The Agricultural Policy Environmental EXtender (APEX) Model: An Emerging Tool for Landscape and Watershed Environmental Analyses

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Technical Report 09-TR 49
April 2009

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This study was funded in part from support provided by the U.S. Department of Agriculture, Natural Resources Conservation Service (Project No. Q683H753122#33).

Abstract

The Agricultural Policy Environmental eXtender (APEX) model was developed by the Blacklands Research and Extension Center in Temple, Texas. APEX is a flexible and dynamic tool that is capable of simulating a wide array of management practices, cropping systems, and other land use across a broad range of agricultural landscapes, including whole farms and small watersheds. The model can be configured for novel land management strategies, such as filter strip impacts on pollutant losses from upslope cropfields, intensive rotational grazing scenarios depicting movement of cows between paddocks, vegetated grassed waterways in combination with filter strip impacts, and land application of manure removal from livestock feedlots or waste storage ponds. A description of the APEX model is provided, including an overview of all the major components in the model. Applications of the model are then reviewed, starting with livestock manure and other management scenarios performed for Livestock and the Environment: A National Pilot Project (NPP), and then continuing with feedlot, pesticide, forestry, buffer strip, conservation practice, and other management or land use scenarios performed at the plot, field, watershed, or regional scale. The application descriptions include a summary of calibration and/or validation results obtained for the different NPP assessments as well as for other APEX simulation studies. Available APEX Geographic Information System–based or Windows-based interfaces are also described, as are forthcoming future improvements and additional research needs for the model.

Keywords: APEX, best management practices, farm and watershed simulations, soil carbon, water quality.

INTRODUCTION

Extensive hydrologic and environmental model development has been carried out over the past four decades by the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) and Texas A&M University, Texas AgriLIFE[1] research units located in Temple, Texas, at the Grassland, Soil and Water Research Laboratory (GSWRL) and Blacklands Research and Extension Center (BREC), respectively (Williams et al., 2008). Early model investigation focused on unit hydrographs, flood routing estimation, sediment yield functions, and single event storm routing, followed by the development of weather generators, crop growth models, nutrient cycling routines, single event sediment and nutrient routing models, and the first daily time step continuous simulation water yield model. Many of the concepts developed in these earlier functions and models were incorporated into the Environmental Policy Impact Climate[2] (EPIC) model (Williams et al., 1984; Williams, 1990, 1995; Gassman et al., 2005; Izaurralde et al., 2006) and the Simulator for Water Resources in Rural Basins (SWRRB) model (Williams et al., 1985; Arnold and Williams, 1987), which were designed to evaluate water quality and other agricultural environmental problems at the field scale and watershed scale, respectively. The SWRRB model was interfaced with the Routing Outputs To the Outlet (ROTO) model (Arnold et al., 1995) and other model algorithms to construct the Soil and Water Assessment Tool (SWAT) model (Williams and Arnold, 1997; Arnold et al., 1998; Arnold and Fohrer, 2005; Gassman et al., 2007; Williams et al., 2008), which essentially replaced SWRRB for watershed analyses and extended the modeling capability to large river basin systems.

Both the EPIC and SWAT models have experienced continuous evolution since their inceptions and have emerged as key tools that are being used worldwide for analyzing a wide variety of environmental problems (Gassman et al., 2005; Gassman et al., 2007). Examples of EPIC applications include plot- or field-level assessments of sediment, nutrient, and/or pesticide

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[1] Formerly Texas Agriculture Experiment Station.
[2] Originally known as the Erosion Productivity Impact Calculator.

loss as a function of different cropping or management systems (Jackson et al., 1994; Chung et al., 2002; Lu et al., 2003; Wang et al., 2006b), field-level crop yield, nitrogen cycling, or soil carbon sequestration evaluations (Williams et al., 1989; Cabelguenne et al., 1990; Cavero et al., 1999; Wang et al., 2005; Izaurralde et al., 2006), regional-level assessments of nitrogen leaching, soil carbon sequestration, or other environmental indicators (Wu and Babcock, 1999; Cepuder and Shukla, 2002; Gaiser et al., 2008) including interfaces with economic analyses (Feng et al. 2005; 2007), and global assessments of crop yield as a function of climate change, land use change, or water management (Tan and Shibaski, 2003; Wu et al., 2007; Liu et al., 2007). SWAT applications range from hydrologic and/or pollutant loss validation studies (Arnold et al., 2000; Saleh et al., 2000; Jha et al., 2007; Reungsang et al., 2007; Green and van Griensven, 2008; Stehr et al., 2008), to hydrologic assessments of climate change, reservoir, wetland, or tile drainage effects, or land use change across a variety of watershed scales (Jha et al., 2006; Gosain et al., 2006; Green et al., 2006; Wu and Johnston, 2007; Jones et al., 2008; Wang et al., 2008e; Cao et al., 2008), to best management practice (BMP), land use, and other scenario analyses on pollutant losses (Nelson et al., 2005; Secchi et al., 2007; Volk et al., 2008; Ghebremichael et al., 2008; Parajuli et al., 2008), to hydrologic balance, climate change or other analyses of huge river basins or water resource systems at the national, subcontinent, or entire continent scale (Arnold et al., 1999; Thomson et al., 2003; Schuol et al., 2008a,b). A comprehensive review of dozens of SWAT studies performed worldwide is provided by Gassman et al., 2007.

Significant gaps in the ability to simulate key landscape processes at the farm or small watershed scale persisted, despite the versatility of these two models. This weakness was acutely revealed at the onset of the Livestock and the Environment: A National Pilot Project (NPP), which was commissioned in the early 1990s to address water quality and other environmental problems associated with intensive livestock production. A key objective of the NPP was to evaluate a wide range of alternative manure management scenarios that included relatively complex combinations of farm-level landscapes, cropping systems, and/or management practices.

Thus, the NPP served as a catalyst for the development of the initial versions of the Agricultural Policy Environmental EXtender (APEX) model (Williams et al., 1995; Williams, 2002; Williams and Izaurralde, 2006; Williams et al., 2006; Williams et al., 2008), which bridged the gap that existed between the EPIC and SWAT models.

The APEX model is a flexible and dynamic tool that is capable of simulating management and land use impacts for whole farms and small watersheds. APEX is essentially a multi-field version of the predecessor EPIC model and can be executed for single fields similar to EPIC as well as for a whole farm or watershed that is subdivided based on fields, soil types, landscape positions, or subwatersheds. APEX functions on a daily time step, can perform long-term continuous simulations, and can be used for simulating the impacts of different nutrient management practices, tillage operations, conservation practices, alternative cropping systems, and other management practices on surface runoff and losses of sediment, nutrient, and other pollutant indicators. The model can also be configured for novel land management strategies such as filter strip impacts on pollutant losses from upslope cropfields, intensive rotational grazing scenarios depicting movement of cows between paddocks, vegetated grassed waterways in combination with filter strip impacts, and land application of manure removal from livestock feedlots or waste storage ponds. Routing of water and pollutants can be simulated between subareas and through channel systems in the model. According to Srivastava et al. (2007), APEX is one of the few existing models that is capable of simulating flow and pollutant transport routing at the field scale.

The objective of this study is four-fold: (1) briefly describe the major components of APEX and differentiate between existing important versions; (2) provide a review of APEX applications reported in the peer-reviewed literature and other sources, including validation assessments versus measured data; (3) describe GIS and other interface tools that have been developed to facilitate APEX applications for watershed- and regional-scale assessments as well as nested applications within a SWAT watershed study; and (4) discuss future research and development needs for the model.

APEX MODEL DESCRIPTION

Williams et al. (1995) provided the first qualitative description of the APEX, which included a description of the major components of the model, including the manure management component. Expanded qualitative descriptions of the model are reported by Williams (2002) and Williams et al. (2006), the latter of which provides overviews of the manure erosion and routing components, including some mathematical description. Williams and Izaurralde (2006) provide an exhaustive qualitative description of the model coupled with mathematical theory for several of the components. Complete theoretical descriptions of APEX were initially compiled by Williams et al. (2000) and Williams and Izaurralde (2005); Williams et al. (2008) provide an updated, in-depth theoretical manual for the latest APEX model (version 0604).

A brief qualitative overview of key APEX components is provided here, based in part on the discussion provided in Williams et al. (2006). The above referenced documents should be consulted for more detailed descriptions of the different model components. Previous documentation for the EPIC model also provides relevant background information for APEX, which is cited in Gassman et al., 2005.

Overview of APEX

The APEX code is written in FORTRAN and can be executed on a PC (for most operating systems) and also on a UNIX platform. The model consists of 12 major components: climate, hydrology, crop growth, pesticide fate, nutrient cycling, erosion-sedimentation, carbon cycling, management practices, soil temperature, plant environment control, economic budgets, and subarea/routing. Management capabilities include sprinkler drip or furrow irrigation, drainage, furrow diking, buffer strips, terraces, waterways, fertilization, manure management, lagoons, reservoirs, crop rotation and selection, cover crops, biomass removal, pesticide application, grazing, and tillage. Simulation of liquid waste applications from concentrated animal feeding operation (CAFO) waste storage ponds or lagoons is a key component of the model. Stockpiling and subsequent land application of solid manure in feedlot or other animal feeding areas can also be simulated in APEX. Groundwater and reservoir components have been incorporated in APEX in addition to the routing algorithms. The routing mechanisms provide for evaluation of interactions between subareas involving surface run-off, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow. Water quality in terms of soluble and organic N and P and pesticide losses may be estimated for each subarea and at the watershed outlet.

Climate Inputs

Precipitation, maximum and minimum temperature, and solar radiation are the daily climate inputs required for driving APEX. Wind speed and relative humidity are also required for some evapotranspiration options as described below, and wind speed is further required if wind erosion is simulated. Climate data can be entered from recorded measurements, generated internally in the model, or provided in several different combinations of both measured and generated data. Tabulated monthly weather statistics are required for generating weather in APEX and are also required for other stochastic processes, and thus must be inputted for every APEX simulation.

Precipitation is generated in the model based on a first-order Markov Chain model developed by Nicks (1974), which is also used in the CLIGEN weather generator (Meyer et al., 2008). Precipitation can also be generated spatially for watershed applications covering larger areas and/or encompassing regions with steep rainfall gradients. Air temperature and solar radiation is generated in the model using a multivariate generation approach described by Richardson (1981). Wind generation in APEX is based on the Wind Erosion Continuous Simulation (WECS) model (Potter et al., 1998), which requires estimation of wind speed distribution within each day and the dominant wind direction. Average relative humidity is estimated each day from the tabulated average monthly value using a triangular distribution.

Hydrologic Balance

The hydrologic balance component of APEX encompasses all of the key processes that occur in the hydrologic cycle. Initially, incoming precipitation, snowmelt water, or irrigation input is partitioned between surface runoff and infiltration. Infiltrated water can be stored in the soil profile, percolate vertically to groundwater, be lost via evapotranspiration, or routed laterally in subsurface or tile drainage flow. Return flow to stream channels from groundwater or lateral subsurface flow is accounted for. Fluctuations in water table depth can also be simulated to account for offsite water effects; however, there is no direct linkage between the water table calculations and other hydrologic processes simulated in the model.

Surface runoff volume can be estimated with two different methods in APEX: a modification of the Soil Conservation Service (SCS) runoff curve number (RCN) technique (USDA-NRCS, 2004) described by Williams (1995), and the Green and Ampt infiltration equation (Green and Ampt, 1911). Two additional options are provided regarding the estimation of the RCN retention parameter, which are based on either the traditional soil moisture approach or an alternative algorithm computed as a function of evapotranspiration. The alternative retention parameter option is described by Kannan et al. (2007) and Yin et al. (2008) and can result in more accurate runoff estimations for some soil and land cover conditions. Daily rainfall data is used with the RCN technique while subdaily rainfall is used in the Green and Ampt approach, which is computed by distributing daily rainfall exponentially with stochastically generated parameters.

The peak runoff rate is also estimated in APEX for each storm event, which is used in calculating erosion loss as described below. The peak runoff rate can be estimated using the modified Rational Formula (Williams, 1995) or the USDA-SCS TR-55 method (USDA-SCS,

1986) as a function of rainfall intensity and other factors. A peak runoff rate is also estimated for snowmelt events, assuming a uniform distribution of rainfall over a day and no rainfall energy.

Subsurface flow is calculated as a function of both vertical and horizontal subsurface flows. Simultaneous computation of the vertical and horizontal subsurface flows is performed in the model, using storage routing and pipe flow equations. Vertical percolation of infiltrated water is routed through successive soil layers using a storage routing approach as a function of key soil parameters including the field capacity (maximum soil water holding capacity), saturated conductivity, and porosity. Flow from an upper soil layer to the next soil layer occurs when the soil water content in the first soil layer exceeds field capacity and continues from that layer until the soil water content reaches field capacity again. This routing process continues until the flow reaches groundwater storage, which can lose water because of deep percolation from the overall system and also return flow to the stream channel; the return flow is routed to the channel flow in the subarea in which the return flow was calculated. Upward water movement from a soil layer can also occur when the soil water content of the lower layer exceeds field capacity while the upper layer soil water content is less than field capacity. In frozen soils, water can percolate into a frozen layer but cannot percolate into a lower layer.

Horizontal flow is partitioned into lateral and quick return flow. Lateral subsurface flow enters the subarea immediately downstream and is added to that subarea’s soil water storage. Quick return flow is added to the channel flow from the subarea. Tile drainage flow can also be simulated, which is calculated as a modification of the natural lateral subsurface flow. The tile drainage calculations are performed as a function of tile drainage depth and the time (in days) required for the drainage system to reduce crop stress due to excess water in the soil profile.

Five different options are provided in APEX for estimating potential evaporation: Hargreaves (Hargreaves and Samani, 1985), Penman (1948), Priestley-Taylor (1972), Penman-Monteith (Monteith, 1965), and Baier-Robertson (1965). The Penman and Penman-Monteith methods are the most data intensive, requiring solar radiation, air temperature, wind speed, and relative humidity as input. The Priestly-Taylor method requires solar radiation and air temperature as input while the Hargreaves and Baier-Robertson methods require only air temperature. The Baier-Robertson method was developed in Canada and can provide more accurate potential evaporation estimates for colder climate conditions. The model computes evaporation from soils and plants separately, as described by Ritchie (1972).

Water and Wind Erosion

Water-induced erosion is calculated in APEX in response to rainfall, snowmelt, and/or irrigation runoff events. Eight different equations are provided in APEX for calculating water erosion: the Universal Soil Loss Equation (USLE) method (Wischmeier and Smith, 1978), the Onstad-Foster (AOF) modification of the USLE (Onstad and Foster, 1975), the Modified USLE (MUSLE) method (Williams, 1975), two MUSLE variants (Williams, 1995) referred to as MUST (theoretical version) and MUSS (small watershed version), a MUSLE approach that uses input coefficients (referred to as MUSI), the Revised USLE (RUSLE) method (Renard, et al. 1997), and RUSLE2. Multiple equations can be activated during a simulation, but only one interacts with other APEX components, as specified by the user. The seven equations are similar except for their energy components. The USLE and RUSLE depend strictly upon rainfall as an indicator of erosive energy while the MUSLE and its variations use only runoff variables to simulate erosion and sediment yield. The runoff variables result in increased prediction accuracy, eliminate the need for a delivery ratio (used in the USLE to estimate sediment yield), and allow the various MUSLE equation variants to predict single storm estimates of sediment yields.

The original wind erosion model used in EPIC was the Wind Erosion Equation (WEQ) (Williams, 1995), which has since been replaced by the Wind Erosion Continuous Simulator (WECS) approach (Potter et al., 1998). The potential wind erosion is estimated for a smooth, bare soil each day by integrating the wind erosion equation over the day as a function of the inputted wind speed distribution. The actual erosion is computed based on adjustments to the potential erosion by factoring in the effects of soil properties, surface roughness, vegetation cover, and distance across the field in the wind direction.

Carbon Cycling Routine

The latest versions of APEX incorporate enhanced carbon and nitrogen cycling algorithms, initially developed by Izaurralde et al. (2006) for EPIC, which are based on concepts used in the Century model (Parton et al., 1987, 1993). These routines estimate soil carbon sequestration as a function of climatic conditions, soil properties, and management practices and simulate storage of carbon and nitrogen compounds in either structural or metabolic litter, biomass, or slow and passive soil humus pools. Direct interaction is simulated between these pools and the EPIC soil moisture, temperature, erosion, tillage, soil density, leaching, and translocation functions. Other features of the carbon cycling approach in APEX include the following: (1) organic materials' movement from surface litter to subsurface layers are estimated by the leaching equations currently in APEX; (2) temperature and water controls affecting transformation rates are calculated with equations currently in APEX; (3) the surface soil layer in APEX has a slow but no passive humus compartment (unlike the Century model which has both); and (4) the lignin concentration in APEX is modeled as a sigmoidal function of plant age.

Nitrogen Cycling and Losses

The complete nitrogen (N) cycle is simulated in APEX, including atmospheric N inputs; fertilizer and manure N applications; crop N uptake; denitrification; mineralization; immobilization; nitrification; ammonia volatilization; organic N transport on sediment; and nitrate-nitrogen (NO_3-N) losses in leaching, surface runoff, lateral subsurface flow, and tile flow.

As one of the microbial processes, denitrification is a function of temperature and water content (Williams, 1995). Anaerobic conditions are required and a carbon source must be present for denitrification to occur. Nitrification, the conversion of ammonia N to NO_3-N, is estimated using a combination of the methods of Reddy et al. (1979) and Godwin et al. (1984). The approach is based on the first-order kinetic rate equation of Reddy et al. (1979). The equation combines nitrification and volatilization regulators. The nitrification regulator is a function of temperature, soil water content, and soil pH.

Simulation of atmospheric emissions of N gases from the soil profile in APEX include N_2 and N_2O, as products of denitrification, and ammonia volatilization. The N_2 and N_2O emissions are simulated in APEX by using a common rational of adjusting a maximum, empirically determined emission rate using factors that control the total denitrification rate. The total denitrification rate is then partitioned into N_2 and N_2O fluxes. Volatilization, the loss of ammonia to the atmosphere, is estimated simultaneously with nitrification. Volatilization of surface-applied ammonia is estimated as a function of temperature and wind speed (Williams, 1995). Depth of ammonia within the soil, cation exchange capacity of the soil, and soil temperature are used in estimating below-surface volatilization.

A loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978) for application to individual runoff events is used to estimate organic N loss. The loading function considers sediment yield, organic N loss in the soil surface, and an enrichment ratio. The amount of NO_3-N lost when water flows through a layer is estimated by considering the change in loss (Williams, 1995). NO_3-N loss in a soil layer decreases exponentially as a function of flow volume. The average loss during a day is obtained by integrating the exponential function with respect to flow. Amounts of NO_3-N contained in runoff, lateral flow, and percolation are estimated as products of the volume of water and the average loss.

Phosphorus Cycling and Losses

The APEX approach is based on the concept of partitioning pesticides into the solution and sediment phases (Knisel, 1980). Because P is mostly associated with the sediment phase, the soluble P runoff equation is a linear function of soluble P loss in the top soil layer, runoff volume, and a linear adsorption isotherm. Sediment transport of P is simulated with a loading function as described in organic N transport. The P loading function considers sediment yield, organic P loss in the top soil layer, and the enrichment ratio. The P mineralization model developed by Jones et al. (1984) is a modification (Williams, 1995) of the PAPRAN mineralization model (Seligman and van Keulen, 1981). Mineralization from the fresh organic P pool is estimated as the product of the mineralization rate constant and the fresh organic P content. Mineralization of organic P associated with humus is estimated for each soil layer as a function of soil water content, temperature, and bulk density. The P immobilization model was also developed by Jones et al. (1984). The daily amount of immobilization is computed by subtracting the amount of P contained in the crop residue from the amount assimilated by the microorganisms.

