - 0.9). Storage depletion routing exponent used to estimate travel time outflow relationship.
74	0.2	Groundwater N concentration ratio(0.01_0.99), N conc in return flow / N conc in percolate. (Set to 0.5 for most regions).
75	0.05	**Furrow irrigation erosion coefficient** (t/m^3) (Range is from 0.01 - 0.05). Potential sediment concentration in a furrow when flow velocity = 1. (m/s).
76	1.0-2.0	**Furrow irrigation sediment routing exponent** (Range is from 1 - 1.5). Exponent of water velocity function for estimating potential sediment concentration.
77	0.0	**Runoff amount to delay pest application** (mm) (Range is from 0.0 – 25). Pesticide is not applied on days with runoff greater than Parm(77).
78	10.0	**Soil water value to delay tillage** (Range is from 0.0 – 1.0) Tillage is delayed when PDSW/FCSW>Parm(78). PDSW = Plow depth soil water content; FCSW = Field capacity soil water content.
79	0.01	standing dead fall rate coef(.0001_.1) governs rate of standing dead conversion to flat residue.
80	0.0	puddling saturated conductivity(mm/h)(0.00001_0.1) simulates puddling in rice paddys by setting second soil layer saturated conductivity to a low value.
81	0.0	Technology coefficient (0.0_0.01). Linear adjustment to harvest index-base year=2000.
82	0.0	Runoff CN rainfall intensity coefficient (0.0_1.0). Increase runoff for high intensity rainfall.
83	4.0	Regulates lateral hydraulic conductivity (0.1_10.0), multiplied by vertical HD cond to compare with APEX calculated Hyd to obtain max (used in simulation).
84	0.0001	P flow in and out of labile and active pools
85	0.0001	P flow in and out of active and stable mineral pools

The APEX crop database

The crop database contains information needed by APEX to simulate the growth of a particular crop. The growth parameters in the plant growth database define plant growth under ideal conditions and quantify the impact of some stresses on plant growth. Each crop is characterized with 56 parameters (Table 7).

Table 7. The crop file

Column	Variable	Description
	CNUM	*Crop Number.*
	CPNM	*Crop Name.* A four character name to represent the crop.
1	WA	*Biomass-Energy Ratio (CO2=330ppm).* This is the potential (unstressed) growth rate (including roots) per unit of intercepted photosynthetically active radiation. This parameter should be one of the last to be adjusted. Adjustments should be based on research results. This parameter can greatly change the rate of growth, incidence of stress during the season and the resultant yield. Care should be taken to make adjustments in the parameter only based on data with no drought, nutrient or temperature stress. WA is also known as radiation use efficiency.
2	HI	*Harvest index.* The ratio of economic or harvestable yield to the total biomass of the crop. This crop parameter should be based on experimental data where crop stresses have been minimized to allow the crop to attain its potential. HI is the maximum harvest index that could possibly be attained under nonstressed conditions. APEX adjusts HI as water stress occurs from near flowering to maturity. This HI only pertains to grain and cotton crops. For forage and root crops, the Override Harvest Index (ORHI) should be set in the iatill.dat file for the harvest equipment being used to harvest the crop.
3	TG	*Optimal temperature for plant growth.* The optimum temperature at which the crop will grow without being physiologically damaged by heat. TB and TG are very stable for cultivars within a species. They should not be changed once they are determined for a species. Varietal or maturity type differences are accounted for by different sums of thermal units.
4	TB	*Minimum temperature for plant growth.* The minimum (base) temperature at which the crop will grow without being physiologically damaged by cold. TB and TG are very stable for cultivars within a species. They should not be changed once they are determined for a species. Varietal or maturity type differences are accounted for by different sums of thermal units.
5	DMLA	*Maximum potential leaf area index.* Leaf area index refers to the ratio of the surface area of the leaves (one side only) of the crop to the area of the ground covered by the plants. This parameter refers to the greatest leaf area index that the crop is able to attain. The parameters in the CROP0604.DAT data set are based on the highest expected plant densities for crops not expected to have water stress. DMLA is internally adjusted for drought-prone regions as planting densities are much smaller in these areas unless irrigation is used.