Livestock Grazing

All subareas are identified by an ownership number, and each owner may have livestock and poultry. The owner may have up to 10 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. Only one herd may occupy a subarea at any time. All livestock rotations among subareas are performed automatically by APEX within user constraints. There is a provision for leading and trailing rotations. For example, 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 the 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. Grazing may occur throughout the year or may be allowed only at certain times. 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 such conditions as confined or partially confined area feeding, intensive rotational grazing, and cropland grazing after harvest.

Manure Management

Manure may be applied in solid or liquid form. Confined feeding areas may contain a lagoon to catch runoff from the feeding area plus wash water that is used in the barn. The lagoon is designed automatically by the model considering normal and maximum volumes. Effluent from the lagoon is applied automatically to a field designated for liquid manure application. The liquid manure application rules are as follows: (1) pumping begins when the lagoon volume exceeds 0.75 of the difference between maximum and normal lagoon volumes; (2) the pumping rate is set to reduce the lagoon volume from maximum to normal in a user-supplied number of days; (3) pumping can also be triggered by a user-supplied date—usually before winter or a high rainfall season. Solid manure is scraped from the feeding area automatically at a user input interval in days and stockpiled for automatic application to designated fields. An owner may have any number of solid manure application fields. When an application is triggered (the stockpile is adequate to supply the specified rate), manure is applied to the field with the lowest soluble P concentration in the top 50 mm of soil. A variety of livestock, including cattle, swine, and poultry, may be considered because manure production in kg head^{-1} d^{-1} and its ingredients (mineral and organic N and P) are inputs. APEX simulates runoff, soil erosion, and manure erosion. Routing mechanisms simulate soluble nutrient transport with water, organic nutrient transport by sediment, and manure transport by water.

Manure Erosion

Nutrient losses from feedlots and manure application fields can be estimated in APEX using a manure erosion equation based on the previously described MUST equation, which provides direct estimates of organic nutrient and carbon losses. The simulated erosion can consist of essentially just manure to a combination of manure and soil, depending on the extent of manure coverage across a feedlot or field. Since manure is considered residue, a heavy manure cover in a feedlot may completely eliminate soil erosion because of the “residue effect” of the manure; however, this condition could potentially result in extreme manure erosion. Analogous results can occur for fields with well-established stands of grass or similar vegetative cover.

APEX Routing Component

Current versions of APEX now offer two options for routing water through channels and flood plains: a daily time step average flow method, and a short time interval complete flood routing method. If the primary purpose is to simulate long-term water, sediment, nutrient, and pesticide yields from whole farms and small watersheds, the daily time step method should produce realistic estimates and is computationally efficient. However, the complete flood routing provides estimates of actual stream flow and potentially increases accuracy in estimating pollutant transport, especially when simulating larger watersheds.

The average flow rate for a runoff event is estimated as a function of runoff volume, watershed area, rainfall duration, and time of concentration for the daily time step average flow method. The channel capacity is estimated using Manning’s equation assuming a trapezoidal shape. The flow velocity is calculated using Newton’s method for solving nonlinear equations if the daily flow rate is less than channel capacity flow contained in the channel. The solution involves adjusting flow depth to give the correct flow rate. Then channel flow velocity is computed by dividing rate by cross-sectional area. If the channel capacity is exceeded, the excess flow occurs in the floodplain. Flow depth is calculated using Manning’s equation. Flow velocity is computed by dividing rate by area. Travel time through the reach floodplain is length divided by velocity. The inflow volume is reduced by floodplain infiltration.

The Variable Storage Coefficient (VSC) flood routing method (Williams, 1975) is used for simulating hydrographs with short (typically 0.1 to 1.0 h) time steps for the more complete flood routing approach. Runoff hydrographs from subareas are simulated and routed downstream to the watershed outlet. This complete flood routing approach simulates dynamic stream flow whereas the daily time step method can only estimate daily water yield (daily simulated runoff from all subareas arrives at the watershed outlet at the end of the day). This is an important feature for watersheds with times of flow concentration of 0.5 d or more. It is also important in estimating flood stages and durations and pollutant transport capacities. Storm event rainfall-time distributions are derived from daily rainfall. Rainfall excess is then estimated and applied to the accumulated rainfall distributions in user specified time steps. Runoff hydrographs are simulated with a variation of the VSC method called the storage depletion technique. The watershed storage volume is computed at each time interval by adding the simulated rainfall excess for that time interval to the existing storage volume.

Sediment is routed through the channel and floodplain separately. The same sediment routing equations are used for daily time step routing and for the VSC method. If daily time step routing is used, the velocities and flow rates are the averages for the day and the volume is the total for the day. If the VSC method is used, average velocity, flow rate, volume, and sediment transport are calculated for each time interval. Thus, the VSC produces time distributions of sediment concentration and transport (sediment graphs). The sediment routing equation is a variation of Bagnold’s sediment transport equation (Bagnold, 1977); the new equation estimates the transport concentration capacity as a function of velocity.

The organic forms of N and P are transported by sediment and are routed using an enrichment ratio approach. The enrichment ratio is estimated as the ratio of the mean sediment particle size distribution of the outflow divided by that of the inflow. Mineral forms of N and P are considered conservative and thus maintain a constant loss as they flow through a reach. Mineral nutrient losses occur only if flow is lost within the reach. The pesticide routing approach is the same as described for nutrients. The adsorbed pesticide phase is transported with sediment using the enrichment ratio and the soluble phase is transported with flow in a conservative manner.

The Reservoir Component

A reservoir may be placed at the outlet of any subarea, and inflow is derived from the subarea plus all other contributing subareas. Reservoirs are designed with principal and emergency spillways to accommodate a variety of structures. Typically the principal spillway elevation is set at the top of the sediment pool. The amount of flood storage is determined by the storage volume between the principal and emergency spillways. Sediment and attached nutrients and pesticides are deposited in reservoirs, but soluble materials are considered conservative.

APEX APPLICATIONS

Similar to EPIC and SWAT, the APEX model has continuously evolved since the release of the original version used in the initial phase of the NPP project. The evolution of APEX is briefly chronicled via the key versions of the model listed in Table 1. The first three versions of the model were used within three respective phases of the NPP: the Upper North Bosque River watershed (UNBRW) located in north central Texas, the Lake Fork Reservoir watershed (LFRW) located in northeast Texas, and the Upper Maquoketa River watershed (UMRW) located in northeast Iowa. The other versions have been developed since that time and reflect ongoing improvements to the model, including an enhanced carbon cycling routine, an expanded reservoir component, and a complete streamflow routing submodel. The first APEX user's manual was produced for APEX version 8190 (BRC, 1999); more recent user's manuals have been published for APEX versions 1310 (Williams, et al., 2003), 2110 (Williams et al., 2006) and 0604 (Steglich and Williams, 2008).

The application domain of the model has expanded greatly since the first versions were developed for the NPP and now includes a variety of field-level, whole farm, and watershed-level applications. Documentation is first provided here regarding the range of applications that APEX was used for in the NPP and related projects. Additional discussion is then focused on other applications of the model, including validation studies performed at the plot, field, or watershed scales, which provide important insight into how well APEX has replicated measured data. Previous applications of EPIC, which has been extensively tested and applied for a wide variety conditions in the U.S. and other regions (Gassman et al., 2005), provide a further validation foundation for APEX.

NPP-Related APEX Applications

The APEX model was used for the three previously mentioned NPP projects and two other closely related applications: the Mineral Creek watershed (MCW) located in east

Table 1. Overview of key APEX versions including available documentation

APEX version	Documentation	Comments
5140	-	Original version. Included subarea, routing, & liquid manure routines, & export of output to SWAT. First comparisons with field measurements. Used for NPP UNBRW study in north central Texas.
7045	-	Automatic feedlot manure removal routines introduced. First applications for rotational grazing. Used for NPP LFRW study in northeast Texas.
8190	BRC (1999)	Testing with Iowa tile drainage data. Applied for NPP UMRW study in northeast Iowa.
1310	Williams et al. (2003)	Improved reservoir (including playa lake applications) and forest hydrology subcomponents. Ability to simulate multiple livestock species introduced.
2110	Williams et al. (2006)	Introduction of Century-based carbon cycling submodel. Version used for the National CEAP study (slightly modified).
0604	Steglich and Williams (2008)	Most recent version. Includes complete streamflow routing submodel. Additional reservoir component enhancements. RUSLE2 erosion equation added.
0806	-	64-bit version. Not publically released. Can simulate large numbers of subwatersheds. Being used for Bosque River application in Texas with 15,000 subwatersheds.

central Iowa and the Duck Creek watershed (DCW) located in east central Texas. The associated projects and characteristics of the five watersheds are listed in Table 2. Each of these watersheds was simulated within part or all of the Comprehensive Economic Environmental Optimization Tool – Livestock and Poultry (CEEOT-LP), an integrated economic and environmental modeling system that was developed for the NPP assessments.

The schematic (Figure 1) shows the key data and information flows used in the CEEOT-LP system. The system was initiated with alternative policy and management practice scenarios that were then imposed on both the environmental component, consisting of APEX and SWAT, and the Farm Economic Model (FEM), which was used to estimate economic impacts of the different scenarios. The approach used in the environmental component was to simulate land application of manure in APEX; input the edge-of-field surface runoff, sediment, and nutrient loadings into SWAT at the subwatershed level; and then simulate the subsequent routing of flow

Table 2. Associated project and watershed characteristics for the NPP-related watershed studies

Watershed	Associated Project	Watershed characteristics[a]
Upper North Bosque River (UNBRW)	USEPA NPP	North central Texas, 93,000 ha. Rangeland (43%), woodland (23%), forage fields (23%). Dairy waste application fields (7%). 95 dairies with over 34,500 cows (confined feedlots).
Lake Fork Reservoir (LFRW)	USEPA NPP	Northeast Texas, 127,048 ha. Improved pasture (44%), unimproved pasture (27%), water (9%), woodland (8%). 205 dairies with nearly 32,000 cows.
Upper Maquoketa River (UMRW)	USEPA NPP	Northeast Iowa, 16,224 ha. Corn or soybeans (66%), woodland (9%), alfalfa (7.5%), CRP[b] (4%), pasture (4%). 90 operations with dairy cows, feeder cattle, swine, beef cows, & calves.
Mineral Creek (MCW)	USDA-CSREES 405	East central Iowa. 12,400 ha. Cropland (mix of corn, soybean, & alfalfa: 68%), pasture & CRP (19%), woodland (13%). 33 operations with feeder cattle, swine, & beef cows.
Duck Creek (DCW)	USEPA EI[c]	East central Texas, 39,000 ha. Range (45%), pasture (28%), forest (14%), hayland (9%). 9 operations with 8.5 million broiler chickens.

[a] At the time of the studies.

[b] Conservation Reserve Program (CRP) land.

[c] Full name: "Environmental Issues (EI): The Next Generation."

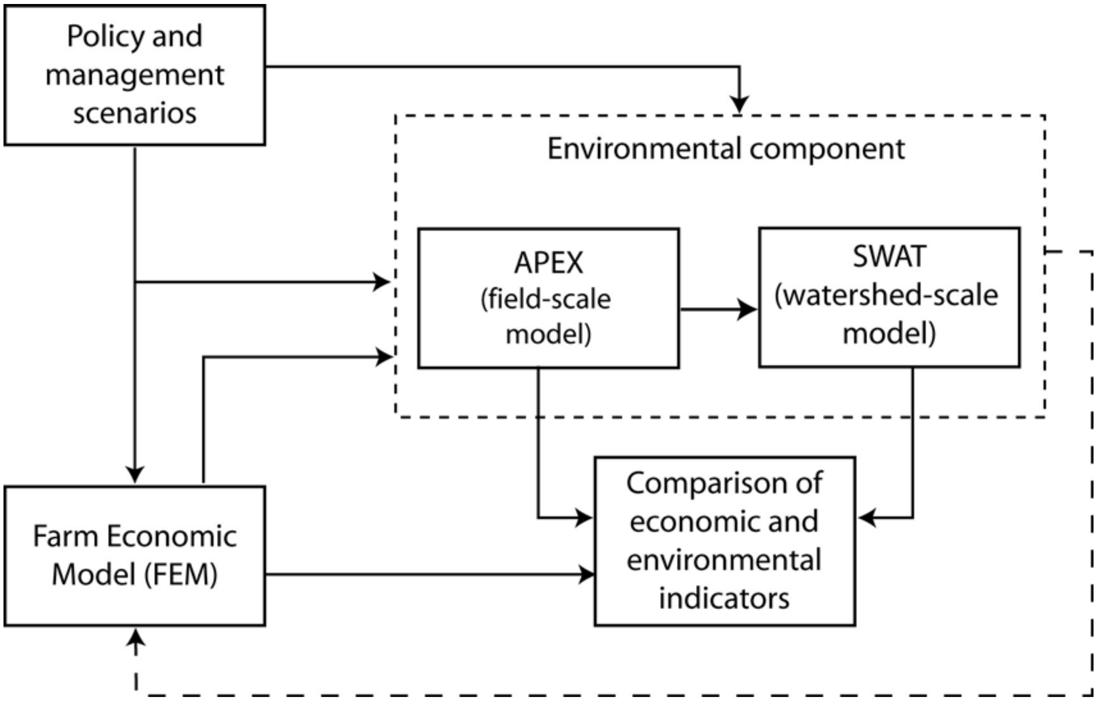


Figure 1. Schematic of the NPP Comprehensive Economic Environmental Policy Tool—Livestock and Poultry (CEEOT-LP)

and pollutant loadings from all source areas through the stream system and ultimately to the watershed outlet. The effects of fertilizer applications, tillage, and other management practices on pollutant loads were also accounted for in either APEX or SWAT as appropriate. Output from SWAT could then be compared with economic indicators generated from FEM; alternatively, APEX output could also be used. Feedback from the environmental component could also be used to adjust FEM. This approach proved adaptable to the three different watersheds studied under the NPP as well as the other two related studies, which contained diverse types of livestock, cropping systems, landscapes, climatic inputs, and/or manure application and other practices.

The following discussion highlights key data inputs, watershed configurations, and calibration/validation results for the five studies, followed by a summary of policy scenario outcomes previously reported for the watershed studies. Previous descriptions of the APEX applications for the three NPP studies are drawn in part from Osei et al., 2000b. They describe the CEEOT-LP system in greater detail, including more in-depth descriptions of the three key models used in the system, the linkages between the three models, and the APEX simulation assumptions. The APEX-SWAT linkages that were initially developed for the UNBRW NPP study are described in further detail in Gassman and Hauck, 1996.

UNBRW Baseline and Scenario Simulation Assumptions

The UNBRW study focused on evaluating alternative manure applications and other management scenarios for 95 dairies (Table 3) that were distributed across the watershed, as shown in Figure 2. Actual herd sizes estimated at the time of the UNBRW study (Table 3) were used to test baseline conditions (referred to as the environmental baseline) for APEX simulations nested in SWAT, to represent as accurately as possible the true nutrient load from the dairies located in the watershed. However, permitted herd sizes (Table 3) obtained from Texas Natural Resource Conservation Commission (TNRCC) dairy permits were used for the policy scenarios to reflect the potential total manure nutrient load that could be land-applied in the watershed.

Table 3. Total herd size distributions by dairy size class for estimated actual and permitted dairy herds in the UNBRW

	Estimated actual herds		Permitted herds[a]	
	Dairies	Cows	Dairies	Cows
Small (0-249)	46	6,669	40	6,979
Medium (250-599)	34	14,309	20	8,740
Large (>600)	15	13,567	34	29.975
Total	95	34,545	94	45,694

[a] Total maximum number of cows in each size category that could have been milked if the full extent of all permits had been utilized at the time of the study (Sources: Osei et al., 2000b; Gassman et al., 2002).

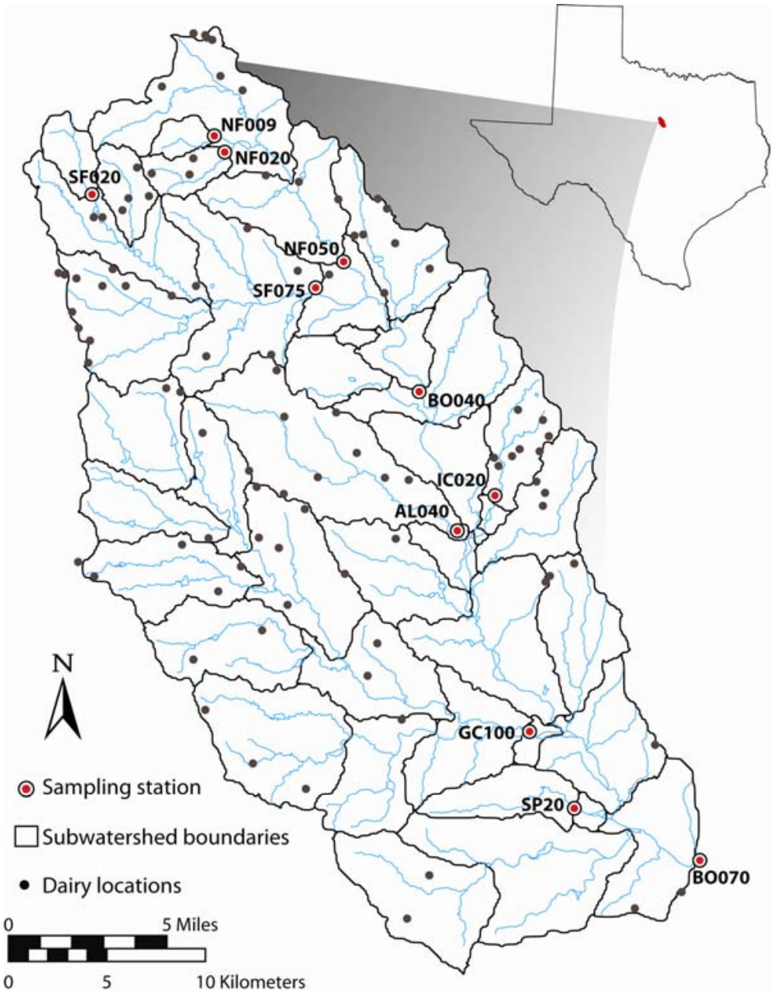


Figure 2. The Upper North Bosque River watershed (UNBRW) located in north central Texas, showing location of the SWAT subbasins, dairy operations, and sampling sites

Representative farm models were developed in FEM for small (225 cows), medium (400 cows), and large (1,200 cows) dairies that represented the size classes of 0-249, 250-600, and >600 cows listed in Table 3.

The development and execution of the APEX manure application scenarios were based on specific data available for the majority of these dairies from TNRCC permits (which had to be filed for dairies with 250 or more cows). The permitted dairies were required to land-apply both liquid and solid manure according to TNRCC regulations. Separate APEX runs were performed for individual liquid and solid manure application fields for each dairy, for both the baseline and policy scenario simulation runs as described in Gassman, 1997; Gassman further discusses reasons why simulation of multiple fields in APEX was found to be unnecessary for the UNBRW study. Table 4 lists the specific categories of permit information, for four example dairies, that were used to define the APEX scenarios. The dairy manure application rates were simulated on a nitrogen (N) basis for the policy baseline (Table 4), determined as a function of TNRCC manure N availability and volatilization loss assumptions as described further in Flowers et al., 1998 and Gassman et al., 2002; both studies also describe phosphorus (P) application rate scenarios developed for the UNBRW study. The resulting total N and P rates applied in the manure were much higher than the corresponding agronomic rates for each cropping system. The assumed timing of manure applications was based on local expert and anecdotal information. All pertinent production costs were accounted for in FEM, as was the total land required for manure application.

UNBRW APEX Calibration/Validation Studies

The testing of APEX within the UNBRW study occurred in three phases: (1) comparisons with measured data collected from field plots, (2) further calibration for baseline conditions, and (3) validation at the watershed level with APEX simulations embedded within SWAT. The first phase compared the model output with surface runoff, sediment loss, and

Table 4. Characteristics of permitted waste application fields for four example UNBRW dairies[a]

		Liquid manure fields			Solid manure fields		
Dairy	Herd Size	Crop type	Soil type	Acres	Crop type	Soil type	Acres
6	400	coastal bermuda	WoB2	30	coastal/wheat[b]	Wob	91
					sorghum/wheat[c]	DuC2	30
7	100	coastal/wheat	WoB	7	Sorghum	DuC2	6
					coastal bermuda	WsC2	21
					coastal bermuda	DuC2	7
					coastal bermuda	DuC2	14
8	250	coastal bermuda	BdC	78	coastal bermuda	WoB2	360
10	500	coastal/wheat	WoB2	51	sorghum/wheat	WoB2	37
					sorghum/wheat	WoB2	45
					coastal bermuda	WoB2	53
					coastal bermuda	WoB2	128
					coastal bermuda	WoB2	34
					Sorghum	WoB2	60
					coastal bermuda	WoB2	40
					Sorghum	Pd	80

[a] Source: Osei et al., 2000b.
[b] coastal/wheat = coastal bermuda overseeded with winter wheat.
[c] sorghum/wheat = sorghum double-cropped with winter wheat.

nitrogen and phosphorus data collected from eight plots ranging in size from 0.01 to 0.52 ha in Erath County, Texas (Flowers et al., 1996). Six of the eight plots were established on existing cropland dairy waste application fields, while the other two were installed as a cropfield/filter strip combination on a hay production operation (with limited cattle grazing). The fields were monitored for periods that ranged from roughly one year to 17 months between December 1993 and August 1995. Three of the fields (plots FP001, FP002, and FP006) received irrigated dairy wastewater applications that ranged between 94 and 586 mm during the monitored periods. Solid dairy manure applications were applied to the other five field plots.

Figures 3 through 5 show comparisons of simulated cumulative surface runoff, total nitrogen losses, and total phosphorus losses versus corresponding measured values reported by Flowers et al. (1996) for the eight test plots. These results indicate that the APEX predictions

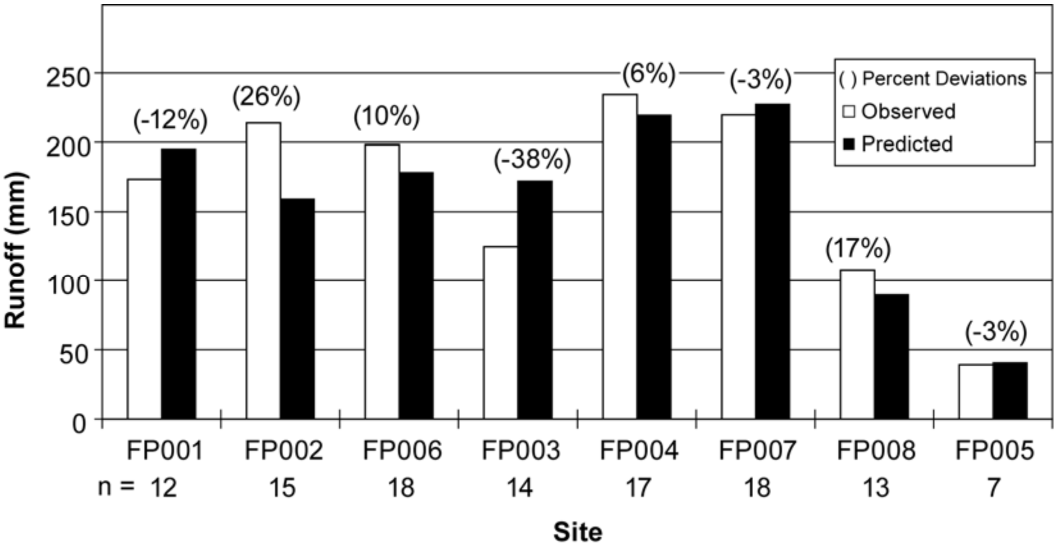


Figure 3. Comparison of predicted to observed cumulative runoff for UNBRW APEX plot-level testing (Source: Flowers et al., 1996)

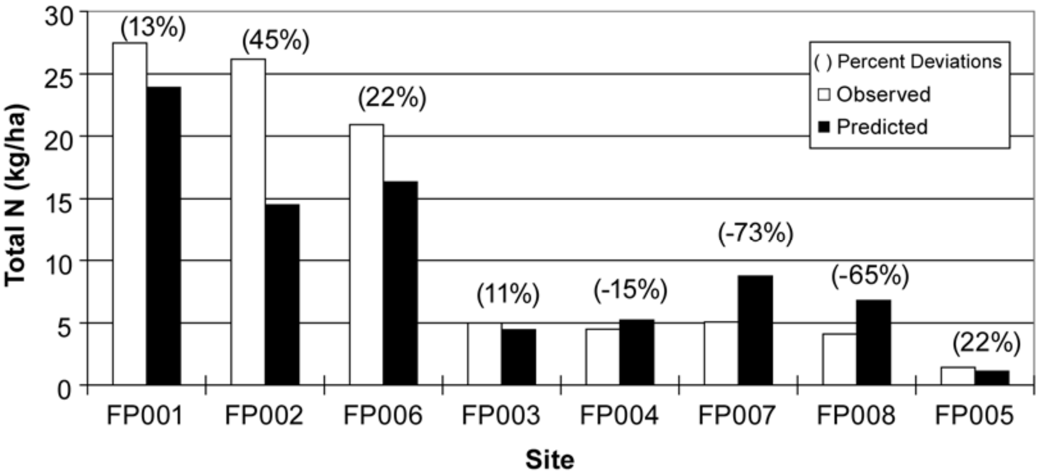


Figure 4. Comparison of predicted to observed cumulative total nitrogen loss for UNBRWAPEX plot- level testing (Source: Flowers et al., 1996)

were generally consistent with the total measured amounts of each indicator, and similar results were found for other indicators. The overall cumulative ranking of each simulated field plot, determined on the basis of summing up the individual estimates of surface runoff, sediment loss, and nutrient loss rankings, were very similar to the order of total runoff, sediment losses, and nutrient losses observed across the eight monitored plots. Flowers et al. (1996) concluded that APEX was an appropriate tool for assessing the relative response of nutrient losses and other

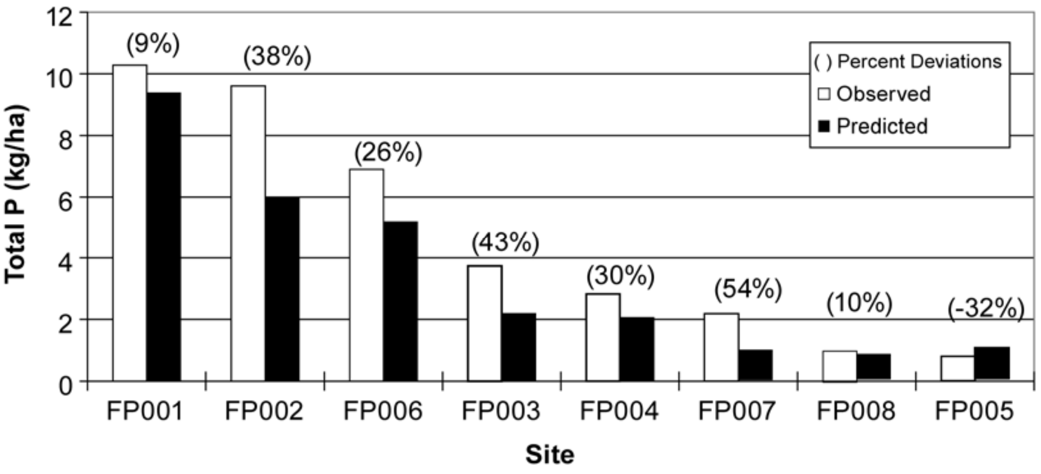


Figure 5. Comparison of predicted to observed cumulative total phosphorus loss for UNBRW APEX plot-level testing (Source: Flowers et al., 1996; Osei et al., 2003a)

indicators for the array of several hundred dairy waste application fields located in the UNBRW. Further details regarding the results of the study, including additional comparisons between APEX predictions and measured values, can be obtained in their report.

Gassman (1997) conducted a second UNBRW APEX calibration study to test the model for conditions incorporated in the environmental baseline. Measured data were not available to test APEX directly for this phase of the study, so target crop yields used in FEM were used as a basis for calibrating the model. Key assumptions and input data used in the UNBRW baseline simulations are reported, including tillage practices, solid manure application methods and rates, simulated capture of feedlot manure nutrient runoff by waste storage ponds (lagoons) and subsequent land application of the pond effluent, soil data, and climate data. Extensive graphical and/or tabulated results are reported for a variety of hydrologic, nutrient loss and cycling, and crop yield indicators.

The third phase of UNBRW testing was reported by Saleh et al. (2000), who performed the previously mentioned environmental baseline by executing APEX simulations for the dairy waste application fields and then inputting the APEX output into SWAT, which was then used to route surface runoff and pollutant losses from other areas in combination with the APEX inputs to the watershed outlet. The predicted streamflows and pollutant levels were compared with measured data collected at 11 monitoring sites (Figure 2) during a 22-month period between October 1993 and August 1995. Both graphical and statistical evaluations of the simulated output were performed, including computation of Nash-Sutcliffe model efficiency (NSE) statistics (Nash and Sutcliffe, 1970). Values of NSE can range from $-\infty$ to 1 and indicate how accurately simulated values fit corresponding measured data on a 1:1 line. An NSE value of 1 indicates a perfect fit between the model and the measured data. However, the mean value of the measured data would be considered a more accurate predictor than the simulated output if the NSE value is 0 or less. Calibration and validation NSE statistics were computed for monthly comparisons between simulated and measured streamflows, sediment losses, nitrogen (organic, nitrate, and total) losses, and phosphorus (organic P, PO_4-P, and total P) losses. The majority of the NSE statistics ranged from 0.54 to 0.99, indicating that the nested modeling approach accurately tracked most of the measured streamflows and pollutant losses. Additional details of the environmental baseline testing results are provided in Saleh et al. (2000).

Saleh and Gallego (2007) also tested the same nested modeling system within the automated APEX-SWAT (SWAPP) automated GIS interface using data collected from January 1994 to July 1999 at the UNBRW outlet and two other monitoring sites. The computed NSE values between the predicted and measured streamflow, sediment yield, and nutrient loadings ranged from 0.65 to 0.74, 0.55 to 0.74, and -0.04 to 0.88, respectively, with all values exceeding 0.69 at the watershed outlet. Further description of SWAPP is given in the GIS interface section.

LFRW Baseline and Scenario Simulation Assumptions

Dairy production was also extensive in the LFRW, dominated by pasture-based dairies that were considerably smaller than the UNBRW dairy operations as shown by the herd size categories in Table 5. The LFRW dairy milking herd sizes were obtained from the Texas Department of Health (TDH) or estimated from other sources. The distribution of the 205 dairy

Table 5. Mean LFRW herd sizes, pasture acreages, and hayfield acreages by dairy size category

Dairy Category	Herd size range	Total dairies in category	Mean total herd Size	Mean pasture acreage (ac)	Mean hayfield acreage (ac)
Very small	< 101	85	91	34.6	12.7
Small	101 – 200	93	156	76.9	18.7
Medium	201 – 300	16	257	100.2	36.0
Large	> 300	11	500	225.0	85.0

Sources: Osei et al., 2003b; Gassman et al., 2002.

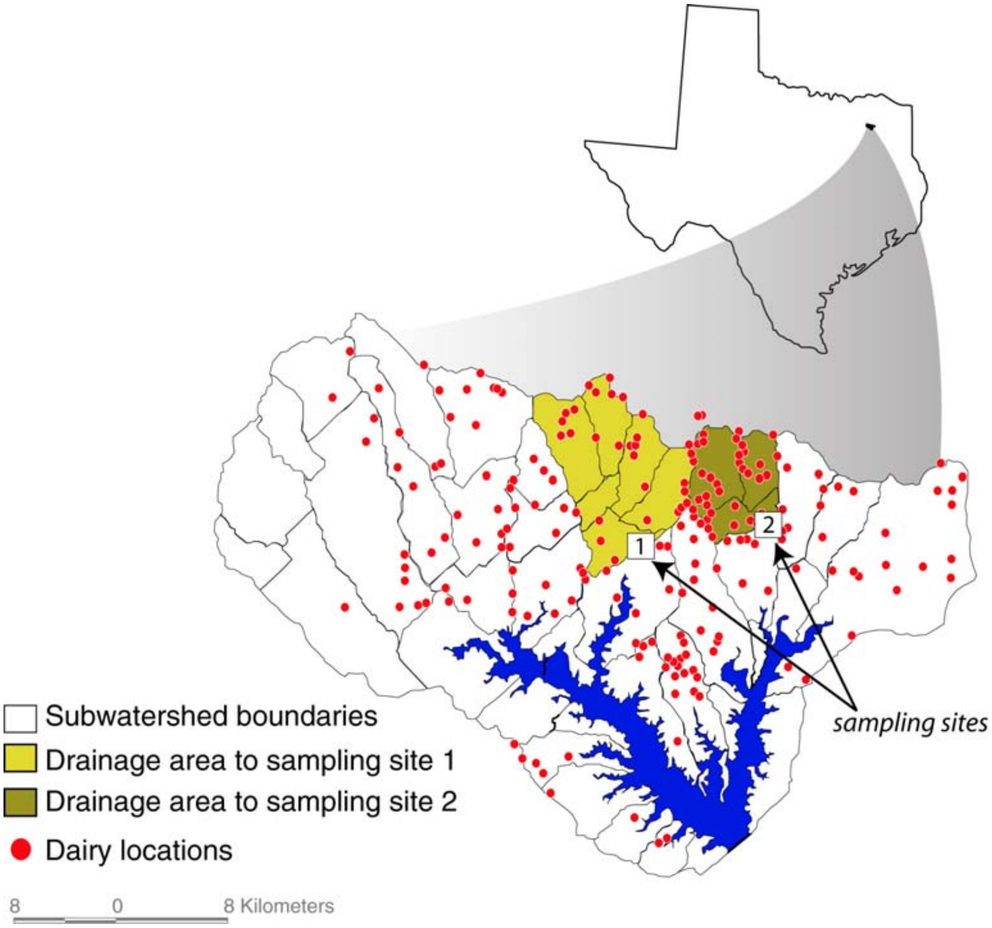


Figure 6. The location of the Lake Fork Reservoir Watershed (LFRW) in northeast Texas, including sampling sites and producer locations

operations across the LFRW is shown in Figure 6, along with the location of two monitoring sites that were used to collect a limited number of pollutant loss samples. Detailed permit information was not available for these smaller dairies, in contrast to the data accessible for the UNBRW dairies. Thus, a more generic approach was developed to configure the LFRW APEX simulations of land-applied solid and liquid manure.

Typical LFRW dairy operations were managed with Open Access Grazing (OAG; Figure 7) with milking and dry cow herds maintained on separate pastures, milking parlor effluent (stored in waste storage ponds) periodically applied via irrigation to hay fields, and additional hayland managed just with fertilizer. Accurate estimates of individual dairy pasture and hayfield acreages were unavailable at the time of the study. Thus, algorithms were developed to generate baseline pasture and hayfield acreage estimates for each dairy as a function of mean total herd sizes, pasture acreages, and hayfield acreages that were provided by the Texas State Soil and Water Conservation Board (TSSWCB) for the four different dairy size classifications listed in Table 5.

Milking cows were assumed to split time between the milking parlor and milking herd pasture as shown in Figure 7; manure deposition in the two areas was adjusted accordingly (the milking parlor area was simulated essentially as feedlots in APEX). A greater amount of manure (factor of three) was

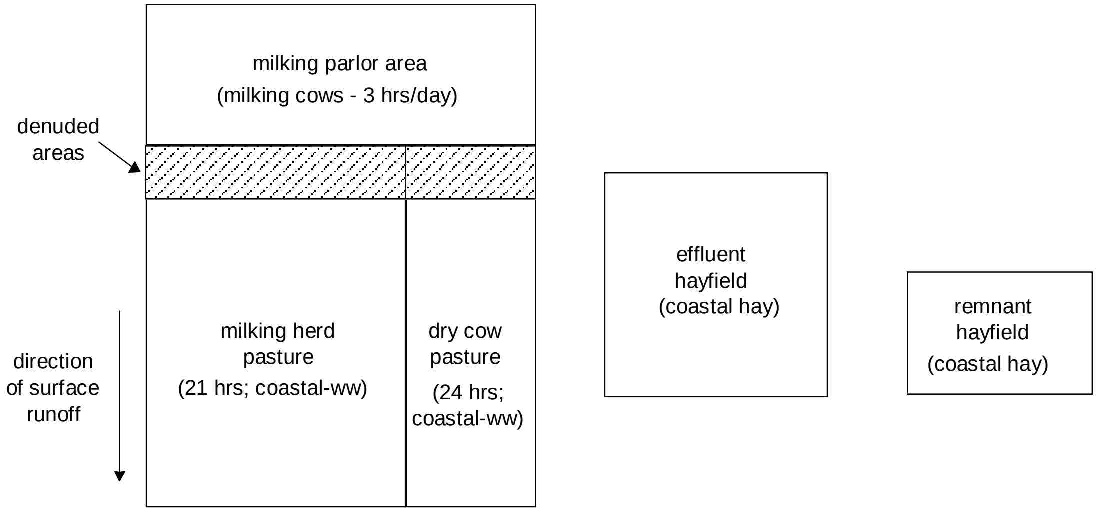


Figure 7. Baseline APEX scenario for each LFRW dairy showing milking cow and dry cow pastures (coastal bermuda overseeded with winter wheat) with associated denuded areas, plus the effluent hayfield (coastal bermuda hay) where the milking parlor waste water is applied to and the remnant or excess hayfield that is managed only with commercial fertilizer; e.g., receives no waste water or other manure applications (Source: Osei et al., 2000b)

assumed to be deposited in the heavily trampled, unvegetated “denuded areas,” which covered 5% of both the milking herd and dry cow pastures and represented standard feeding and watering areas that are characterized by consistently higher densities of cows. Routing of flow, sediment, and nutrient losses were simulated from these upslope erosion-prone areas onto the main milking herd and dry cow pastures. No other routing was simulated between any of the pastures and hayfields. Thus, four separate APEX simulations were performed for each individual pasture and hayfield. The output of all the APEX runs simulated within a given SWAT subwatershed were aggregated and inputted into SWAT in the same manner as previously described.

Policy scenarios were performed with APEX for the LFRW by modifying the basic scenario shown in Figure 7. Adjustments of cow stocking rates on pastures, to reflect manure deposition at different manure nutrient application rates, were performed by simply expanding or contracting the baseline pasture acreages as needed. A similar procedure was used for adjusting application rates for the effluent hayfields.