6	DLAI	*Fraction of growing season when leaf area declines.* Point in the growing season (expressed as a fraction of heat units required for maturation) when the leaf area index begins to decrease due to leaf senescence. The fraction of the growing season in heat units is divided by the total heat units accumulated between planting and crop maturity. If the date at which leaf area normally declines is known, one of the options in APEX can be used to estimate the fraction of heat units accumulated. A multi-run APEX simulation is setup with IGSD equal to 366. A one-year simulation followed by a one-year multi-run will produce a multi-run simulation, which has average heat units per month and the total heat units to maturity. The harvest date kill operations should be set to the crop maturity date. The estimated heat units at maximum leaf area can then be divided by the heat units at maturity to estimate the fraction of the growing season at which leaf-area-index start to decline.
7	DLAP1	*First point on optimal leaf area development curve.* This is the first of two points on the optimal (nonstressed) leaf area development curve. Numbers before decimal are % of growing season. Numbers after decimal are fractions of maximum potential LAI. For example 15.01 states that at 15% of the growing season, 1% of the LAI has developed. Research results or observations on the % of maximum leaf area at two points in the development of leaf area can be used in conjunction with an APEX simulation like that described for DLAI. The results of the one-year multi-run will establish the cumulative heat units by month from planting to maturity. Then calculate percent of cumulative heat units by dividing estimated cumulative heat units for each of the two dates where you've estimated percent of Max LAI by the average annual heat units shown on the bottom of the crop parameter set at the beginning of the APEX run. The percent of heat units for first monthly estimate is the number on the left of the decimal for DLAP1 and the estimated percent of the Max LAI is the number in the right of the decimal.
8	DLAP2	*Second point on optimal leaf area development curve.* The second of two points on optimal (nonstressed) leaf area development curve. Numbers before decimal are % of growing season. Numbers after decimal are fractions of maximum potential LAI. For example 50.95 states that at 50% of the growing season, 95% of the LAI has developed. Research results or observations on the % of maximum leaf area at two points in the development of leaf area can be used in conjunction with an APEX simulation like that described for DLAI. The results of the one-year multi-run will establish the cumulative heat units by month from planting to maturity. Then calculate percent of cumulative heat units by dividing estimated cumulative heat units for each of the two dates where you've estimated percent of Max LAI by the average annual heat units shown on the bottom of the crop parameter set at the beginning of the APEX run. The percent of heat units for second date estimate is the number on the left of the decimal for DLAP2 and the estimated percent of the Max LAI is the number in the right of the decimal. The following graph illustrates how DLPI = 15.01 and DLP2 = 50.95 define the leaf area development of a crop. **Figure 2.12: Leaf area development of crop based on DLAP1 and DLAP2**
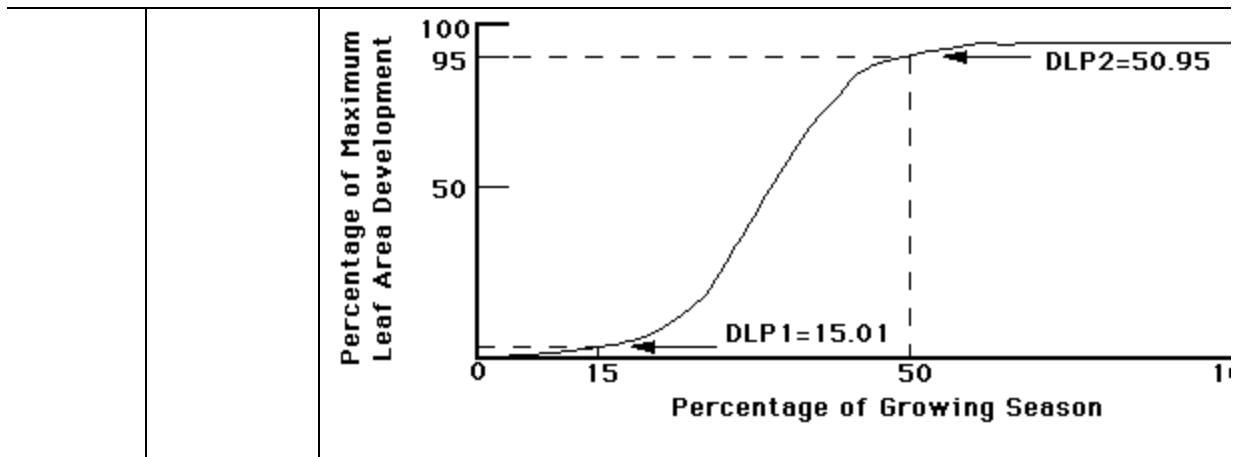
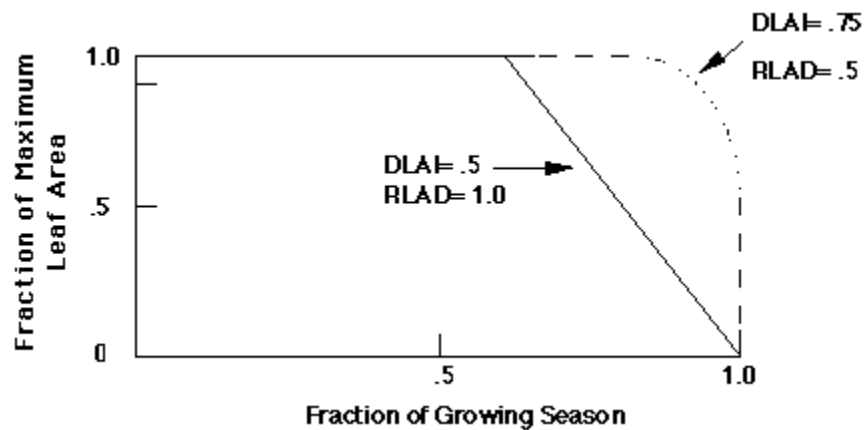| 9	RLAD	*Leaf area index decline rate parameter.*

For most grain crops, leaf area declines due to leaf senescence as the crop approaches physiological maturity. In most cases, leaf senescence begins with yellowing of the older (lower) leaves and proceeds upward until, in crops like corn, wheat, and soybeans, all leaves senesce and the plant dies. In many grain crops, leaf area index declines linearly with time after grain filling begins. Nutrients and carbohydrates in the senescing leaves are often translocated into the grain. In EPIC the crop parameter DLAI (described above) controls the point in the growing season when leaf area begins to decline. The crop parameter RLAD controls the rate of decline. If RLAD is set to 1.0, the rate of decline is linear. If RLAD < 1.0, the rate of decline is initially slow,

then increases until all leaves are dead at maturity. If RLAD > 1.0, the rate of senescence is initially rapid, then slows as maturity approaches. In all cases, APEX assumes that leaf area begins to decline when the fraction of the growing season equals DLAI, and the leaf area index approaches zero at maturity.

1. 1.0 is linear
2. >1 accelerates decline
3. < 1 retards decline rate.
4. Values range from 0 to 10.

The graph below illustrates how DLAI and RLAD interact to control leaf area decline.

Figure 2.13: Leaf area development of crop based on DLAI and RLAD

10	RBMD	**_Biomass-energy ratio decline rate parameter._**

1. Biomass-energy ratio decline rate parameter for late in the cropping season. This crop parameter functions like the RLAD above for values ranging from 0-10. It reduces the efficiency of conversion of intercepted photosynthetically active radiation to biomass due to production of high energy products like seeds and/or translocation of N from leaves to seeds. In most crops this rate is relatively constant during the vegetative stage of growth, when structural carbohydrates like cellulose are the principal products of growth. However, when grain crops begin to form seeds, the conversion of intercepted solar radiation into biomass begins to decline. That is, less dry matter is formed for each unit of absorbed solar radiation. In addition, as leaf area yellows and begins to senesce, the conversion efficiency declines still more. APEX uses the crop parameter RBMD to reduce the rate of conversion of intercepted solar radiation to biomass as the crop approaches maturity (when the fraction of the growing season is greater than DLAI). Computationally, RBMD reduces WA like RLAD reduces leaf area index (see graph above) For example, RBMD = 1.0 causes a linear decline in WA as the crop matures from DLAI to physiological maturity.

1. 1.0, decline is linear
2. <1.0, the rate of decline is initially slow, then increases until all leaves are dead at maturity.
3. >1.0, the rate of decline is initially rapid, then slows as maturity approaches.
4. Values range from 0 to 10.