More complex routines were required for two alternative grazing scenarios performed with APEX, referred to as Grassed Loafing Lots (GLL) and Intensive Rotational Grazing (IRG). For example, each milking herd pasture was split into 30 paddocks for the APEX IRG scenario (Figure 8). The goal of this rotational scheme is to manage pasture grasses in such a way as to avoid overgrazing and associated denuded areas, which is reflected in the assumption that no denuded areas were present for the milking cow pastures (Figure 8). The assumption of better grass management was also simulated for the dry cow pastures, which were simulated with the baseline OAG approach but without denuded areas. It was assumed under IRG that the milking cows grazed each paddock for only one day before being rotated to the next paddock. Also, the grazing rates simulated per cow reflected the assumption that a much higher percentage of each cow’s daily feed intake was obtained directly from the pasture (a key goal of the IRG approach), as compared to the OAG and GLL scenarios. Commercial N fertilizer was assumed to be

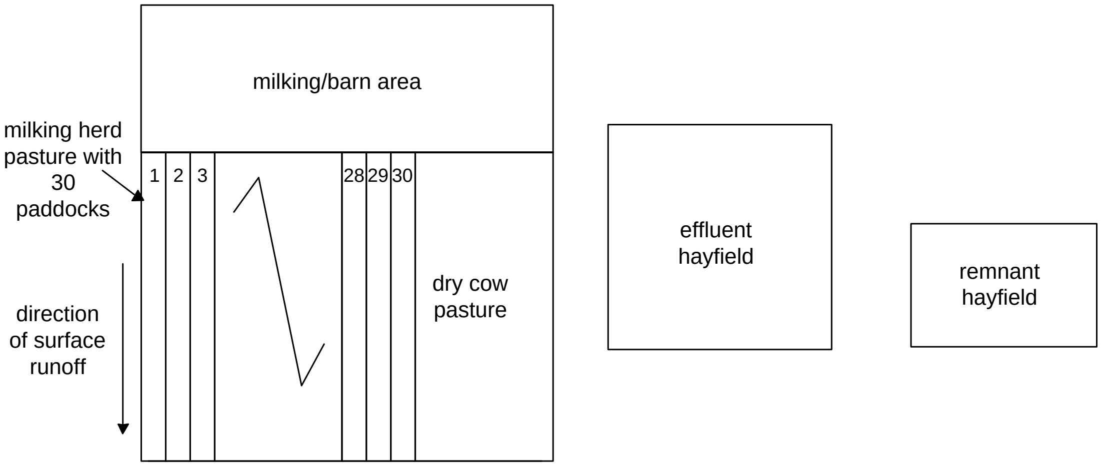


Figure 8. Schematic of the LFRW Intensive Rotational Grazing (IRG) scenario simulated in APEX (Source: Osei et al., 2000b)

applied at a rate that was slightly more than twice that for OAG in order to produce the required forage levels under IRG. Management of the hayfields was identical to that simulated for baseline conditions.

Another key LFRW APEX scenario was the insertion of filter strips planted in coastal bermuda grass below each pasture and hayfield (Figure 9). The focus of this scenario was to simulate the impact of the filter strips in reducing sediment and associated nutrients contained in surface runoff (full filter strip effects on solution phase nutrients could not be simulated with apex7045). Guidelines developed by the USDA Natural Resources Conservation Service (NRCS) were used in configuring the appropriate widths of the filter strips.

LFRW APEX Calibration Results

Streamflow data was available for the LFRW from 1978 to 1989 at sampling site 1 shown in Figure 6. Pollutant monitoring data available for the LFRW was very sparse as compared to what had been collected in the UNBRW. Sediment and/or nutrient data were collected at five sites in uneven intervals during 1994-96, but only data collected at sampling site 2 (Figure 6) was useful for model testing. A 30-year baseline simulation, with APEX simulations nested within SWAT subwatersheds (as previously described for the UNBRW), was executed from 1967 to 1996. Flow calibration was performed

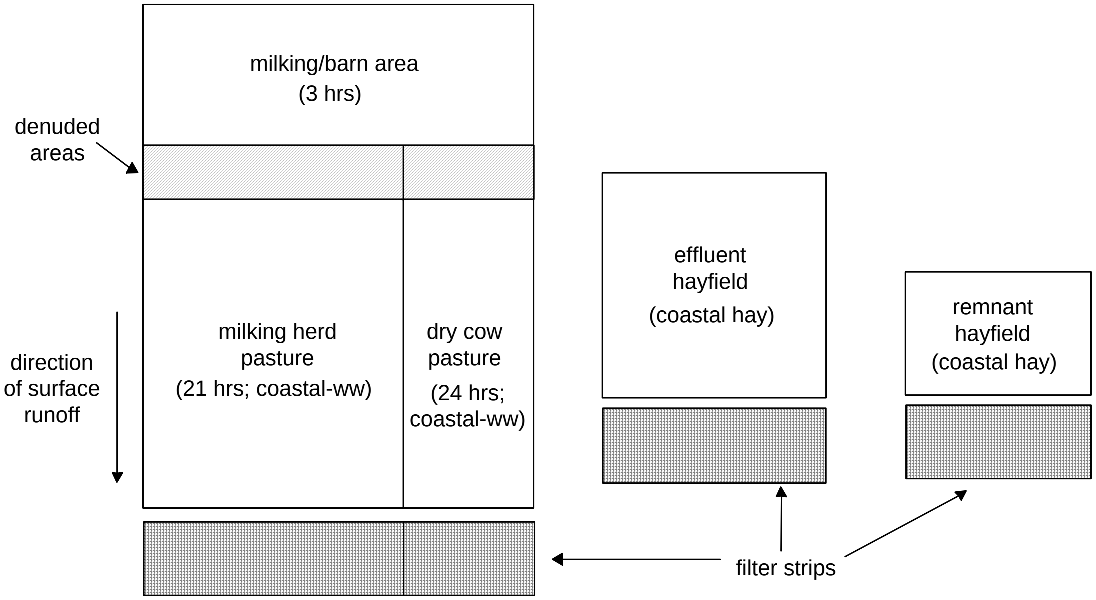


Figure 9. Schematic of the LFRW filter strip scenario simulated in APEX (Source: Osei et al., 2000b)

within the baseline simulation by comparing model output with measured streamflow values at sampling site 1 during the 1978 to 1989 period. Similar comparisons were made with measured nutrient and sediment loss data collected at sampling site 2 from 1994 to 1996.

Evaluation of the APEX/SWAT predicted streamflow was performed by Neitsch (1998) using both graphical and statistical comparisons, including the previously described Nash-Sutcliffe modeling efficiency (E) statistic and the coefficient of determination (r^2). The r^2 measures how well the simulated versus observed regression line approaches an ideal match and ranges from 0 to 1, with a value of 0 indicating no correlation and a value of 1 representing that the predicted dispersion equals the measured dispersion (Krause et al., 2005). The regression slope and intercept also equal 1 and 0, respectively, for a perfect fit; the slope and intercept are usually not reported for most studies. The resulting annual E and r^2 values were 0.76 and 0.79 while corresponding values of 0.58 and 0.59 were computed for the monthly comparisons. These statistics indicate that the APEX/SWAT modeling system accurately replicated the LFRW streamflow at sampling site 1. Further comparisons of simulated versus measured mean streamflow, nitrate (NO_3), soluble P, total P, and sediment (Table 6) show that the model simulated the

Table 6. Mean values of key measured and simulated water quality indicators for the LFRW

Indicator	Site[a]	Number of observations[b]	Measured[c]	Simulated[c]
Flow (m^3s^{-1})	1	133	0.67	0.73
NO_3 (mg liter^{-1})	2	31	2.46	2.93
Soluble P (mg liter^{-1})	2	32	0.27	0.44
Total P (mg liter^{-1})	2	32	0.67	0.47
Sediment (mg liter^{-1})	2	30	112	64

Source: Osei et al., 2003b.

[a] See Figure 1 for location of sites 1 and 2.

[b] Monthly streamflow values were measured between September 1978 and September 1989 at site 1; nutrient and sediment measurements were performed between 12 April 1994 and 11 November 1996.

[c] Standard deviations for observed and simulated flows were 0.875 and 0.703; other standard deviations not reported.

general pollutant loss trends well for most of the indicators. The weakest predictions occurred for sediment, which was underpredicted by a factor of almost two.

UMRW Baseline APEX Scenarios

The Upper Maquoketa River Watershed (UMRW) is located in northeast Iowa in the upper reaches of the Maquoketa River watershed (Figure 10). The UMRW was characterized by mixed livestock production and cropping systems dominated by corn and soybean production at the time of the study (Table 2). The majority of cropland was also determined to be drained with subsurface tile drains, which are key sources of nitrate to the watershed stream system. The UMRW livestock herd sizes (Table 7) were determined through a combination of personal observation and interviews with producers and local experts (Rodecap, 1999). A total of 90 operations were identified as having dairy, swine, beef cows, feeder cattle, or calves and heifers, and several operations had two or more types of livestock. Some of the smaller herd sizes reflect the fact that manure generated by some operations was primarily land applied outside of the watershed boundaries, which required an adjustment to the UMRW-equivalent herd size to more accurately account for manure nutrient inputs in the watershed. The distribution of livestock operations and water quality sampling sites are shown within the UMRW in Figure 20.

Similar to the LFRW, generic APEX configurations were developed in consultation with Rodecap (1999) to perform the UMRW baseline and policy scenarios. Five different types of scenarios had to be developed to cover the required simulation runs: dairy, beef cattle, swine open lot or feeder

Table 7. Distribution of UMRW livestock operations and herd sizes

Livestock type	Number of Operations	Herd size range
Dairy	42	12 – 135
Swine	22	100 - 10,800
Beef cattle	14	6 – 100
Feeder cattle	22	2 – 250
Calves/heifers	5	7 – 40

Source: Gassman et al., 2002.

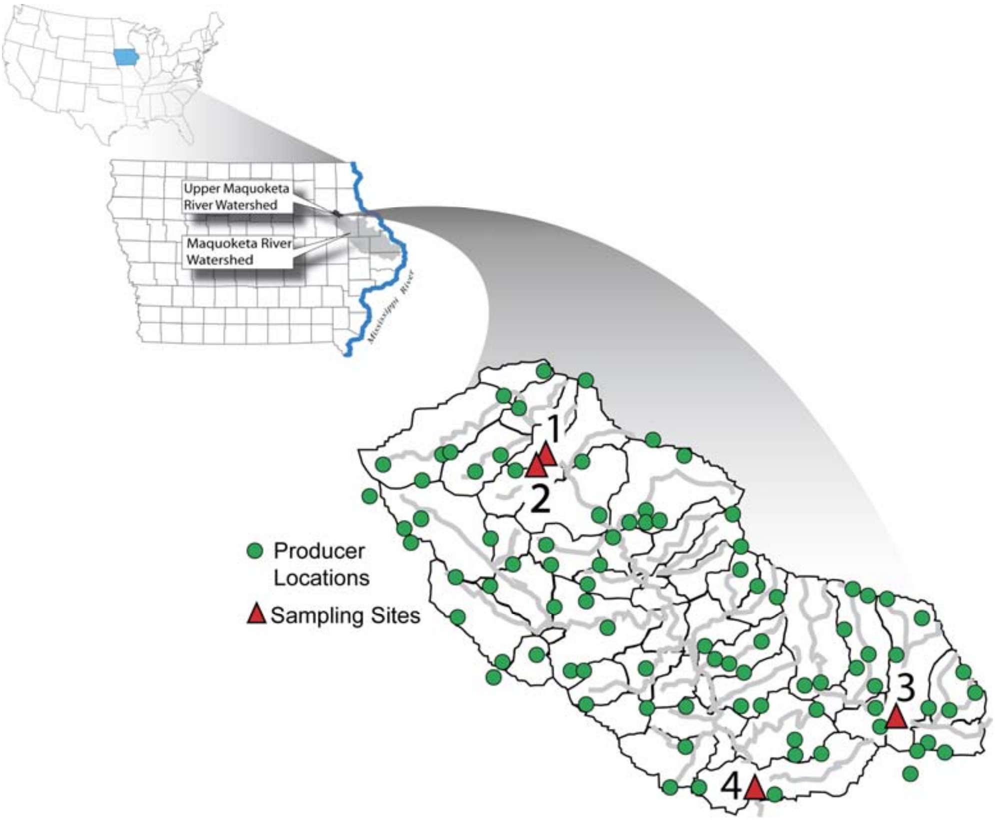


Figure 10. The location of the Upper Maquoketa River watershed (UMRW) in northeast Iowa, including sampling sites, producer locations, and SWAT subwatershed boundaries

cattle, swine confinement, and calve/heifer grazing. Mixed livestock farms were redefined as single livestock species operations, because APEX8190 was not capable of simulating multiple livestock types in a single run. However, a "composite manure" that accounted for the relative manure contribution of all livestock on the farm was used for each multi-livestock operation.

An example APEX configuration constructed for the UMRW dairy simulations is shown in Figure 11, which was based on a tie-stall dairy production system that was the dominant dairy management method used at the time of the study. It was assumed for this system that the milking cows were maintained on open lots during the summer period (April 16 to October 15), except for the four hours each day that they were milked in the milking barn. In winter (October 16 - April 15), the milking cows were assumed to be kept in the milking barns the entire time. The replacement cow herd (younger calves and heifers), assumed to be the same size as the milking cow herd, were kept on an open lot throughout the winter period. In summer, it was assumed that the one-third of the replacement cows were managed on pasture using OAG.

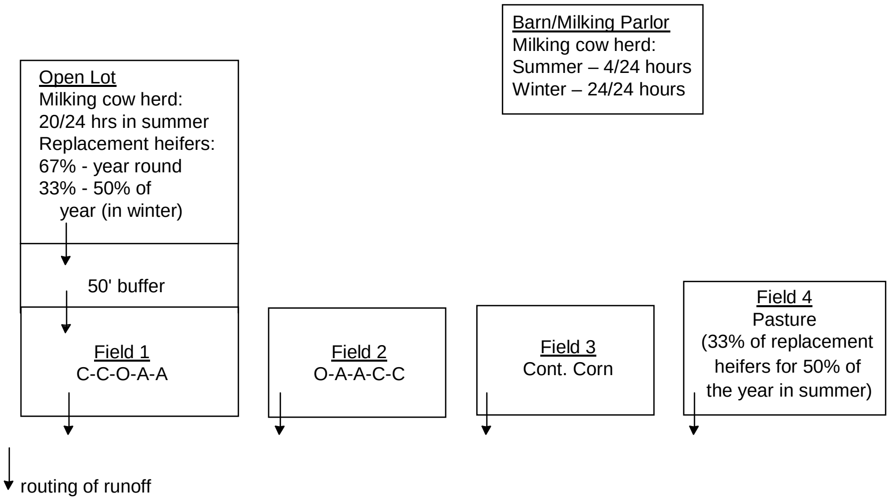


Figure 11. Schematic of a baseline UMRW dairy simulation. The barn/milking parlor was not actually simulated in APEX; manure was assumed scraped from this area, stockpiled, and later land-applied. The CCOAA rotation in field 1 was a five-year rotation of corn-corn-oats-alfalfa-alfalfa. The field 2 rotation is a variant of field 1. Routing of flow and pollutants was simulated from the open lot across the 50-foot-wide grass buffer to field 1 (Source: Osei et al., 2000b)

Routing of flow and pollutants was simulated from the open lot across the 50-foot-wide grass buffer to field 1, which was managed with a five-year rotation of corn-corn-oats-alfalfa-alfalfa (variant of the rotation was grown in field 2). Simulation of all subareas (crop fields, open lots, pastures, etc.) was performed in a single APEX run, as opposed to the previous approach of executing each field or pasture system separately for the UNBRW and LFRW. Similar but less complex generic operations were used to depict the swine and cattle feeder open lot, swine confinement, beef cattle, and calves and heifers operations. The APEX output was aggregated together from each subarea simulated for a livestock operation and then input into SWAT in a manner similar to that performed for the UNBRW and the LFRW.

Both a 10-year environmental baseline, used to compare in-stream concentrations predicted with SWAT against monitoring data, and a 30-year policy baseline were run for the UMRW. The majority of the policy scenarios performed for the UMRW did not require modification of the generic APEX configurations, although adjustment of field sizes and creation of additional fields were required in order to execute some of the manure application rate scenarios. Adjustments were also needed for a scenario depicting the introduction of swine hoop structure production systems. Additional details regarding the APEX generic livestock operations and modeling assumptions for the baseline and scenario simulations are given in Osei et al., 2002, Gassman et al., 2002, and/or Gassman et al., 2006.

UMRW APEX Calibration Results

Calibration efforts in the UMRW focused on testing APEX simulations of tile flow and nitrate losses (Gassman et al., 2006) because of the importance of nitrate discharge via tiles to the Maquoketa River. Comparisons were performed between average monthly and simulated tile flows and nitrate losses for a total of 432 months of data collected at two research sites near Nashua, Iowa, and Lamberton, Minnesota (Figure 12), because of a lack of data in the UMRW. These sites represented several different combinations of cropping and/or tillage systems, as described by Chung et al. (2001, 2002). The overall r^2 values computed for the average monthly tile flow and tile nitrate loss comparisons were 0.70 and 0.63, respectively. These results indicated that APEX could reasonably replicate observed tile flow and nitrate loss trends for tile-drained cropping systems in the upper Midwest. However, the results also indicated a need for additional testing to improve and refine the simplistic tile drainage approach used in APEX.

Additional indirect testing of APEX was performed by comparing SWAT output (with nested APEX simulations) with a set of six-month average streamflows, sediment loss, and nutrient loss data measured at the UMRW outlet, the only in-stream measured data available at the time of the study

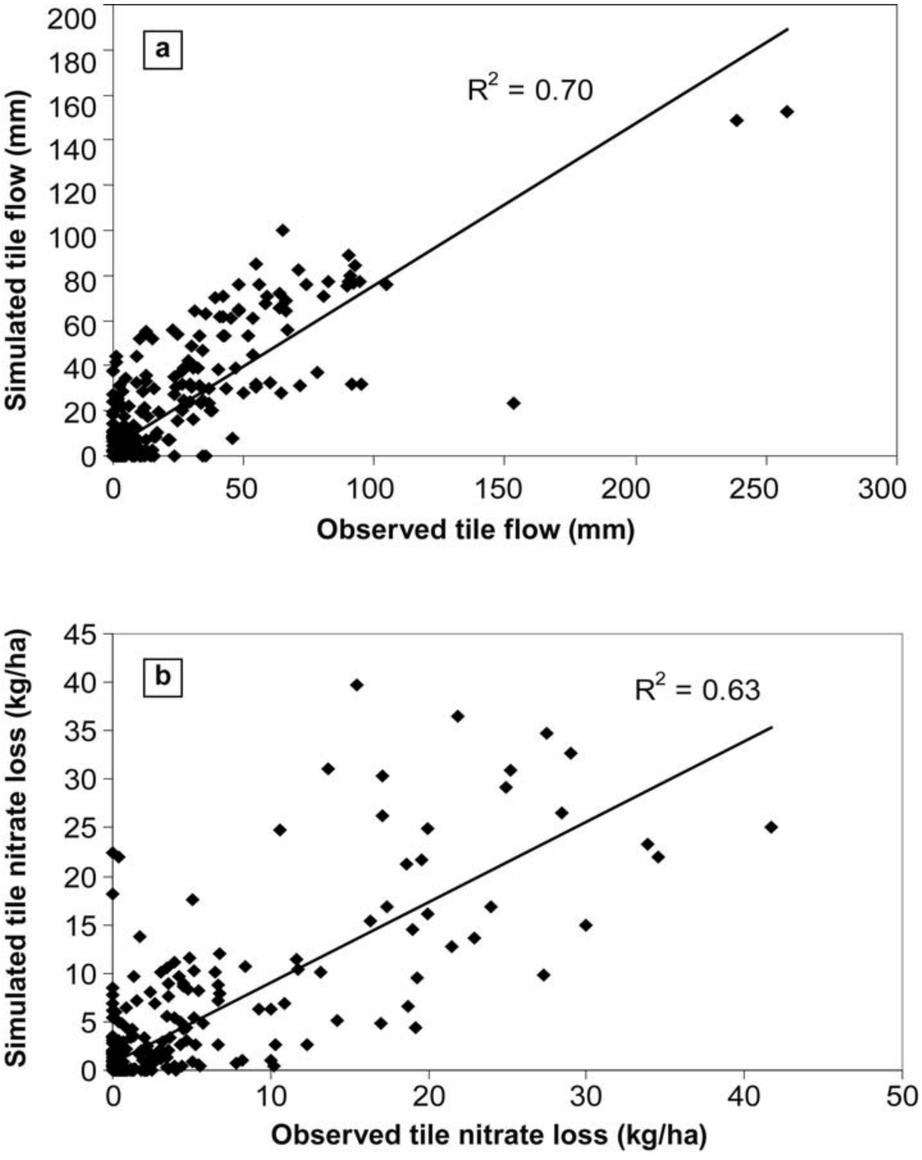


Figure 12. Comparisons of APEX output versus measured data for (a) subsurface tile drainage flows and (b) subsurface tile drain nitrate losses, for 432 average monthly values for a range of cropping and/or tillage systems studied at two research sites near Nashua, Iowa, and Lamberton, Minnesota (Source: Gassman et al., 2006)

(Gassman et al., 2002). The results of this limited testing provided further indication that the combined models could adequately simulate streamflows and pollutant losses in the watershed. More in-depth testing of the combined APEX-SWAT modeling system by Saleh et al. (2003) for January 1999 to December 2001 resulted in r^2 values 0.79 and 0.74 for streamflow and nitrate at the UMRW outlet, but weaker streamflow and nitrate r^2 statistics ranging from 0.39 to 0.51 and 0.24 to 0.42, respectively, for the other three sampling sites (Figure 11). An additional study using just SWAT (Reungsang et al., 2007) resulted in more accurate monthly and annual streamflow and nitrate estimate trends over a three-year period at the UMRW outlet. This second study implied that more accurate rainfall data was needed in order to obtain the best possible results for simulating streamflow and nitrate losses in the UMRW.

Mineral Creek Watershed APEX Application

The Mineral Creek Watershed (MCW) covers slightly more than 12,400 ha and is also located within the MRW in eastern Iowa (Figure 13). A total of 33 operations were identified as having one or more types of livestock at the time of the study (Table 2), with the livestock mix consisting primarily of swine, feeder cattle, and beef cows that were distributed across the watershed, as shown in Figure 14. Similar to the UMRW, the cropland is dominated by corn and soybean production (Table 2) and is underlayed by subsurface tile drains in much of the cropped area, especially in the central portion of the watershed. However, there is more pasture and woodland in the MCW as compared to the UMRW (Table 2), much of which is located in the western and eastern ends of the watershed. The livestock operations were simulated in APEX using the same generic configurations that were developed for the UMRW study. No dairies were present in the MCW at the time of the study.

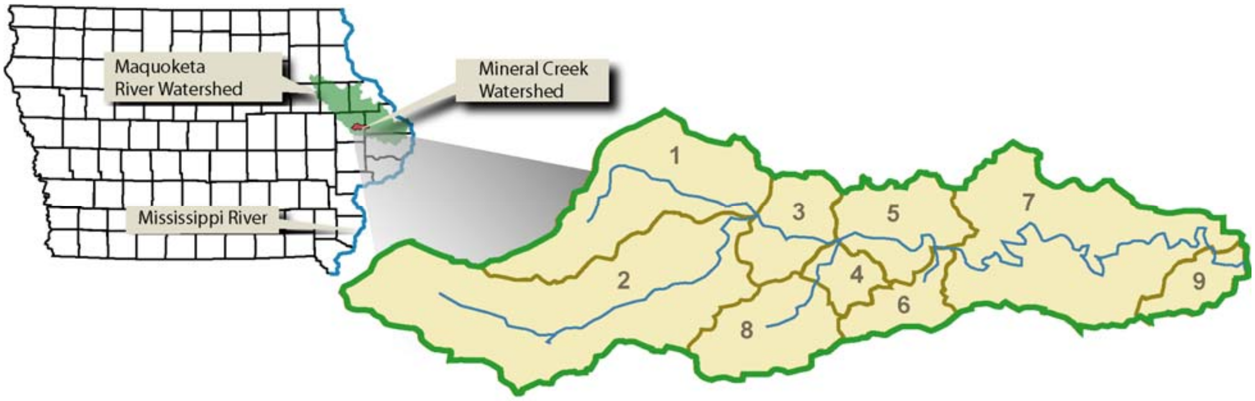


Figure 13. Location of the Mineral Creek watershed (MCW) within the Maquoketa River watershed, and the boundaries of the nine subwatersheds used for the SWAT simulations (Source: Gassman et al., 2003)

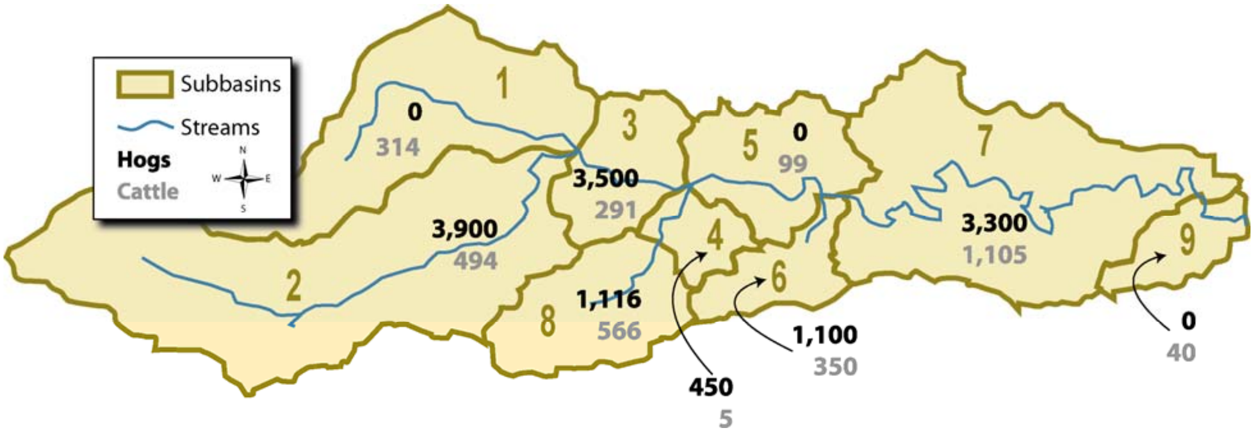


Figure 14. Total number of estimated hogs and cattle by subwatershed within the MCW (Source: Gassman et al., 2003)

Measured data were not available in the MCW to test APEX, either directly or indirectly. However, some assessment of model performance was made by comparing the APEX-SWAT predicted 30-year average nitrate losses at the MCW outlet versus average nitrate losses measured at the outlets of the UMRW and the Sny Magill Creek watershed (SMCW), a relatively unimpacted stream system in northeast Iowa. The predicted MCW nitrate losses fell between the measured levels in the other two watersheds (Table 8), which is consistent with expectations, considering the greater amount of livestock and cropland in the UMRW and less intensive agricultural production in the SMCW. Gassman et al. (2003) provide additional details regarding the watershed description and modeling assumptions.

Table 8. Comparison of APEX-SWAT predicted average annual nitrate concentrations at the MCW outlet versus corresponding reference nitrate concentrations measured at the outlet of two other watersheds in northeast Iowa

Watershed[a]	Nitrate (mg/l)	Comments
UMRW	10.8	Measured: 1999-2001; greater manure/fertilizer inputs
MCW	7.8	30-year simulation average; less intensive agriculture than the UMRW but more intensive than SMCW
SMCW	2.7	Measured: 1990-2000; less agriculture and less impacted

[a] UMRW = Upper Maquoketa River watershed; MCW = Mineral Creek watershed; SMCW = Sny Magill Creek watershed.

Duck Creek Watershed APEX Application

The Duck Creek watershed (DCW) covers over 39,000 ha within the Navasota River watershed (NRW) in east central Texas (Figure 15) and is dominated by grassland in the form of range, pasture, and hayland (Table 2). Bahiagrass was the most common warm-season grass utilized for pasture at the time of the study, which was typically overseeded by ryegrass or clover for winter cover. Hayland was usually planted with coastal bermuda grass. A total of 14 broiler operations were located in or near the DCW at the time of the study. Nine operations located within the boundaries of the DCW grew over 8 million broilers annually (Table 9). Broiler litter was typically removed via both cakeouts (partial cleanouts) after the first five broiler flocks and a complete annual cleanout after the sixth flock (see Table 9 footnote). Application of broiler litter nutrients to hayfields and/or pastures was simulated in APEX for each cakeout or cleanout that occurred for each operation. Most of the broiler operation owners also grazed beef cattle at low stocking rates on pasture land; nutrient deposition from the grazing cattle on the pastures was also accounted for in the APEX simulations.

Indirect testing of APEX was performed in the DCW study by comparing baseline SWAT output, with embedded APEX simulations, at sampling site 1 (Figure 15) near the outlet of the watershed. Comparisons of predicted and measured concentrations for sediment and four nutrient indicators,

Table 9. DCW broiler chicken and associated litter production assumptions

Number of operations	Number of houses	Total annual chicken production per operation[a]	Total annual litter production per operation (t) from cakeouts[b]	Total annual litter production per operation (t) from cleanouts[b]
3	4	660,000	176	706
4	6	990,000	265	1,058
2	8	1,320,000	353	1,411
Totals				
9	52	8,580,000	2,293	9,173

Source: Gassman et al., 2001.

[a] Based on an initial flock size of 27,500 chickens for each of six flocks produced annually; the total actual chickens produced is approximately 8.28(10^6) because of an assumed 3.5% mortality rate.

[b] Cakeouts are partial litter removals from broiler houses that are performed after shipment of the first five flocks in a one-year period. Cleanouts are complete removals of broiler litter that are conducted after shipment of the sixth flock in a one-year period.

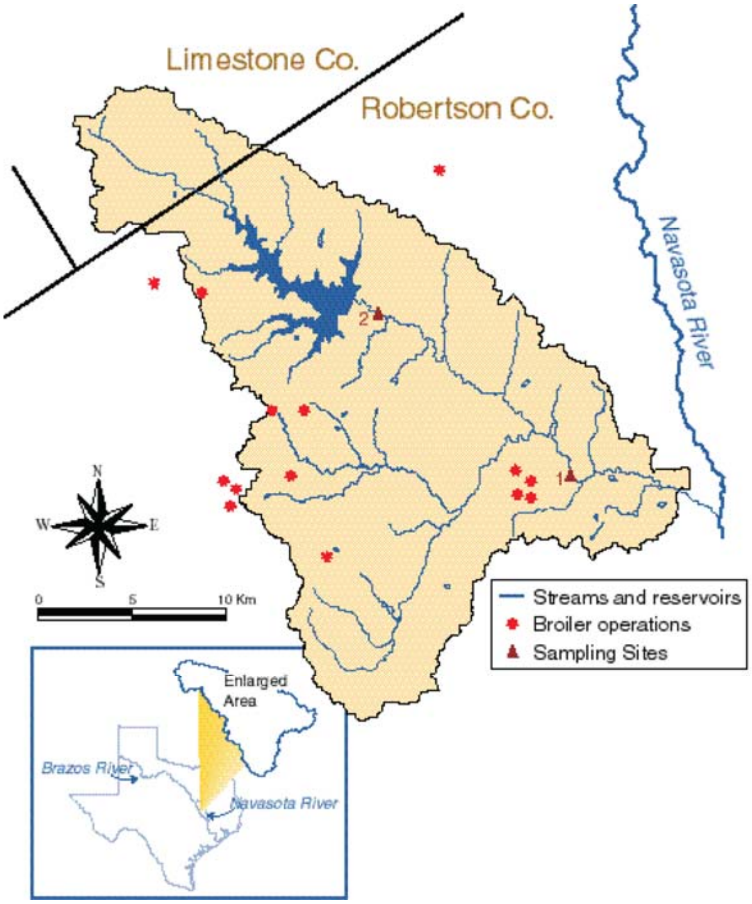


Figure 15. Location of streams and reservoirs, broiler operations, and water quality sampling sites within the Duck Creek watershed (DCW), and location of the DCW relative to the Navasota River and Brazos River (Source: Gassman et al., 2001)

averaged across 48 days that in-stream samples were collected on, are shown in Table 10. The results show the APEX-SWAT modeling system replicated the measured concentrations with acceptable accuracy for all of the indicators except organic N, which was underpredicted by a factor of 3. Scenario simulations were designed for the DCW APEX-SWAT modeling system but were not implemented. Further details regarding the baseline broiler litter management and other modeling assumptions and the baseline simulation results are available in Gassman et al., 2001.

Table 10. Average concentrations measured at sampling site 1 versus predicted average concentrations at the DCW outlet for the APEX-SWAT environmental baselines[a,b]

Environmental indicator	Measured values	APEX-SWAT
	------------------------- (mg/l)	-------------------------
Sediment	91	82
NO_3-N	0.59	0.56
Organic N (TKN)	1.37	0.45
Soluble P	0.11	0.07
Organic P	0.2	0.12

[a] Adapted from Gassman et al., 2001.

[b] Measured and predicted concentrations were averaged across the 48 days that samples were recorded at sampling site 1 during 2000.

Scenario Results for NPP-Related Studies

A wide range of scenarios were performed for the three NPP watersheds (Table 11), which included alternative manure and fertilizer application rate, manure method, structural and other conservation practice, manure handling technologies, and feed modification scenarios. Some scenarios, such as manure applications based on a nitrogen (N) rate, “low” phosphorus (P) rate, and “high” phosphorus (P) rate were simulated for each of the three watersheds. Other scenarios were unique to one of the watersheds, such as the LFRW IRG scenario, haul-off of solid manure for the UNBRW, and variation in fertilizer application rates for the UMRW. Several of the listed scenarios were also executed in combination with one or more of the other listed scenario types for one or more of the NPP watershed studies; e.g., haul-off of solid dairy manure was run in conjunction with applications of liquid manure at

Table 11. Different types of scenarios that were performed using APEX within the NPP[a,b]

Scenario type	Watershed UNBRW	 LFRW	 UMRW
Variation in manure application rates[c]			
Manure applied at an N agronomic rate	Yes	Yes	Yes
Manure applied at a mineral P (high P) agron. rate	Yes	Yes	Yes
Manure applied at a total P (low P) agron. Rate	Yes	Yes	Yes
Variation in fertilizer application rates			
Reduction in commercial N and/or P fert. Rates	No	No	Yes
Split application of reduced N fertilizer rates	No	No	Yes
Variation in grazing rates and patterns			
Stocking rates based on an N agronomic rate	No	Yes	No
Stocking rates based on a high P agronomic rate	No	Yes	No
Stocking rates based on a low P agronomic rate	No	Yes	No
Intensive rotational grazing (IRG)	No	Yes	No
Grassed loafing lots (GLL)	No	Yes	No
Manure incorporation or injection			
Incorporation of solid manure	Yes	No	Yes
Injection of liquid swine waste	No	No	Yes
Reduction of soil erosion			
No-tillage on cropland	No	No	Yes
Use of Contouring or contour buffers on cropland	No	No	Yes
Use of terraces on cropland	No	No	Yes
Enhancing and developing waterways	No	No	Yes
Modification of animal feed rations			
Reduction of P in dairy rations	No	Yes	No
Use of Phytase in swine rations (with reduced P)	No	No	Yes
Impacts of variation in management technologies			
Use of solid separators for dairy manure	yes	No	No
Two-stage lagoon systems for liquid dairy manure	yes	No	No
Haul-off of solid dairy manure (for composting)	yes	No	No
Conversion of swine operations to hoop structures	no	No	Yes
Filter strips			
Filter strips below pasture and hayfields	no	Yes	No
Filter strips below cropfields	no	No	Yes
Long-term buildup of nutrients	yes	No	No
Variation of cropping practices	yes	No	No

[a] Adapted from Osei et al., 2000b.

[b] Some of the scenario types listed here were run in tandem with all other scenarios.

[c] An N agronomic rate refers to applying manure at a rate such that the crop nitrogen needs are met, with accounting for volatilization and other losses as well as the proportion of the manure N that is plant available. The manure high P rate refers to applying manure such that enough inorganic P is applied to meet the crop phosphorus demand, with the assumption that the manure organic P component is not plant available. A low P rates assumes that both the inorganic and organic P components are plant available, such that the total P applied meets the crop phosphorus needs. Application of nitrogen fertilizer is usually needed to compensate for lower amounts of nitrogen applied for both the high P and low P applications. See Gassman et al., 2002 and Osei et al., 2003a for further explanation.

an N rate or high P rate in the UNBRW (Pratt et al., 1997). A complete set of results for the scenarios listed in Table 11 and additional scenarios that report combinations of management strategies are reported in Pratt et al., 1997; McNitt and Jones, 1999; and Keith et al., 2000 for the UNBRW, LFRW, and UMRW, respectively. A brief summary of example results for selected scenarios listed in Table 11 are described here. Additional NPP-related study results are also presented here that describe variants of some of the scenarios listed in Table 11 or expanded sets of scenario results for some of the watersheds. All of the scenarios were run within the CEEOT-LP modeling system for the three NPP watersheds and the MCW in east central Iowa. Economic results are generally not stressed here.

NPP Study Results

Gassman et al. (2002) provide tabulated results of selected key scenarios (Table 12) that were drawn from the overall suite of scenarios listed in Table 11. Graphical results are presented here, in which the total predicted nitrogen (N) and phosphorus (P) losses at the watershed outlets, using the combined APEX-SWAT models (within CEEOT-LP) are compared versus the estimated net returns (Figures 16 and 17). The results show that most of the scenarios were predicted to result in some level of total N loss reduction, with the greatest declines in N losses occurring for the manure haul-off scenario in the UNBRW and the high P and low P scenarios in the UMRW. The UNBRW high P and low P scenarios were predicted to result in substantial increased levels of total N loss, and a minor increase in total N loss was also predicted for the LFRW low P scenario. However, the magnitude of these UNBRW total N loss increases was relatively small due to the small N losses predicted for the baseline. Overall, the LFRW IRG, and UMRW low P, high P, and reduced fertilizer scenarios were the only scenarios that were predicted to be “win-win” for both reduced N loss and economic returns. All of the scenarios were estimated to result in reduced losses of total P, with reductions exceeding 60% for the UNBRW haul-off and LFRW IRG scenarios. Again, the LFRW IRG, and UMRW low P, high P, and reduced fertilizer scenarios were the only subsets found to provide both environmental benefits, in terms of reduced P losses to the stream system, but also provide economic benefits.

Further impacts of manure application scenarios are shown in Figure 18 for the UNBRW as reported by Osei et al. (2003a). These scenario results depict aggregate APEX edge-of-field predictions

Table 12. Selected policy scenarios from the NPP watershed studies

Watershed	High P	Low P	Haul-off	IRG[a]	GLL[a]	Reduced Fertilizer	No-till
UNBRW	yes	yes	yes	no	no	no	no
LFRW	yes	yes	no	yes	yes	no	no
UMRW	yes	yes	no	no	no	yes	yes

Source: Gassman et al., 2002.

[a] IRG = intensive rotational grazing; GLL= grassed loafing lots.