11	ALT	**_Aluminum tolerance index_**
		Index of crop tolerance to aluminum saturation. Ranges from 1 to 5 with 1=sensitive and 5=tolerant.
12	GSI	**_Maximum Stomatal Conductance._**
		The crop parameter GSI is the maximum stomatal conductance (ms-1) at high solar radiation and low vapor pressure deficit. Korner et. al (1979) reported maximum stomatal conductance values for 246 species and cultivars. (Korner, C. H., J. A. Scheel, and H. Bauer. 1979. Maximum leaf diffusive conductance in vascular plants. Photosynthetica 13(1): 45-82.)
13	CAF	**_Critical aeration factor._**
		Fraction of soil porosity where poor aeration starts limiting plant growth. This is set at 0.85 for most crops, with rice being the major exception with a value of 1.0.
14	SDW	**_Seeding rate._**
		Normal planting rate (kg/ha). Note this does not change the plant population. It only impacts seed cost and start crop biomass.
15	HMX	**_Maximum crop height_**
		The greatest potential height the crop will reach. in m.
16	RDMX	**_Maximum root depth_**
		The greatest depth to which the rooting system will penetrate in m. This effects soil moisture extraction.

17	WAC2	*CO₂ Concentration /Resulting WA value (Split Variable).* In APEX, radiation use efficiency is sensitive to atmospheric CO_2 concentration. WAC2 is an "S" curve parameter used to describe the effect of CO_2 concentration on the crop parameter WA. The value on the left of the decimal is a value of CO_2 concentration higher than ambient (i.e., 450 or 660 ul/l). The value on the right of the decimal is the corresponding value WA. This elevated value of WA can be estimated from experimental data on short-term crop growth at elevated CO_2 levels. Calculate the ratio of crop growth rate at elevated CO_2 to crop growth at approximately 330 ul l-1 CO_2. Multiply that ratio by the value of WA at 330 ul l-1 to obtain the value on the right of the decimal. Typical values of the ratio are 1.1 to 1.2, 1.15 used in crop0604. for crops with the C4 photosynthetic pathway and 1.3 to 1.4, 1.35 used in crop0604 for C3 crops. (Kimball, B.A. 1983 Carbon dioxide and agricultural yield: an assemblage and analysis of 770 prior observations. Water Conservation Laboratory Report 14. USDA/ARS. Phoenix, Arizona).
18	CNY	*Fraction of nitrogen in yield.* Normal fraction N in yield (g g⁻¹). The amount of nitrogen removed from the plant through the harvesting of the crop. This is the fraction of nitrogen in the yield compared to the entire plant. This was estimated from Morrison's Feeds and Feeding and other data sources of plant nutrition. The percentage N in Morrison was adjusted to a dry weight by dividing by the fraction of dry matter to total yield.
19	CPY	*Fraction of phosphorus in yield.* The amount of phosphorus removed from the plant through the harvesting of the crop. This is the fraction of phosphorus in the yield compared to the entire plant. Normal fraction of P in yield (g g⁻¹). Estimated by same procedure as CNY above.
21	WSYF	*Lower limit of harvest index.* Fraction between 0 and HI value that represents the lowest harvest index expected due to water stress. A few crops can have slight increases in harvest index ie. the sugar content is higher in somewhat stressed sugar crops.
22	PST	*Pest (insects and disease) factor.* Fraction of yield remaining after damage. Usually set at 0.60. APEX has an adjustment process that is a function of moisture, temperature and residue. This presently is a reasonable estimate, but future versions may include more detailed procedures. You may wish to adjust the parameter in geographic areas known to have large amounts of damage from pests.
23	COSD	*Seed cost ($ kg⁻¹).* Cost of seed is used for economic analyses only.
24	PRYG	*Price for yield ($ t⁻¹).* Price for grain yield is used for economic analyses only.
25	PRYF	*Price for forage yield ($ t⁻¹).* Price for forage yield is used for economic analyses only.
26	WCY	*Fraction water in yield.* The amount of water present in the yield at the time of harvest. Expressed as a fraction. The yields of most grain crops are reported at a standard grain water content; however, for some applications, grain dry weight is appropriate (WCY = 0). APEX yield output is all in dry weight (WCY = 0).
27	BN1	*Nitrogen uptake parameter (N fraction in plant at emergence).* Normal fraction of N in crop biomass at emergence - This parameter is based on research results published in the literature for this or a similar crop.

28	BN2	*Nitrogen uptake parameter (N fraction in plant at 0.5 maturity).* Normal fraction of N in crop biomass at mid-season - Same as BN1.
29	BN3	*Nitrogen uptake parameter (N fraction in plant at maturity).* Normal fraction of N in crop biomass at maturity - Same as BN1.
30	BP1	*Phosphorus uptake parameter (P fraction in plant at emergence).* Normal fraction of P in crop biomass at emergence - Same as BN1.
31	BP2	*Phosphorus uptake parameter (P fraction in plant at 0.5 maturity).* Normal fraction of P in crop biomass at mid-season - Same as BN1.
32	BP3	*Phosphorus uptake parameter (P fraction in plant at maturity).* Normal fraction of P in crop biomass at maturity - Same as BN1.
36	BW1	*Wind erosion factor for standing live.* Wind erosion factor for standing live biomass - Based on the Manhattan wind erosion equations for this crop or a similar crop used in the Manhattan wind erosion equations.
37	BW2	*Wind erosion factor for standing dead.* Wind erosion factor for standing dead crop residue - Same as BW1.
38	BW3	*Wind erosion factor for flat residue.* Wind erosion factor for flat residue - Same as BW1.

39	IDC	*Crop category number:*
		1 Warm season annual legume.
		2 Cold season annual legume.
		3 Perennial legume.
		4 Warm season annual.
		5 Cold season annual.
		6 Perennial.
		7 Evergreen Tree crop
		8 Deciduous Tree crop
		9 Cotton
		NOTE: Other crop parameters (TB, TG, FRS1, FRS2) also differentiate between cold and warm climate crops.

40	FRST1	*First point on frost damage curve.* The first of two points on the frost damage curve. Numbers before decimal are the minimum temperatures (degrees C) and numbers after decimal are the fraction of biomass lost each day the specified minimum temperature occurs.
		NOTE: 10.20 means 20 percent of the biomass is lost each day a temperature of -10C is reached. The negative sign on degrees is added by APEX since no frost damage is assumed to occur above 0 degrees C. These two parameters should be based on a combination of research results and observation. Precise data for field application is subject to microclimate variation across the landscape. Current parameters are reasonable estimates; However, they are more likely to understate frost damage than to overstate frost damage.

41	FRST2	**Second point on frost damage curve.**
		Second of two points on the frost damage curve. Numbers before decimal are the minimum temperatures (C) and numbers after decimal are the fraction of biomass lost each day the specified minimum temperature occurs.
		NOTE: 10.20 means 20 percent of the biomass is lost each day a temperature of -10C is reached. The negative sign on degrees is added by APEX since no frost damage is assumed to occur above 0 degrees C. These two parameters should be based on a combination of research results and observation. Precise data for field application is subject to microclimate variation across the landscape. Current parameters are reasonable estimates. However, they are more likely to understate frost damage than to overstate frost damage.
42	WAVP	**Parm relating vapor pressure deficit to WA.**
		In APEX, radiation use efficiency (RUE) is sensitive to vapor pressure deficit (VPD). As VPD increases, RUE decreases. The crop parameter WAVP is the rate of the decline in RUE per unit increase in VPD. The value of WAVP varies among species, but a value of 6 to 8 is suggested as an approximation for most crops.
43	VPTH	**Threshold VPD (KPA)**
		In APEX, leaf conductance is insensitive to VPD until VPD (calculated hourly) exceeds the threshold value, VPTH (usually 0.5 to 1.0 kPa).
44	VPD2	**VPD value (KPA)**
		In APEX, leaf conductance declines linearly as VPD increases above VPTH. VPD2 is a double parameter in which the number on the left of the decimal is some value of VPD above VPTH (e.g. 4.0), and the number on the right of the decimal is the corresponding fraction of the maximum leaf conductance at the value of VPD (e.g., 0.7).
45	RWPC1	**Fraction of root weight at emergence.**
		This is one of the partitioning parameters to split biomass between above ground and roots. RWPC1 is the partitioning fraction at emergence and RWPC2 is partitioning fraction at maturity. Between those two points there is a linear interpolation of the partitioning fraction relative to accumulative heat units.
46	RWPC2	**Fraction of root weight at maturity.**
		This is one of the partitioning parameters to split biomass between above ground and roots. RWPC1 is the partitioning fraction at emergence and RWPC2 is partitioning fraction at maturity. Between those two points there is a linear interpolation of the partitioning fraction relative to accumulative heat units.
47	GMHU	**Heat Units required for Germination.**
		This delays germination from the planting date or the date at which the temperature of soil layer 2 exceeds TG. Heat units are accumulated on an annual basis.
48	PPLP1	**Plant Population for Crops & Grass-1st Point on curve.**
		First of two points on population curve. Plant Population for crops, grass etc., except trees or plants requiring more than 1 m2/plant. The number to the left of the decimal is the number of plants and the number to right is the fraction of maximum leaf area at that population. Plant population is expressed as plants per square meter.

|		
		If the crop is trees, the population is expressed as plants per hectare and the second plant population point is placed in the SMR1 position and the first point placed in the SMR2 position. The first point should be the higher population. » If entering PLANTS/m^2 then PPLP1(SMR1)<PPLP2(SMR2) » If entering PLANTS/ha then PPLP1(SMR1)>PPLP2(SMR2)
49	PPLP2	*Plant Population for Crops & Grass - 2nd Point on curve.* Second of two points on population curve. The number to the left of the decimal is the number of plants and the number to right is the fraction of maximum leaf area at the population. Plant population is expressed as plants per square meter. If the crop is trees, the population is expressed as plants per hectare and the second plant population point is placed in the SMR1 position and the first point placed in the SMR2 position. The first point should be the higher population. » If entering PLANTS/m^2 then PPLP1(SMR1)<PPLP2(SMR2) » If entering PLANTS/ha then PPLP1(SMR1)>PPLP2(SMR2) For example, corn has a PPLP1 = 30.43 and PPLP2 = 50.71. This means at 30 plants per square meter 43% of maximum leaf area can be attained which is also the 1st point on the population curve. PPLP2 means at 50 plants per square meter 71% of maximum leaf area can be attained. This is the 2nd point on population curve for corn production. Since PPLP1 is less than PPLP2, it shows the population density of a crop other than trees. However, for pine tree, PPLP1 = 1000.95 and PPLP2 = 100.10. While the numbers before and after decimal have the same explanations as given for corn, it indicates the population density is for a tree crop because here PPLP1 is greater than PPLP2. **Figure 2.14: Illustration of a plant population curve.**
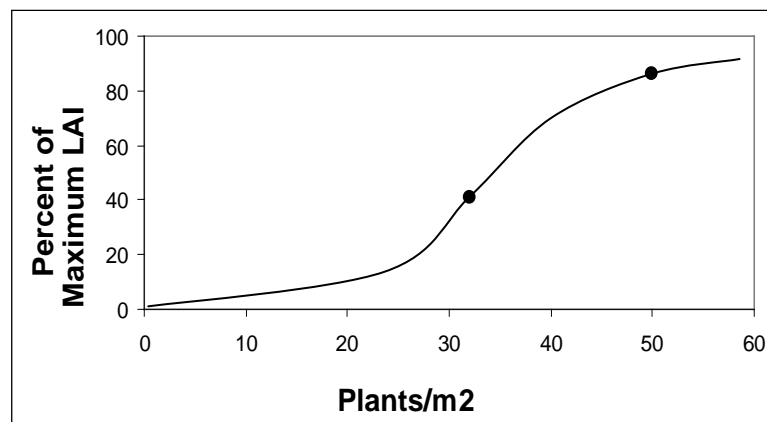
52	BLG1	*Lignin fraction in plant at 0.5 maturity*
53	BLG2	*Lignin fraction in plant at full maturity*

54	WUB	**_Water use conversion to biomass (t/mm)_**
		The amount of biomass produced per unit of water applied (irrigation + rainfall).
55	FTO	**_Fraction turnout for cotton_**
		The fraction of lint present in the total plant material (lint + seed + trash (leaf and stem particles)) harvested. This value is higher for cotton which is picked compared to stripped because less trash is collected along with the lint and seed as it is harvested. A typical value for picker cotton is 0.38 and 0.27 for stripper cotton.
		Turnout fraction = (lint weight / (seed weight + lint weight + trash weight))
56	FLT	**_Fraction lint for cotton_**
		The fraction of lint present in the total seedcotton (seed + lint) harvested. This variable differs from FTO in that trash is not included in the total harvested weight. Lint fraction cannot be greater than turnout fraction.
		Lint fraction = (lint weight / (seed weight + lint weight))

The APEX tillage/operation database

The tillage operations include common field management activities in agricultural land use. There are 28 parameters being used to describe each tillage operation and those parameters are all listed in a single line in the file (Table 8).