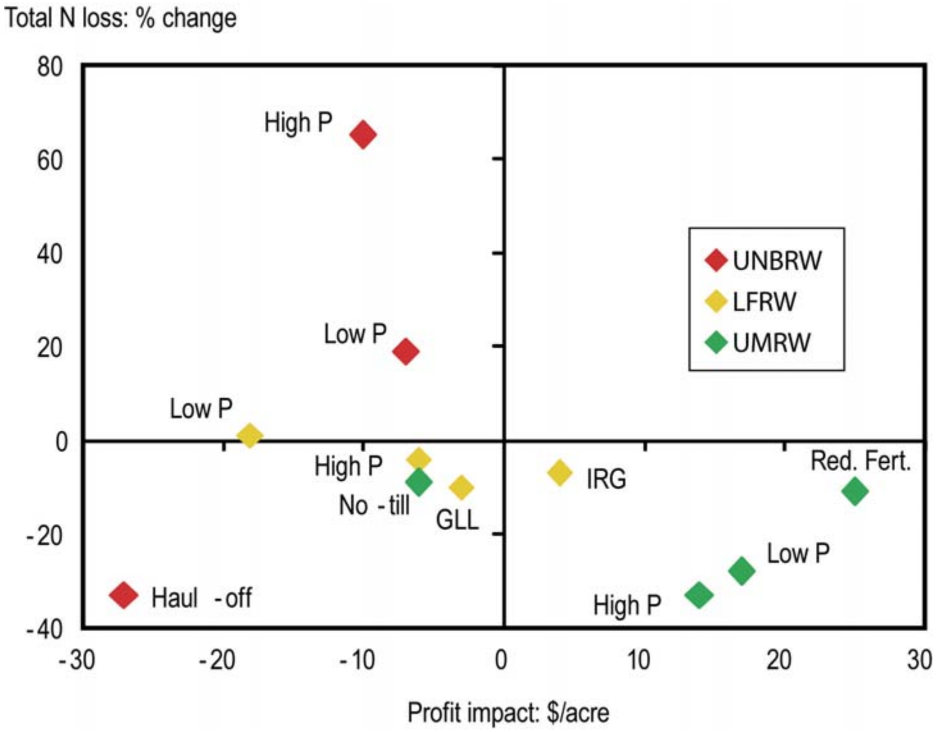


Figure 16. Comparison of total nitrogen (N) losses versus aggregated net returns for selected UNBRW, LFRW, and UMRW scenarios (Tables 10 and 11); % change from the baseline

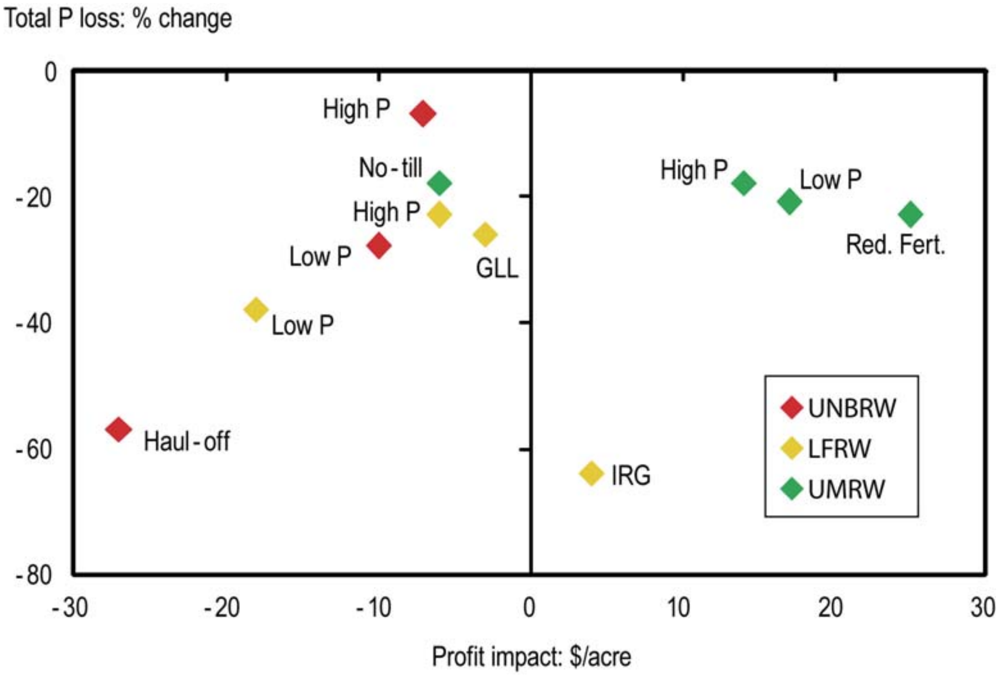


Figure 17. Comparison of total phosphorus (P) losses versus aggregated net returns for selected UNBRW, LFRW, and UMRW scenarios (Tables 10 and 11) (% change from the baseline)

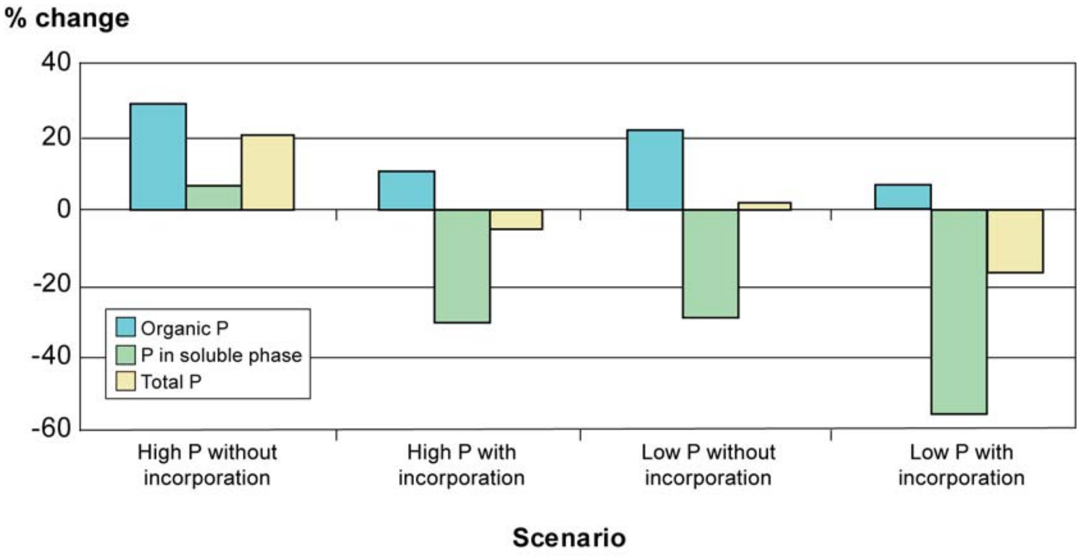


Figure 18. Impacts of P-based application rates with and without incorporation on aggregate organic P, soluble P, and total P for all UNBRW dairy waste application fields (Source: Osei et al., 2003a)

for all UNBRW dairy waste application fields in which the manure application rates were shifted from baseline N-based rates to one of four P-based/tillage combinations: high P rate without tillage incorporation, high P rate with tillage incorporation, low P rate without tillage incorporation, and low P rate with tillage incorporation. Two tandem disk passes were simulated in the spring and fall for all four scenarios; two additional tandem disk operations were performed for the incorporation scenarios, to simulate manure nutrient incorporation after both spring and fall applications. The APEX scenario results (Figure 16) show that the predicted losses of sediment-bound organic P increased for every scenario, with greater losses occurring for the unincorporated manure applications. These results reflect the effects of increased erosion that occurred from the tandem disk passes. However, the soluble P portion of the applied manure was predicted to decrease in all of the scenarios except the unincorporated high P rate scenario, with the predicted reduction approaching 60% for the incorporated low P rate scenario as compared to the N rate baseline. Overall, total P losses were predicted to decrease only when the manure was incorporated for both the high P and low P application rates. Osei et al. (2003a) reported additional results for the P rate/incorporation study.

Osei et al. (2000a) reported a second set of UNBRW scenarios that feature variations of the solid manure haul-off/composting scenario listed in Table 11. Table 13 shows the suite of nine scenarios considered for the study, which includes the previously described land applied manure application rates (N, high P, and low P) and six solid manure composting scenarios that assume composting at a central composting facility by a private contractor on a custom basis, or on-site at the respective dairy farm. The N, high P, and low P land application scenarios (scenarios I, II and III; Table 13) included both solid and liquid manure. However, only liquid manure was applied for the composting scenarios, because of composting of the solid manure, and it was assumed that the liquid manure was applied at either an N rate (scenarios IV, V, and VI) or a high P rate (scenarios VII, VIII, or IX) as shown in Table 13. The environmental effects were thus the same between scenarios IV, V, and VI and between scenarios VII, VIII, or IX , but the predicted economic impacts differed among most of the scenarios. The results (Table 14) show dramatic area weighted reductions of average P losses for both the high P and low P scenarios relative to the baseline, and large aggregate reductions in total P losses ranging between 14% and 37%. The areal weighted average P reductions were not as great for the liquid manure applied for the composting scenarios, but the aggregate reductions in total P loss were much greater at 81% and 86% for the liquid manure applied at an N rate or high P rate, respectively. Further scenario results are reported in the study.

Table 13: Summary of simulated scenarios for the UNBRW composting study

Agronomic Rate	Mode of solid manure handling/disposal Apply on land	Central compost[a]	Custom compost[a]	On-site compost[a]
N	Scenario I	Scenario IV	Scenario V	Scenario VI
High P	Scenario II	Scenario VII	Scenario VIII	Scenario IX
Low P	Scenario III			

Source: Osei et al., 2000a.

[a]It was assumed for all three composting scenarios that all solid manure from the UNBRW dairies was compostable.

Table 14. Predicted phosphorus loads for the UNBRW manure land application and composting scenarios

Scenario[a]	Per hectare nutrient loads			Total nutrient loads		
	Organic-P	Soluble P kg/ha/year	Total P	Organic-P	Soluble P metric tons/year	Total P
Scenario I (N): Baseline	4.7	4.2	8.9	12.3	11.2	23.5
Scenario II (High P)	1.0	0.8	1.8	11.5	8.7	20.2
Scenario III (Low P)	0.6	0.3	0.8	10.2	4.7	14.8
Scenario IV, V or VI	5.7	3.9	9.6	2.7	1.9	4.5
Scenario VII, VIII or IX	1.4	0.7	2.1	2.2	1.1	3.3
	% changes from the baseline					
Scenario II (High P)	-78	-82	-80	-7	-23	-14
Scenario III (Low P)	-88	-94	-91	-18	-59	-37
Scenario IV, V or VI	22	-7	8	-78	-83	-81
Scenario VII, VIII or IX	-69	-84	-76	-82	-90	-86

Source: Osei et al., 2000a.

[a]The P loadings reported for scenarios I – III are based on the averages of both the solid and liquid manure field losses, while the loadings reported for scenarios IV – IX reflect average loads from only the liquid application fields.

Alternative dairy cow stocking rate OAG scenarios were also reported by Osei et al. (2003b) for the LFRW, which included an N rate scenario in addition to high P and low P scenarios. The N rate stocking density scenario assumed that the manure N deposition was sufficient to meet the agronomic N needs of the pasture grass, such that fertilizer N would not have to be applied (as required in the N rate stocking density baseline). The predicted sediment and nutrient losses for the OAG scenarios were estimated in APEX and then input into SWAT. The overall 30-year average APEX-SWAT watershed-level impacts are shown in Figure 19. The results confirm the effectiveness of the P rate scenarios in reducing P losses, especially for

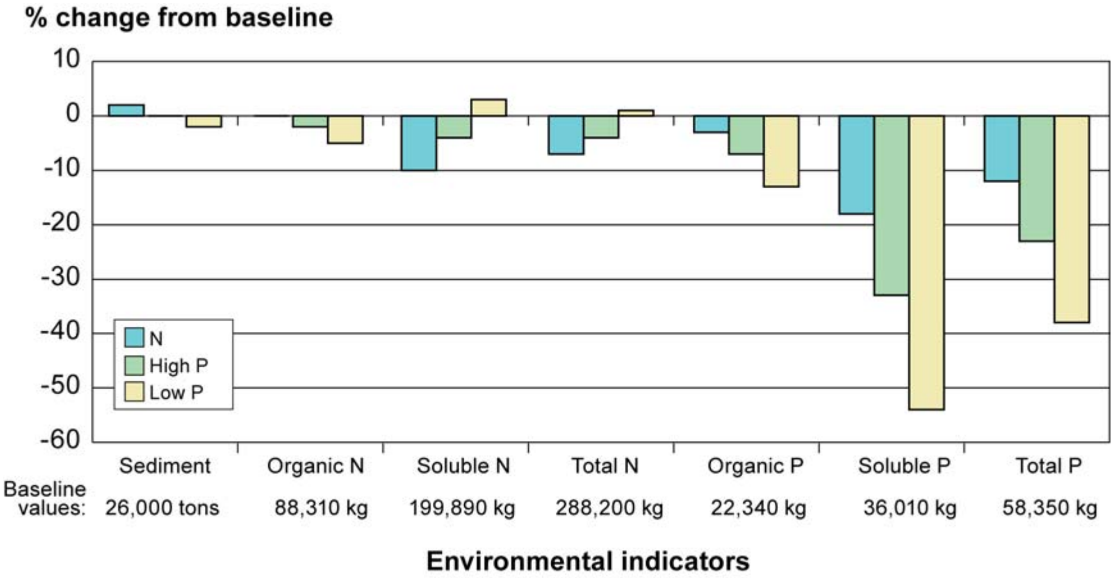


Figure 19. Environmental impacts predicted for the three LFRW stocking rate scenarios based on percent changes from baseline values (Source: Osei et al., 2003b)

soluble P. However, the N rate scenario resulted in higher reductions of N loss, although the relative magnitude was much less than the P loss reductions. Slight increases in soluble and total N losses were predicted for the low P scenario, because of the need to apply relatively high rates of N fertilizer. Osei et al. (2003b) provided further details regarding modeling results for the study.

A broad suite of nutrient management and conservation practices were simulated in both the UMRW and MCW studies (Gassman et al., 2006, 2003). Table 15 presents the predicted impacts of 11 different UMRW practice scenarios on flow, sediment, and multiple N and P indicators, based on 30-year average annual APEX-SWAT simulations (e.g., SWAT watershed outlet predictions with embedded APEX simulations), as compared to baseline conditions. These practices were simulated in both APEX and SWAT as appropriate for UMRW row crop fields. Large reductions in most indicators were predicted for many of the practice scenarios, including terraces and combinations of reduced fertilizer rates with contour buffers or contouring. Increases in nitrate and corresponding total N were predicted for several scenarios, especially for no-till in which nitrate and total N increased by over 13% and 9%, respectively. These increased nitrate results show that several of the simulated practices resulted in greater subsurface

Table 15. 30-year annual average baseline Soil and Water Assessment Tool (SWAT) model results, and the percentage changes from the baseline for each 30-year scenario, at the watershed outlet for selected indicators

	Scenario	Flow	Sediment	Organic[a] N	Nitrate	Total N	Organic P	Soluble[a] P	Total P
		(m^3 s^{-1})	(tons)	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
	Baseline	1.0	54,300	49,000	649,900	698,900	3,267	6,966	10,233
		------------------------- Percentage changes from baseline values -------------------------							
1	No-till	-2.1	-28.6	-43.4	13.1	9.2	-40.7	-7.3	-18.0
2	Incorporation	0.0	0.8	3.0	1.9	2.0	3.3	-3.0	-1.0
3	Injection	0.0	0.0	-0.2	4.1	3.8	-0.8	-6.8	-4.9
4	Terraces	-3.8	-63.9	-72.8	4.9	-0.6	-74.2	-29.6	-43.8
5	Contouring	-3.8	-34.0	-35.6	4.0	1.2	-35.4	-23.4	-27.2
6	In-field contour buffers	-3.5	-43.7	-47.3	3.9	0.3	-48.2	-22.4	-30.6
7	Grassed waterways	-3.0	-45.9	-46.1	2.4	-1.0	-44.8	-14.5	-24.2
8	No-till & reduced fertilizer	-2.9	-29.0	-44.2	-9.3	-11.7	-44.4	-36.6	-39.1
9	Contour buffers & reduced fertilizer	-3.9	-43.5	-47.1	-15.5	-17.7	-49.7	-45.7	-46.9
10	Contours & reduced fertilizer	-4.2	-33.9	-35.6	-15.5	-16.9	-37.6	-46.5	-43.6
11	No-till & injection	-0.3	-5.1	-16.0	13.2	11.2	-19.7	-9.1	-12.5

Source: Gassman et al., 2006.

[a] Organic refers to sediment-bound N and P while soluble refers to P in the solution phase.

and tile drainage flow, resulting in increased nitrate transport relative to the baseline. Further description of the practices, edge-of-field APEX results, and economic impacts are given in Gassman et al., 2006.

Table 16 lists a suite of similar scenarios that were simulated for the MCW. The choice of scenarios was influenced by the MCW Watershed Council, which consisted of local land owners and other stakeholders at the time of the study. Their interests included looking at no-till and other practices on specific percentages of the row-cropped acreage (e.g., 25%) rather than just assuming that it was applied to the entire cropped area. The results of the combined 30-year average APEX-SWAT scenarios at the watershed outlet, relative to the MCW baseline, are shown for sediment, total N, nitrate, and total P versus profit ($/acre) in Figures 20 to 23. The impacts of the scenarios were similar to those predicted for

Table 16. Selected scenarios that were simulated for the MCW with CEEOT-LP

Scenario	Name	Description
1	CT25	Contouring practiced on 25% of the cropped acreage; limited to slopes ≥ 3.5%
2	CT75	Contour practiced on 75% of the cropped acreage; limited to slopes ≥ 3.5%
3	CB25	Contour buffers implemented on 25% of the cropped acreage
4	CB75	Contour buffers implemented on 75% of the cropped acreage
5	GW100	Grassed waterways with excellent vegetative cover used on 100% of the cropped acreage
6	NF25	No applications of fall crop removal fertilizer on 25% of the cropped acreage
7	NF75	No applications of fall crop removal fertilizer on 75% of the cropped acreage
8	NT25	No-till practiced on 25% of the cropped acreage
9	NT75	No-till practiced on 75% of the cropped acreage
10	NT100	No-till practiced on 100% of the cropped acreage
11	NTCT75	No-till and contouring practiced on 75% of the cropped acreage
12	TR25	Terracing practiced on 25% of the cropped acreage; limited to slopes ≥ 3.5%
13	TR75	Terracing practiced on 75% of the cropped acreage; limited to slopes ≥ 3.5%
14	VRT25	Variable rate tech. (reduced fall crop removal rates) used on 25% of cropped acreage
15	VRT75	Variable rate tech. (reduced fall crop removal rates) used on 75% of cropped acreage

Source: Gassman et al., 2003.