Table 8. The tillage file

Column	Variable	Description
	TNUM	**Equipment number** For reference purposes only. Operations are accessed by their sequential location in the file. For example, an operation number 9 will access the ninth operation regardless of the setting of this variable.
	TIL	**Tillage operation name.** A descriptive name of the operation
	PCD	**Power code.** 1. POWE: the machine with its own engine for power is generally used to pull other machinery or equipment, like a tractor 2. SELF: the machine has its own engine for power but it does the operation by itself like a combine 3. NON: the machine (or equipment) has no engine for power and it must be pulled by other machinery with engine power 4. IRRI: irrigation equipment 5. CUST: customized equipment.
1	PRIC	**Purchase price ($)** EXCEPTION: for a custom operation = cost ($/ha) The amount of money the equipment was actually purchased for. To estimate purchase price subtract 10% from the initial list price.
2	XLP	**Initial list price in current ($)** The price of the equipment when new. The dollar amount takes into account inflation. To estimate Initial list prices add 10% to the purchase price.
3	HRY	**Annual use (h)** Amount of time per year the equipment is used.
4	HRL	**Life of equip (h)** The amount of time the equipment will be capable of being used.
5	PWR	**Power of unit (KW)** This is the horsepower or the number of kilowatts of the equipment Kilowatts x 1.341 = horsepower
6	WDT	**Width of pass (m)** This refers to the width the equipment covers when it is moved across the land.
7	SPD	**Operating speed (km/h)** The speed at which the equipment is operated at.
8	RC1	**Repair cost coef 1** Refer to the American Society of Agricultural Engineers Standards Engineering Practices Data handbook for this value
9	RC2	**Repair cost coef 2** Refer to the American Society of Agricultural Engineers Standards Engineering Practices Data handbook for this value
10	XLB	**Lubricant factor** Refer to the American Society of Agricultural Engineers Standards Engineering Practices Data handbook for this value

11	FCM	*Fuel consumption multiplier* Refer to the American Society of Agricultural Engineers Standards Engineering Practices Data handbook for this value
12	VR1	*Remaining farm value parm 1* Refer to the American Society of Agricultural Engineers Standards Engineering Practices Data handbook for this value
13	VR2	*Remaining farm value parm 2* Refer to the American Society of Agricultural Engineers Standards Engineering Practices Data handbook for this value
14	EFM	*Machine efficiency* The fraction of efficiency loss due to the overlap of passes. For example, if each time when a pass is made across the field, the implement covers 10% of the last pass, then the machine efficiency is 0.90.
15	RTI	*Annual real interest rate ($/$)* The difference between the nominal interest rate (the current rate of interest) and the inflation rate.
16	EMX	*Mixing efficiency (0-1).* The mixing efficiency of the operation (EMX) is the fraction of materials (crop residue, pesticides and nutrients) on the soil surface that is mixed uniformly in the plow depth of the implement. The remaining fraction of residue and nutrients is left in the original location (soil surface or layer).
17	RR	*Random surface roughness created by tillage operation in mm.* This characterizes the soil surface roughness due to soil aggregates. Random roughness has been used to describe the effects of tillage on surface roughness and to estimate the surface roughness after tillage based on the tillage implement used. (Potter, K.N. 1990. Soil properties effect on random roughness decay by rainfall. Transactions of the ASAE 33 (6) 1889-1892.) The random roughness index is the standard error of adjusted natural log transformed surface elevations.
18	TLD	*Tillage depth in mm*. 1. (+) Positive depth is below the surface; 2. (-) Negative indicates above ground cutting height. 3. Also used as the lower limit of grazing height (mm)
19	RHT	*Ridge height in mm* The height of the ridge created by the implement. This affects wind erosion.
20	RIN	*Ridge interval in m* The distance between ridges created by the implement. Also known as row spacing. To set the row spacing of the crop, the ridge interval should be set accordingly for the planter in the TILL0604.DAT file.
21	DKH	*Height of furrow dikes in mm. (blank if dikes are not used)* This will affect the amount of water the furrow dike is capable of storing.
22	DKI	*Distance between furrow dikes in m. (blank if dikes are not used)*

23	IHC	*Operation Code:*

    1   Kill crop.
2   Harvest without kill.
3   Harvest once during simulation without kill.
4
5   Plant in rows.
6   Plant with drill.
7   Apply pesticide.
8   Irrigate.
9   Fertilize
10   Bagging and Ties (cotton)
11   Ginning
12   Hauling
13   Drying
14   Burn
15   Puddle
16   Destroy puddle
17   Builds furrow dikes
18   Destroys furrow dikes
19   Start grazing Stop grazing
20
21   Auto mow
22   Plastic cover
23   Remove plastic cover
24   Stop drainage system flow
25   Resume drainage flow

24	HE	***Harvest efficiency (0-1), or Pesticide application efficiency.***

As a harvest operation (IHC=2.0): This is the ratio of crop yield removed from the field to total crop yield.

Besides its normal function, harvest efficiency can be used in simulating grazing (HE approx. equal to 0.1) or growing green manure crops (HE=0.0).

As pesticide application efficiency, it is the fraction of the pesticide which is deposited on the foliage or soil surface. The remaining is lost.

25	ORHI	*Override Harvest Index for Forage and Root Crops* The ratio of the economic or harvestable yield to the total biomass of the crop. This value overrides the harvest index set in CROP0604.DAT if a forage or root crop is chosen. Over rides simulated Harvest Index (HI) if 0. < ORHI < 1 or it equals the grazing rate (kg/ha/d) if ORHI > 1. As the crop grows, these values may be adjusted for water stress. For some crops like hay, the harvest index is not affected by water stress. Thus, the harvest index override (ORHI) is used to give a constant harvest index. Another important feature of ORHI is the provision for two different types of harvest of the same crop. For example, the seed could be removed from a crop and the later the straw could be baled. The water-stress-adjusted HI is appropriate for the seed harvest but probably not for baling the straw. Thus, two separate harvest machines are required. The second harvester sets ORHI approx. equal to 0.9 to override the adjusted HI used in the first harvest. Values greater than 1 are kg/ha of biomass removed per day by grazing. For example, one animal/month is about the equivalent to 24 kg/day (12 kg/day consumed and an equivalent amount trampled).
26	FRCP	*Fraction of soil compacted* (tire width/tillage width).
27	FPOP	*Fraction plant population reduced by operation.* This operation can be used for thinning operations to reduce the plant population which was actually planted. It can also be used to decrease plant population after a harvest (i.e. sugarcane) or due to a tillage operation. It is a correction to the seeded rate.
28	COTL	*Tillage cost ($/Ha)*

The APEX fertilizer database

The fertilizer database summarizes nutrient fractions for various fertilizers and types of manure. The definition of the variables are listed in Table 9.

Table 9. The fertilizer file

Column	Variable	Description
1	FTNM	*Fertilizer name.* A descriptive name that usually includes the N-P-K analysis or the type of manure.
2	FN	*Mineral N fraction.* Fraction of nitrogen in the fertilizer which is in the mineral form.
3	FP	*Mineral P fraction* Fraction phosphorus in the fertilizer which is in the mineral form.
4	FK	*Mineral K fraction* Fraction of potassium in the fertilizer which is in the mineral form.
5	FNO	*Organic N fraction* This applies to organic fertilizers such as manures. This number must be obtained from an analysis test of the product. The amount is reported as a fraction.
6	FPO	*Organic P fraction* This applies to organic fertilizers such as manures. This number must be obtained from an analysis test of the product. The amount is reported as a fraction.
7	FNH3	*Ammonia N fraction* The fraction of nitrogen in the fertilizer that is in the ammonia (NH_3) form.
8	FOC	*Organic C fraction* Organic carbon = organic matter / 1.72
9	FSLT	*Salt fraction* Amount of salt in fertilizer
10	FCST	*Cost of Fertilizer ($/kg)* Used for economic analyses only.

The APEX pesticide database

The pesticide database in APEX characterize properties of the active ingredients in pesticides. These properties are defined in Table 10. Properties are provided for 929 active ingredients. APEX simulations of pesticide losses are evaluated with human, fish, aquatic crustacean, and aquatic plant toxicity thresholds to determine potential risk. All 929 pesticide records are taken from the NRCS, UMass Extension Pesticide Properties Database (2008), Amherst, MA.

Table 10. The pesticide file

Column	Variable	Description
1	PSTN	*Pesticide name.* Common or brand name of the pesticide.
2	PSOL	*Pesticide solubility in ppm.* The amount of the pesticide product which can dissolve in water. (ppm)
3	PHLS	*Pesticide half life in soil in days.* The time that it takes for the pesticide product concentration in the soil to be reduced by half. (days)

4	PHLF	*Pesticide half life in foliage in days.* The time that it takes for the pesticide product concentration on the foliage to be reduced by half. Degradation occurs through microbial activity and/or sunlight. (days)
5	PWOF	*Pesticide wash off fraction.* Percentage of the pesticide product that is applied to foliage that is washed off into the soil. (%)
6	PKOC	*Pesticide organic C absorption coefficient.* Amount of pesticide products attached to the soil divided by the amount of the pesticide product in solution, normalized by organic carbon % in the soil. Refer to Environmental Contaminant Toxicological Reviews 123:1-164.
7	PCST	*Pesticide cost in $/KG.* Used for economic analyses only.

References

Apezteguía, H.P., R.C. Izaurralde, and R. Sereno. 2002. Simulation of soil organic matter dynamics as affected by land use and agricultural practices in semiarid Córdoba, Argentina. Agronomy Abstracts. CD-ROM.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., and Williams, J.R. 1998. Large area hydrologic modeling and assessment part I: model development. J. American Water Resources Association 34(1):73-89.

Atwood, J.D., D. Moffitt, M. Lee Norfleet, A.D. King, J. Lemunyon. 2009. Transforming Survey Data to APEX Model Input Files.

Babcock, B.A., J. Wu, T. Campbell, P.W. Gassman, P.D. Mitchell, T. Otake, M. Siemers, T.M. Hurley. 1997. RAPS 1997: Agriculture and the environmental quality. Ames, IA: CARD, Iowa State University.

Baumer, O., P. Kenyon, and J. Bettis. 1994. MUUF v1.24 User's Manual. Natural Resources Conservation Service, National Soil Center, Lincoln, Nebraska.

Bernardo, D.J., H.P. Mapp, G.J. Sabbagh, S. Geleta, K.B. Watkins, R.L. Elliott, and J.F. Stone. 1993. Economic and environmental impacts of water quality protection policies 2. application to the Central High Plains. *Water Resour. Res.* 29(9): 3081-3091.

Bernardos, J.N., E.F. Viglizzo, V. Jouvet, F.A. Lértora, A.H. Pordomingo, and F.D. Cid. 2001. The use of EPIC model to study the agroecological change during 93 years of farming transformation in the Argentine pampas. *Agric. Syst.* 69:215-234.

Brown, R.A. and N.J. Rosenberg. 1999. Climate change impacts on the potential productivity of corn and winter wheat in their primary United States growing regions. *Climatic Change* 41(1): 73-107.

Cabelguenne, M., C.A. Jones, and J.R. Williams. 1995. Strategies for limited irrigations of maize in southwestern France – a modeling approach. *Trans. ASAE* 38(2):507-511.

Cavero, J., R.E. Plant, C. Shennan, D.B. Friedman, J.R. Williams, J.R. Kiniry, and V.W. Benson. 1998. Application of EPIC model to nitrogen cycling in irrigated processing tomatoes under different management systems. Agricultural Systems 56(4): 391-414.

Chung, S.W., P.W. Gassman, D.R. Huggins, and G.W. Randall. 2001. Evaluation of EPIC for tile flow and tile nitrate losses from three Minnesota cropping systems. *J. Environ. Qual.* 30(3):822-830.

Chung, S.W., P.W. Gassman, R. Gu, and R.S. Kanwar. 2002. Evaluation of EPIC for assessing tile flow and nitrogen losses for alternative agricultural management systems. *Trans. ASAE* 45(4):1135-1146.

Currie, J.A. 1965. Diffusion within soil microstructure a structural parameter for soils. Europ. J. Soil Sci. 16:279–289.

Daly, C., G. H. Taylor, and W. Gibson. 1997. "The PRISM approach to mapping precipitation and temperature." Preprints, 10th Conf. On Applied Climatology, Reno, NV, Amer. Meteor. Soc., 10–12.

Daly, C., W. P. Gibson, G.H. Taylor, G. L. Johnson, and P. A. Pasteris. 2002. "A knowledge-based approach to the statistical mapping of climate." Climate Res., 22, 99–113.

Del Grosso S.J., W.J. Parton, A.R. Mosier, D.S. Ojima, A.E. Kulmala, and S. Phongpan. 2000. General model for N_2O and N_2 gas emissions form soils due to denitrification. Global Biogeochemical Cycles 14:1045-1060.

Di Luzio M., G.L. Johnson, C. Daly, J. Eischeid, and J. G. Arnold. 2008. "Constructing Retrospective Gridded Daily Precipitation and Temperature Datasets for the Conterminous United States." Journal of Applied Meteorology and Climatology 47(2):475-497.