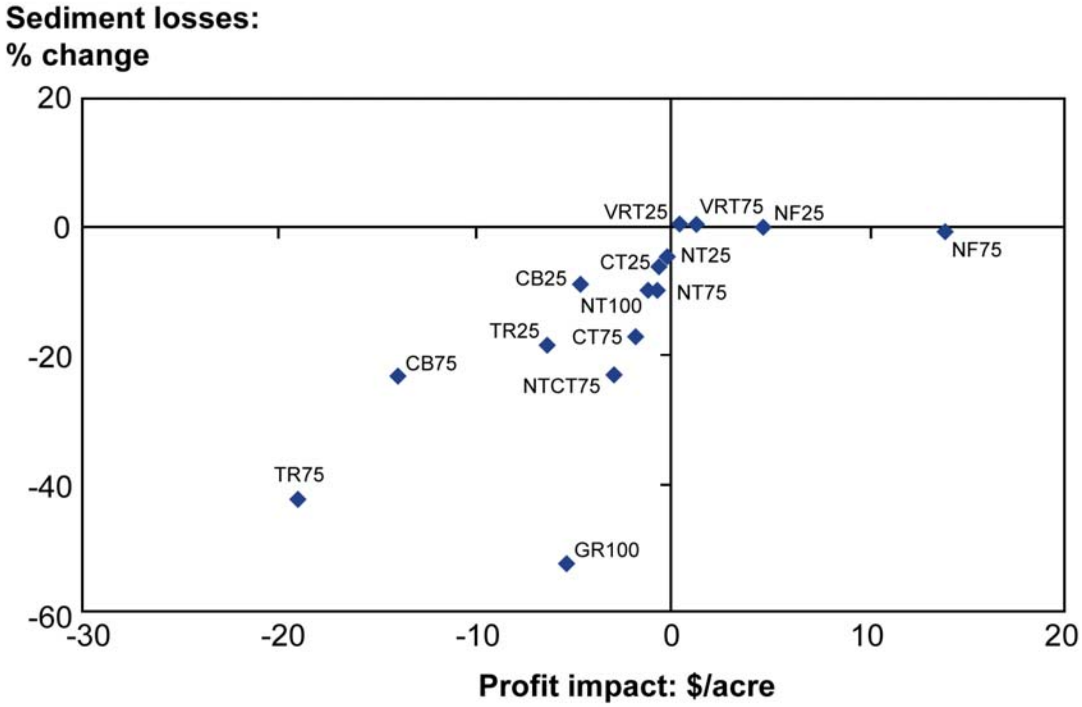


Figure 20. Predicted change in sediment losses versus profit impact for the suite of scenarios (Table 15) executed for the MCW

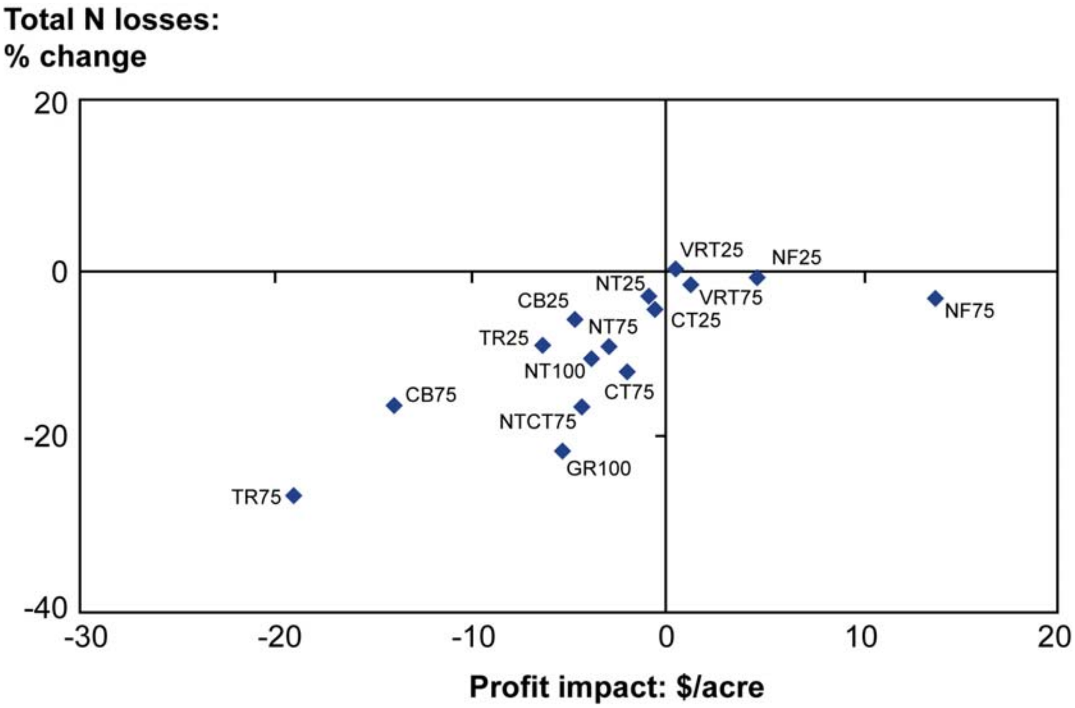


Figure 21. Predicted change in total N losses versus profit impact for the suite of scenarios (Table 15) executed for the MCW (Source: Gassman et al., 2003)

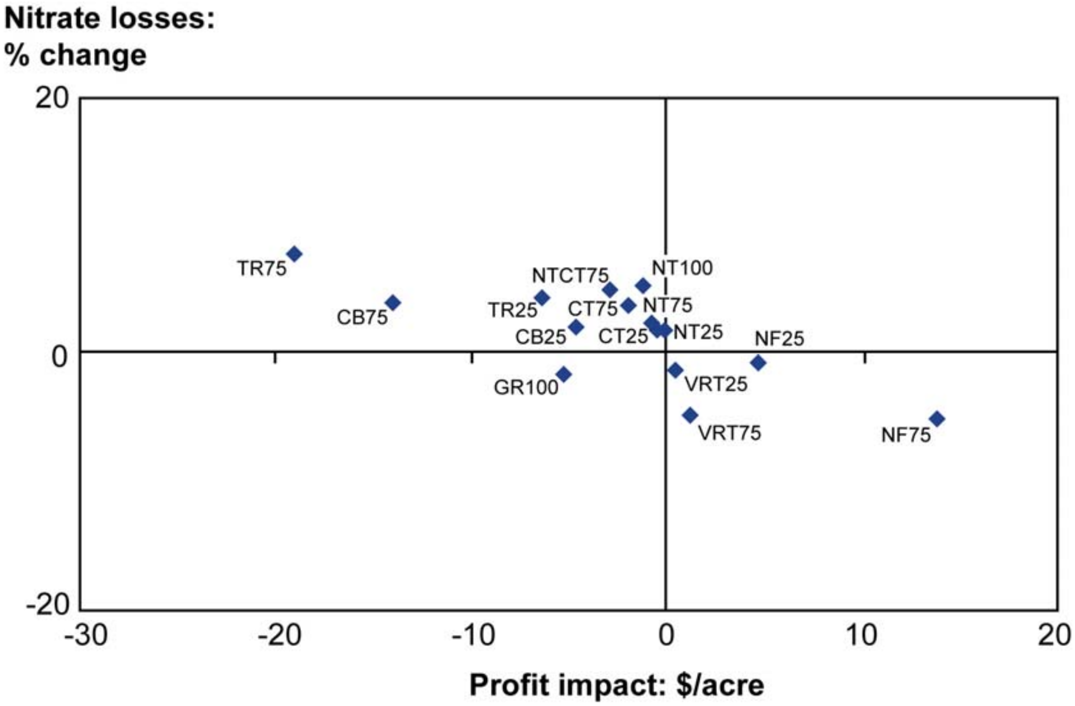


Figure 22. Predicted change in nitrate losses versus profit impact for the suite of scenarios (Table 15) executed for the MCW

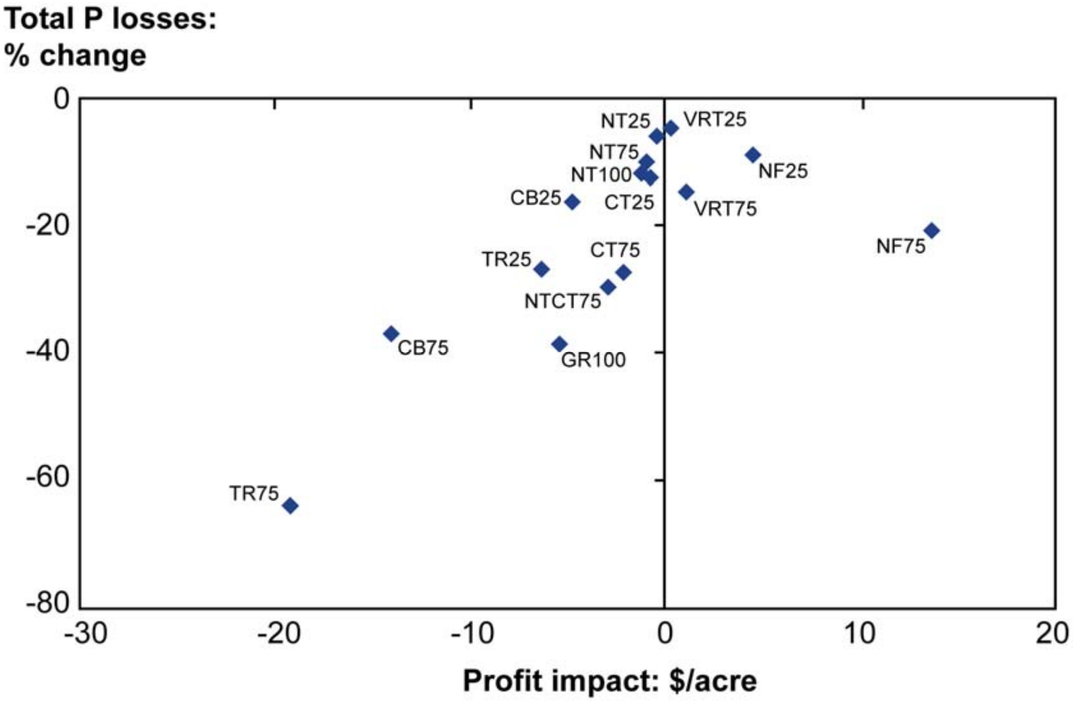


Figure 23. Predicted change in total P losses versus profit impact for the suite of scenarios (Table 15) executed for the MCW (Source: Gassman et al., 2003)

the UMRW, with large reductions predicted for several practices for sediment and total P, which contrasted with increases in nitrate that were estimated for most of the practices. The effect of the simulated practices on total N differed somewhat from the UMRW, with the majority of practices indicated to result in fairly large decreases. This result reflects the fact that the nitrate component of the total N loss was not as dominant for the MCW, because of less overall N inputs to cropland and less subsurface tile drainage in the watershed. Further study details are given in Gassman et al., 2003. The only scenarios that were predicted to result in profit gains were scenarios that were designed for more efficient use of fertilizer inputs.

In general, the scenarios performed within the NPP demonstrate the flexibility and effectiveness of using APEX to evaluate a wide range of alternative cropping system and management practice strategies. However, there were weaknesses in the depiction of some practices; e.g., overreliance on simplified P factors for depiction of contour buffers and other practices for the UMRW simulations. Further development of model algorithms (e.g., Table 1) and continued application of APEX in other studies beyond the NPP, such as the National CEAP study, has resulted in development of improved methods of representing different BMPs in APEX.

Additional Plot-, Field-, and Watershed-Scale APEX Studies

APEX has been applied in a variety of calibration/validation and scenario studies since the NPP. Several of these studies focused primarily on testing of the model with field data, although some of these studies also report scenario results. Additional studies have been performed that focus on different scenario applications of APEX at the field, watershed, or regional level but in some cases also report calibration and/or validation results. The studies that report comparisons with field data have been performed primarily for small plots or watersheds and have been conducted both for agricultural applications as well as for forested areas. A brief overview of studies that focused principally on testing the model is given below in the APEX Calibration/Validation section. Agricultural and silvicultural scenario studies are then summarized; this discussion first covers applications of APEX at the landscape, field, or small watershed scales followed by applications of the model for larger watersheds and then finally within macro-scale applications.

APEX Calibration/Validation Studies

APEX testing results have been reported using a variety of statistical and graphical indicators, including the previously described R^2 and NSE values, which Gassman et al. (2007) found were the most widely used statistics for evaluating SWAT hydrologic and pollutant loss predictions. A compilation of R^2 and NSE values for eight APEX studies are reported in Table 17 for several different hydrologic and pollutant loss indicators. While these sets of statistics are not nearly as extensive as those reported for SWAT (Gassman et al., 2007), they do provide useful insights into the ability of APEX to replicate observed hydrologic balance components and pollutant transport for different cropping and forestry production systems. Statistical criteria for establishing satisfactory water quality model performance have been proposed by Moriasi et al. (2007), including a lower bound for NSE values of 0.5 for monthly comparisons. The authors further suggested that their NSE and other statistical criteria be relaxed or tightened as appropriate for shorter or longer time steps. Based on their NSE criteria (and assuming it is also appropriate for R^2 values), the majority of studies listed in Table 17 report satisfactory NSE and R^2 values. Weak statistics were reported for some of the results, particularly the statistics reported by Saleh et al. (2004). However, they cite issues with the monitoring data and also note other measures of model verification that showed that APEX performed adequately, as discussed below. Further discussion of the other statistics shown in Table 17 are also incorporated in summaries of the corresponding studies except for Gassman et al., 2006, which was previously discussed in the UMRW APEX Calibration Results subsection (see Figure 10).

Williams et al. (2006) reported a test of the APEX feedlot submodel using data collected for feedlots located near Bushland, Texas, and Carrington, North Dakota (Table 18). The assessment focused on tests of both the hydrologic balance and the manure erosion subcomponents of the model. The Carrington feedlot test resulted in R^2 statistics of 0.72 and 0.73 (Table 17), depending on the choice of curve number. A curve number of 95 was selected for final testing of the North Dakota feedlot conditions. The results of the model testing are shown in Table 19. These comparisons show that APEX replicated the average storm event runoff and pollutant indicators for the two feedlots. An extensive set of APEX vegetated filter strip scenario results was also reported by Williams et al. (2006) and accounted for different filter strip lengths and other factors downslope of a hypothetical feedlot.

Table 17. Summary of reported APEX surface runoff , sediment, and other calibration and validation results at the test plot, field, and watershed scales.

Reference	Watershed(s) or test site(s)	Area (km^2)	Indicator	Time period (C = calibration; V = validation)	Calibration Daily		Calibration Monthly		Calibration Annual		Validation Daily		Validation Monthly		Validation Annual	
					r^2	E	r^2	E	r^2	E	R^2	E	r^2	E	r^2	E
Gassman et al. (2006)	Research test plots (Nashua, Iowa & Lamberton, Minnesota)	-	tile flow	432 total monthly comparisons			.70									
			tile nitrate loss				.63									
Mudgal et al. (2008)	Goodwin Creek watershed (north central Missouri); 14 research plots	.270	surface runoff	C: 1997-1999 V: 2000-2002	.52-.93		.46-.67				.62-.98	`	.52-.94			
			atrazine		.52-.91		.45-.68				.53-.97		.45-.86			
Saleh et al. (2004)	9 forested watershed (eastern Texas); undisturbed control (CON; 3 watersheds)	.026 – .027	storm runoff	V:1980-1985								.84-.88				
			peak discharge									.39-.74				
			sediment									.12-.33				
			nitrate									-1.4 - .80				
			organic N									.64-.83				
			ortho-phosphate									-1.6 - -1.3				
			organic P									.49-.63				
			total N									.58-.84				
			total P									.55-.67				
	clearcutting, chopping, etc. (CHP; 3 watersheds)		storm runoff									.74-.85				
			peak discharge									-.05 - .65				

Table 17. Continued.

Reference	Watershed(s) or test site(s)	Area (km^2)	Indicator	Time period (C = calibration; V = validation)	Calibration						Validation					
					Daily		Monthly		Annual		Daily		Monthly		Annual	
					r^2	E	r^2	E	r^2	E	R^2	E	r^2	E	r^2	E
Saleh et al. (2004) continued	clearcutting, chopping, etc. (CHP; 3 watersheds)	.026 – .027	sediment	V:1980-1985								-1.4 - .29				
			nitrate									-2.0 - .11				
			organic N									-.65 - .75				
			ortho-phosphate									-6.6 - -1.5				
			organic P									-1.1 - .64				
			total N									.09-.77				
			total P									-1.1 - .69				
	clearcutting, shearing, etc. (SHR; 3 watersheds)		storm runoff									.74-.85				
			peak discharge									.30-.52				
			sediment									.26-.78				
			nitrate									-.99 - .41				
			organic N									.34-.75				
			ortho-phosphate									.08-.25				
			organic P									.43-.60				
			total N									.32-.77				
			total P									.14-.82				

Table 17. Continued

Reference	Watershed	Area (km^2)	Indicator	Time period (C = calibration; V = validation)	Calibration						Validation					
					Daily		Monthly		Annual		Daily		Monthly		Annual	
					r^2	NSE	r^2	NSE	r^2	NSE	R^2	NSE	r^2	NSE	r^2	NSE
Wang et al. (2007)	9 forested watershed (eastern Texas); undisturbed control (3 watersheds)	.026 – .027	stream flow	V: 1999-2004									.70-.84	.65-.80	.69-.90	.68-.80
			sediment										.87-.99	.85-.97	.94-.99	.86-.97
			organic N										.02-.91		.01-.92	
			mineral N										.44-.70		.83-.95	
			organic P										.70-.95		.40-.99	
			soluble P										.85-.88		.92-.97	
	conventional clear cut (3 watersheds)		stream flow										.71-.91	.71-.86	.93-.97	.88-.94
			sediment										.34-.99	.10-.97	.84-.99	.83-.99
			organic N										.14-.65		.08-.58	
			mineral N										.14-.61		.09-.90	
			organic P										.18-.31		.0-.17	
			soluble P										.64-.72		.53-.96	
	two herbicides		herbicide	V: 2002-2004									.11-.96			
	intensive clear cut (3 watersheds)		stream flow	V: 1999-2004									.54-.76	.44-.81	.79-.95	.74-.85
			sediment										.43-.88	.32-.80	.68-.85	.60-.85
			organic N										.27-.85		.42-.81	
			mineral N										.31-.62		.02-.80	
			organic P										.34-.44		.23-.46	

Table 17. Continued

Reference	Watershed	Area (km^2)	Indicator	Time period (C = calibration; V = validation)	Calibration Daily		Calibration Monthly		Calibration Annual		Validation Daily		Validation Monthly		Validation Annual	
					r^2	NSE	r^2	NSE	r^2	NSE	r^2	NSE	r^2	NSE	r^2	NSE
Wang et al. (2007) continued	intensive clear cut (3 watersheds) continued		soluble P										.27-.81		.05-.71	
	two herbicides		herbicide	V: 2002-2004									04-.99			
	conventional and intensive watersheds (two herbicides)		herbicide	V: 2002-2004											.68 & .74	.65 & .73
Wang et al. (2008b)	Treynor W2 (southwest Iowa)	.344	surface runoff	C: 1976-1987 V: 1988-1995			.51	.41					.68	.62	.97	.95
			sediment				.43	.36					.76	.72	.98	.96
	Treynor W3	.433	surface runoff				.38	.35					.63	.62	.90	.89
			sediment				.35	.32					.41	.41	.66	.65
Wang et al. (2008d)	Shoal Creek (Fort Hood, Texas); pre-BMP	22.5	stream flow	C: April 1997-April 2000 V: March 2002 to April 2004	.76	.73					.60	.33				
			sediment		.80	.77					.62	.61				
	post-BMP		stream flow		.77	.59					.76	.74				
			sediment		.65	.65					.60	.55				
Williams et al. (2006)	Bison feedlot, North Dakota; CN = 93	462 m^2	surface runoff	2001-2002	.72											
	CN = 95				.73											
Yin et al. (2008)	3 test plots, Middle Huaihe River watershed (Henan province, China); plot EHC1	.10 ha	surface runoff	C: 1982 V: 1983-86	.56	.52					.77	.41				
			sediment		.88	.83					.81	.73				
	Plot EHC2	.14 ha	surface runoff		.71	.70					.72	.52				
			sediment		.68	.67					.85	.84				
	Plot EHC4	.06 ha	surface runoff		.98	.89					.72	.50				
			sediment		.66	.48					.55	.49				

Table 18. Characteristics of feedlots used to test the APEX feedlot submodel[a]

Characteristic	Bushland, Texas	Carrington, North Dakota
Livestock type	beef cattle	bison
Feedlot size (ha)	4	.462
Slope (%)	2	4
Stocking rate (m^2)	13.3	46.2
Monitoring years	1971-1973	2001-2002
Average rainfall (mm)	429	440[b]
Soil hydrologic group	C[b]	B

[a] As reported in Williams et al., 2006.
[b] Not reported in Williams et al., 2006.

Table 19. Comparisons of average simulated and observed surface runoff and/or pollutant indicators for two feedlots[a]

Indicator	Simulated	Observed
Bushland, Texas		
Surface runoff (mm/yr)	58	53
Soluble N loss conc. (g/m^3)	1,162	1,083
Soluble P loss conc. (g/m^3)	241	205
Suspended solids conc. (g/m^3)	15,934	15,000
Carrington, North Dakota		
Organic N loss conc. (ppm)	100	95
Soluble N loss conc. (ppm)	67	58
Total P loss conc. (ppm)	51	50

[a] As reported in Williams et al., 2006.