Edwards, D.R., V.W. Benson, J.R. Williams, T.C. Daniel, J. Lemunyon, and R.G. Gilbert. 1994. Use of the EPIC model to predict runoff transport of surface-applied inorganic fertilizer and poultry manure constituents. *Trans. ASAE* 37(2):403-409.

Eischeid, Jon K., Phil A. Pasteris; Henry F. Diaz, Marc S. PLantico, and Neal J. Lott. 2000. "Creating a Serially Complete, National Daily Time Series of Temperature and Precipitation for the Western United States." Journal of Applied Meteorology 39 (September):1580-1591.

Favis-Mortlock, D.T., R. Evans, J. Boardman, and T.M. Harris. 1991. Climate change, winter wheat yield and soil erosion on the English South Downs. *Agric. Syst.* 37:415-433.

Foltz, J.C., J.G. Lee, and M.A. Martin. 1993. Farm-level economic and environmental impacts of Eastern Corn Belt cropping systems. *J. Prod. Agric.* 6:290-296.

Gassman, P.W., E. Osei, A. Saleh, and L.M. Hauck. 2002. Application of an environmental and economic modeling system for watershed assessments. *J. Amer. Water Res. Assoc.* 38(2): 423-438.

Gassman, P.W., J. R. Williams, V. W. Benson, R. C. Izaurralde, L. M. Hauck, C. A. Jones, J. D. Atwood, J. R. Kiniry, and J. D. Flowers. 2004; Historical development and applications of the EPIC and APEX models, ASAE/CSAE Meeting Presentation Paper Number: 042097 St. Joseph, Mich.: ASAE. Also available at: http://econpapers.repec.org/paper/iascpaper/05-wp397.htm.

Gassman, P.W., J.R. Williams, X. Wang, A. Saleh, E. Osei, L. Hauck, C. Izaurralde, and J. Flowers. 2009. The Agricultural Policy Environmental Extender (APEX) Model: An emerging tool for landscape and watershed environmental analyses. Technical Report. Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa.

Goss, D. W., Joaquin Sanabria, R. L. Kellogg, and J. L. Berc. 2001. "A National Assessment of Soil Carbon Sequestration on Cropland: Description of an Analytical Approach." In Soil Carbon Sequestration and the Greenhouse Effect. Soil Science Society of America Special Publication no. 57.

Izaurralde, R.C., J.R. Williams, W.B. McGill, N.J. Rosenberg, and M.C. Quiroga Jakas. 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecol. Modell. 192: 362-384.

Jones, C. A., and J. R. Kiniry. 1986. CERES-Maize, A simulation model of maize growth and development, Texas A&M University Press, college Station, TX, 194 p.

Jones, C.A., P.T. Dyke, J.R. Williams, J.R. Kiniry, V.W. Benson, and R.H. Griggs. 1991. EPIC: an operational model for evaluation of agricultural sustainability. *Agric. Syst.* 37:341-350.

King, K.W., C.W. Richardson, and J.R. Williams. 1996. Simulation of sediment and nitrate loss on a vertisol with conservation tillage practices. *Trans. ASAE* 39(6):2139-2145.

Kiniry, J.R., J.R. Williams, P.W. Gassman, and P. Debaeke. 1992. A general, process-Oriented model for two competing plant species. Trans ASAE. Vol.35(3):801-810.

Knisel, W.G. 1980. CREAMS, A field scale model for chemicals, runoff, and erosion from agricultural management systems. U.S. Dept. Agric. Conserv. Res. Rept. No. 26.

Lee, J.J., D.L. Phillips, and R. Liu. 1993. The effect of trends in tillage practices on erosion and carbon content of soils in the U.S. Corn Belt. *Water Air Soil Poll.* 70:389-401.

Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: Groundwater loading effects on agricultural management systems. Trans. ASAE 30(5):1403-1428.

Mockus, V. 1969. Hydrologic soil-cover complexes. In *SCS National Engineering Handbook, Section 4, Hydrology*, 9.1 – 9.11. Washington, D.C.: U.S. Department of Agriculture, Soil Conservation Service.

NADP. 2004. National Atmospheric Deposition Program 2003 Annual Summary. NADP Data Report 2004-01. NADP Program Office, Champaign, IL., 16 pp.

Nicks, A. D., 1974. "Stochastic Generation of the Occurrence, Pattern and Location of Maximum Amount of Rainfall." In Proceedings of symposium on Statistical Hydrology, Tuscon, Arizona, Aug-Sep 1971, USDA, Misc. Publ. No. 1275.

Nicks, A.D., L.J. Lane. 1989. Chapter 2. Weather Generator. Pp. 2.1-2.19. Profile Model Documentation. USDA-Water Erosion Prediction Project: Hillslope Profile Version. NSERL Report No. 2, USDA-ARS National Soil Erosion Research Lab., West Lafayette, Indiana 47907.

Osei, E., P.W. Gassman, R. Jones, S. Pratt, L. Hauck, L. Beran, W. Rosenthal, and J.R. Williams. 2000a. Economic and Environmental Impacts of Alternative Practices on Dairy Farms in an Agricultural Watershed. *J. Soil Water Cons.* 55(4): 466-472.

Osei, E., P. Gassman, and A. Saleh. 2000b. Livestock and the Environment: a National Pilot Project; Economic and Environmental Modeling Using CEEOT. Report PR0002. Stephenville, Texas: TIAER, Tarleton State University.

Osei, E., P.W. Gassman, L.M. Hauck, S. Neitsch, R.D. Jones, J. Mcnitt, and H. Jones. 2003a. Using Nutrient Management to Control Nutrient Losses from Dairy Pastures. *J. Range Manage.* 56: 218-226.

Osei, E., P.W. Gassman, L.M. Hauck, R. Jones, L. Beran, P.T. Dyke, D.W. Goss, J.D. Flowers, and A.M.S. McFarland. 2003b. Economic Costs and Environmental Benefits of Manure Incorporation on Dairy Waste Application Fields. *J. Environ. Manage.* 68(1): 1-11.

Parton, W.J., Ojima, D.S., Cole, C.V. and Schimel, D.S., 1994. A general model for soil organic matter dynamics: Sensitivity to litter chemistry, texture and management. In: Quantitative Modeling of Soil Forming Processes, SSSA Spec. Public. No. 39, Madison, WI, pp. 147-167.

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Sci. Soc. Am. J.* 51: 1173-1179.

Parton, W.J., Scurlock, J.M.O., Ojima, D.S., Gilmanov, T.G., Scholes, R.J., Schimel, D.S., Kirchner, T., Menaut, J-C, Seastedt, T., Garcia Moya, E., Kamnalrut, A. and Kinyamario, J.I. 1993. Observations and modelling of biomass and soil organic matter dynamics for the grassland biome worldwide. *Global Biogeochemical Cycles* 7: 785-809.

Penman, H.L. 1940. Gas and vapor movements in the soil: 1. The diffusion of vapors through porous solids. J. Agric. Sci. 30:437-461.

Phillips, D.L., P.D. Hardin, V.W. Benson, and J.V. Baglio. 1993. Nonpoint source pollution impacts of alternative agricultural management practices in Illinois: A simulation study. *J. Soil Water Cons.* 48(5): 449-457.

Pierson, S.T., M.L. Cabrera, G.K. Evanylo, P.D. Schroeder, D.E. Radcliffe, H.A. Kuykendall, V.W. Benson, J.R. Williams, C.S. Hoveland, and M.A. McCann. 2001. Phosphorus losses from grasslands fertilized with broiler litter: EPIC simulations. *J. Environ. Qual.* 30:1790-1795.

Potter, S. 2009. Modeling Structural Conservation Practices.

Potter, K.N. and J.R. Williams. 1994. Predicting daily mean temperatures in the EPIC simulation model. *Agron. J.* 86(6):1006-1011.

Potter, Steven R., Susan Andrews, Jay D. Atwood, Robert L. Kellogg, Jerry Lemunyon, Lee Norfleet, and Dean Oman. 2006. Model Simulation of Soil Loss, Nutrient Loss, and Change in Soil Organic Carbon Associated with Crop Production. U.S. Dept. Agriculture, Natural Resources Conservation Service, Conservation Effects Assessment Project (CEAP). 262 pages, June. http://www.nrcs.usda.gov/technical/nri/ceap/croplandreport/

Putnam, J., J. Williams, and D. Sawyer. 1988. Using the erosion productivity calculator(EPIC) model to estimate the impact of soil erosion for the 1985 RCA appraisal. J. Soil Water Conserv. 43(4):321-326.

Renard, K. G., G. R. Foster, G. A. Weesies, D. K. McCool, and D. C. Yoder. 1997. Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE). U. S. Dept. Agric., Agric. Res. Ser., Agriculture Handbook Number 703.

Rinaldi, M. 2001. Application of EPIC model for irrigation scheduling of sunflower in southern Italy. *Agric. Water Manage.* 49:185-196.

Roloff, G., R. de Jong, and M.C. Nolin. 1998a. Crop yield, soil temperature and sensitivity of EPIC under central-eastern Canadian conditions. *Can. J. Plant Sci.* 78(3): 431-439.

Rolston, D.E., D.L. Hoffman, and D.W. Toy. 1978. Field measurement of denitrification. I. Flux of N_2 and N_2O from soils. Soil Sci. Soc. Am. J. 42:863-869.

Sabbagh, G. J., P. E. Norris, S. Geleta, D. J. Bernado, R. L. Elliott, H. P. Mapp, and J. F. Stone. 1992. Environmental and economic impacts of pesticide and irrigation practices: EPIC-PST simulation. *J. Prod. Agric.* 5: 312-317.

Sharpley, A.N. and J.R. Williams (Eds.). 1990. EPIC – erosion/productivity impact calculator: 1. model documentation. USSDA Technical Bulletin No. 1768. Washington, D.C.

Taylor, M.L., R.M. Adams, and S.F. Miller. 1992. Farm-level response to agricultural effluent control strategies: the case of the Willamette Valley. *J. Agric. Resour. Econ.* 17(1): 173-183.

USDA-NRCS. 2004. Chapter 10: Estimation of direct runoff from storm rainfall. In *NRCS National Engineering Handbook, Part 630, Hydrology*, 10.1-10.22. Washington, D. C.: USDA Natural Resources Conservation Service. Available at: www.wsi.nrcs.usda.gov/products/w2Q/H&H/tech_refs/eng_Hbk/chap.html. Accessed 1 February 2008.

USDA-NRCS. 2007. Soil Data MART. U.S. Dept. of Agric., Natural Resources Conservation Service, Washington, DC. Available at: http://soildatamart.nrcs.usda.gov/.

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

Van Bavel, C.H.M. 1952. Gaseous diffusion and porosity in porous media. Soil Sci. 73:91-104.

Vitousek, P.M., Turner, D.R., Parton, W.J. and Sanford, R.L., 1994. Litter decomposition on the Mauna Loa environmental matrix, Hawaii: Patterns, mechanisms, and models. Ecology 75: 418-429.

Wang, X., P.W. Gassman, J. R. Williams, S. Potter, A.R. Kemanian. 2008. Modeling the impacts of soil management practices on runoff, sediment yield, maize productivity, and soil organic carbon using APEX. Soil & Tillage Research 101(1-2): 78-88.

Wesseling, J. 1962. Some solutins of the steady-state diffusion of carbon dioxide through soils. Neth. J. Agric. Sci. 10:109-117.

Williams, J.R. 1975a. HYMO flood routing, J. Hydrology, 26: 17-27.

Williams, J.R. 1975b. Sediment yield prediction with universal equation using runoff energy factor. U.S. Dept. Agric., Agric. Res. Serv., ARS-S-40.

Williams, J.R. 1995. The EPIC Model. In Computer Models of Watershed Hydrology (Ed.: V.P. Singh). Water Resources Publications, Highlands Ranch, CO. pp 909-1000.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Trans. ASAE* 27(1): 129-144.

Williams, J.R., A.D. Nicks, and J.G. Arnold. 1985. SWRRB, a simulator for water resources in rural basins. ASCE Hydr. J., 111(6): 970-986.

Williams, J.R., C.W. Richardson, and R.H. Griggs. 1992. The weather factor: incorporating weather variance into computer simulation. *Weed Technol.* 6: 731-735.

Williams, J. R. and R. C. Izaurralde. 2005. The APEX Model. In: Watershed Models, V.P. Singh and D. K. Frevert editors, Chapter 18, pp 437-482. CRC Press, Taylor & Francis Group, Boca Raton, FL.

Woodruff, N.P. and F.H. Siddoway. 1965. A wind erosion equation. Soil Sci. Soc. Am. Proc. 29(5):602-608.

Wu, L. and M. B. McGechan, 1998. A review of carbon and nitrogen processes in four soil nitrogen dynamics models. J. Agric. Eng. Res. 69:279-305.