Mudgal et al. (2008) reported testing of APEX for atrazine based on research plot data collected at the Missouri Management Systems Evaluation Area (MSEA) within the 72.5 km^2 Goodwater Creek watershed located in north central Missouri. The watershed is located within the Central Claypan Soil Major Land Resource Area (MLRA 115), which is dominated by claypan soils that consist of a relatively impermeable layer that is typically 20 to 40 cm below the soil surface. A total of 30 0.34 km^2 (189 by 18 m) research plots were established in 1991 at the

Missouri MSEA on a sloping landscape, each of which consisted of summit, backslope, and footslope positions; data collected at 14 of the research plots (Table 20) from 1997 to 2001 were used to test the model. The field studies were conducted to evaluate atrazine runoff losses for each cropping/management system on the claypan soils. The APEX calibration and validation results (Table 17) indicate that the model captured the measured surface runoff and atrazine loss trends across the 14 different research plots. The authors also reported a series of surface runoff and atrazine loss scenario results for different combinations of hypothetical landscape sequences (i.e., variations in the relative positions of the summit, backslope, and footslope landforms), cropping systems, and tillage practices.

Table 20. Goodwater Creek watershed research plot cropping systems and other characteristics

Treatment code	Cropping systems	Tillage	Total plots
CS1	corn-soybean	mulch	4
CS2	corn-soybean	notill	4
CS3	corn-soybean-wheat	notill	6

Source: Mudgal et al., 2008.

Tests of APEX were reported by Wang et al. (2008b) for two small watersheds called W2 and W3 (Table 21) that were part of the former USDA Deep Loess Research Station that was located near Treynor in southwestern Iowa (Figure 24). The watersheds were about 6 km from each other and were cropped in continuous corn but were managed with different tillage systems. Comparisons were made between predicted and measured surface runoff and sediment loss at the watershed outlets. Monthly comparisons were performed for the 1976 to 1987 calibration period while both monthly and annual comparisons were made for the 1988 to 1995 validation period. The R^2 and NSE statistics computed for the calibration period were somewhat weak, with the majority of the values below 0.4. However, the percentage errors calculated for the simulated versus observed surface runoff and sediment loss means over the calibration period varied only

Table 21. Characteristics of the two watersheds located near Treynor, Iowa[a]

Watershed ID	Area (ha)	Cropping system	Precipitation[b] (mm)	Tillage type
W2	34.4	continuous corn	808	Conventional
W3	43.2	continuous corn	772	Ridge

[a] As reported in Wang et al. (2008b).

[b] Average annual precipitation for 1976 to 1995.

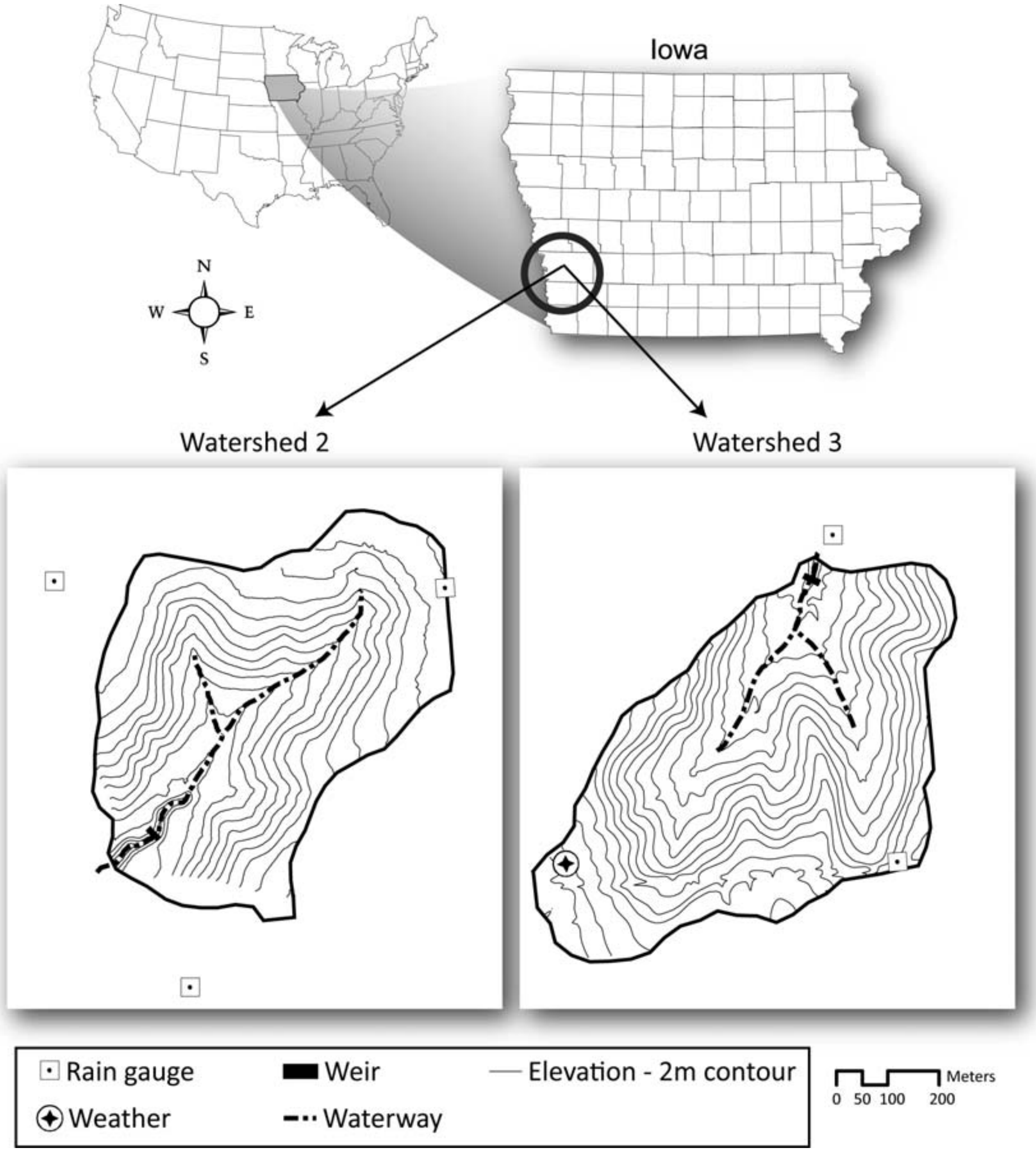


Figure 24. Watersheds W2 and W3 of the Deep Loess Research Station located near Treynor in southwestern Iowa (Source: Wang et al., 2008b)

between -4.2% and 0.3% across the two watersheds. The validation statistics were much stronger, with the majority exceeding 0.6 (Table 17). APEX predicted corn yields and soil organic carbon also compared well with counterpart measured values (Table 22). Further long-term (1976 to 1995) scenario analysis was performed in the study using APEX to compare the effects of adopting ridge-till versus conservation-till on both W2 and W3. The results showed that large reductions in surface runoff (36% for W2 and 39% for W3), sediment loss (86% for W2 and 82% for W3), and soil carbon lost on sediment (67% for W2 and 63% for W3) would occur if ridge-till were adopted instead of conventional-till on the two watersheds.

Table 22. Observed and predicted corn grain yield and soil organic carbon in the top 0.15 m soil

		W2			W3		
Indicator	Year(s)	Observed (Mg ha^{-1})	Predicted (Mg ha^{-1})	% Error	Observed (Mg ha^{-1})	Predicted (Mg ha^{-1})	% Error
Corn grain yield	1976-1995	7.29	6.93	-4.9	7.59	7.36	-3.0
Soil organic carbon	1994	26.6[b]	29.1	9.2	34.7[b]	36.4	5.0

Source: Wang et al., 2008b.

[a]Mean of soil organic carbon in top 0.15 m soil based on about 50 observations as reported in Cambardella et al., 2004.

Yin et al. (2008) describe APEX testing results for three small research plots located in the Middle Hauihe River watershed in China (Figure 25) that ranged in size from 0.06 to 0.14 ha and represented fallow, woodland, and mixed woodland-grass systems with conservation and management practices, as described in Table 23. A sensitivity analysis was performed for 13 key parameters affecting surface runoff and sediment loss using the Fourier amplitude sensitivity test prior to the model testing phase. The APEX calibration was performed using the four parameters that were found to be the most sensitive. The simulated daily surface runoff and sediment values compared favorably with the corresponding observed values for each plot, as evidenced by the R2 and NSE statistics in Table 16. Long-term scenarios were also reported and indicated that adoption of mixed wood-grass or woodland with corresponding conservation practices (as listed

Figure 25. Location of the Hauihe River watershed in China, and location of the study site within the Middle Huaihe River watershed (Source: Yin et al., 2008)

in Table 23) resulted in surface runoff reductions of 35% to 37% and sediment yield reductions as compared to a fallow baseline.

Saleh et al. (2004) describe modifications to APEX that were designed to improve the model performance for silvicultural conditions. They tested the modified APEX for nine small watersheds located near Alto in east central Texas (Figure 26) that ranged in size from 2.6 to 2.7 ha. They evaluated the model for three different forest harvesting and site preparation management systems (Figure 26): undisturbed control (CON), clearcutting by shearing, windrowing and burning (SHR), and clearcutting followed by roller chopping and burning (CHP). Each watershed was subdivided into upland and floodplain subareas in APEX. This step was taken in order to account accurately for channel erosion and floodplain deposition processes that

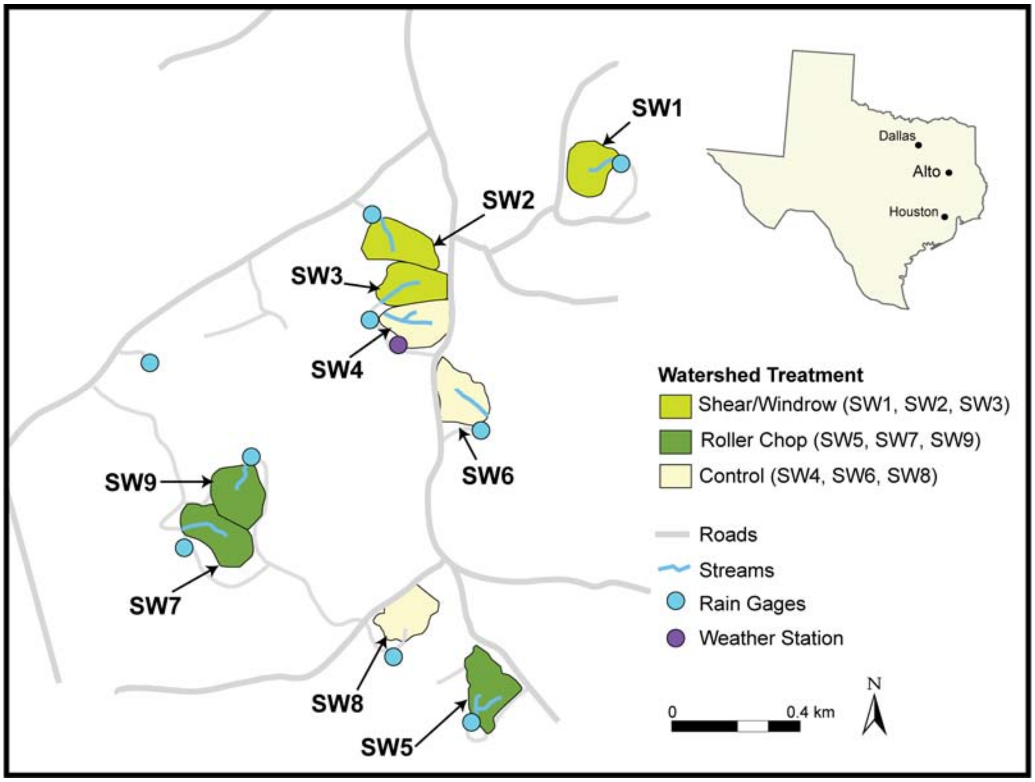


Figure 26. Location of the nine forested watersheds near Alto, Texas (Source: Saleh et al., 2004)

Table 23. Characteristics and management practices of the three plots

Plot	Slope (%)	Upland slope length (m)	Area (ha)	Land Use	Conservation practice	Length (m)	Width (m)	Management Practices[a]
EHC1	29	16.5	0.10	Mixed wood-grass	Horizontal-terrace	50	20	(1) Pine tree transplanting (2) Irrigation (3) Grass planting (4) Irrigation (5) Mowing
EHC2	19	25.0	0.14	Woodland	Horizontal-level ditches	55	25	(1) Poplar transplanting (2) Irrigation
EHC4	27	19.0	0.06	Fallow	None	30	20	Weeding

Source: Yin et al. (2008).

[a] Management practices performed in order of the numbering listed for plots EHC1 and EHC2.

occurred in stream management zones (SMZs) that were preserved in all nine watersheds (stream corridor filter strip areas with unharvested trees). The uncalibrated simulations were performed from 1948 to 1985. It was assumed that all trees were planted at the start of the APEX simulations and then harvested in 1981. Comparisons between simulated and measured data were conducted from 1980 to 1985 at the watershed outlets. Mixed results were found for the APEX predictions, based on the reported average daily NSE statistics ranges (Table 17). Some of the statistics indicated strong model performance while others were quite poor. However, the authors point out that there were obvious errors in some of the measured data and that the simulated means and standard deviations of the different hydrologic and pollutant indicators generally mirrored the measured values. Additional observations of the model testing results were reported in the study, including extensive graphical comparisons, as well as impacts of different SMZ scenarios in controlling surface runoff and sediment losses.

Wang et al. (2007) reported a second APEX testing study for the same nine forested watersheds in east central Texas (Figure 26). The subareas, SMZ depiction, and other simulation assumptions were essentially the same as in Saleh et al. (2004). However, different tree harvesting treatments were applied to the nine watersheds as follows: (1) control (SW3, SW5, and SW8), (2) conventional clear-cut harvest (SW2, SW4, and SW9), and (3) intensive clear-cut harvest (SW1, SW6, and SW7). Comparisons of uncalibrated APEX predictions versus observed data were again made at the watershed outlets for surface runoff, sediment, and nutrient and herbicide losses. The R^2 and NSE statistics reported in Table 17 indicate that the APEX predictions accurately replicated the majority of measured values and were generally stronger than the results reported by Saleh et al. (2004). However, poor statistics were again found for some of the watershed-indicator combinations, especially for some of the nutrient indicator predictions. Several time series and cumulative graphical comparisons also shown in the paper provide additional evidence that the model accurately tracked the measured surface runoff and pollutant losses.

Wang et al. (2008d) reported testing APEX for the 22.5 km^2 Shoal Creek watershed, which is located within the U.S. Army's Fort Hood military reservation in Coryell County, in central Texas (Figure 27). The model was configured with 183 subareas and tested at the watershed outlet, which qualifies the study as the only one reported to date in which APEX has been tested at a relatively large watershed scale. The military reservation covers a total of 880 km^2 and lies in portions of the Edwards Plateau and Blackland Prairie ecoregions. Ongoing military maneuvers result in damaged landscapes characterized by damaged or lost vegetation, soil exposure and erosion, runoff channelization, and gulley system development. BMP strategies have been introduced to mitigate these negative externalities, including the implementation of contour ripping across 22% of the Shoal Creek watershed during the last two months of 2001, and the installation of 211 gulley plugs from 2002 to 2004 (Figure 27). APEX calibration and validation was performed for surface runoff and sediment yield before (pre-BMP) and after (post-BMP) installation of these BMPs in the watershed. The majority of the resulting daily R^2 and NSE statistics (Table 17) exceeded 0.6 for both the calibration and validation periods, indicating strong model performance for both the pre-BMP and post-BMP conditions. The simulated mean and standard deviations also accurately replicated most of the corresponding measured data. Similar calibration and validation results are reported in a related paper by Wang et al. (2008a) that describes the effects of different subwatershed configurations on APEX output for the Shoal Creek watershed.

APEX Landscape, Field, and Small Watershed Scenario Applications

Qiu et al. (2002) used APEX within an economic and environmental modeling study to analyze the potential environmental benefits of "woody draws," which are relatively small, natural drainage areas covered by trees or shrubs in agricultural landscapes. The analysis was

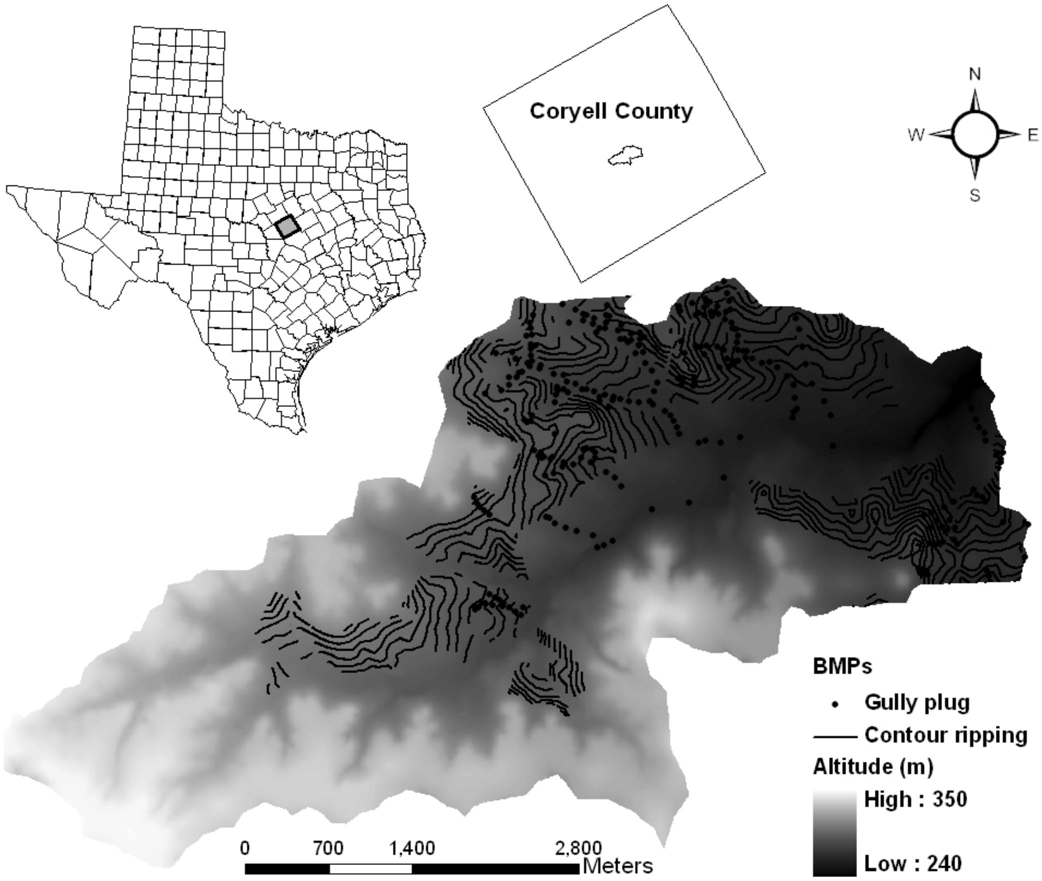


Figure 27. Location of the Shoal Creek watershed in Coryell County, Texas, and the distribution of contour ripping and gully plug conservation practices installed in 2001 and 2002 to 2004, respectively (Source: Wang et al., 2008d)

performed for 20 representative cropfields located within the 268.7 km^2 Long Branch watershed, which covers portions of Macon and Adair counties in Missouri. Each simulation area was 8.09 ha in size and was subdivided into an 0.81 ha draw and 7.28 ha upland cropfield. Three basic scenarios were considered in APEX, using one of three cropping systems (corn-soybean, corn-soybean-wheat, and continuous soybean): (1) the entire upland field draw area is assumed cropped (baseline scenario); (2) upland field cropped and the draw managed with either switchgrass (grass), curly willow (shrub), or cottonwood (trees); or (3) upland field cropped and draw managed with a mixed buffer of switchgrass, curly willow, and cottonwood. A total of 15 12-year APEX simulations were performed for each field, representing 15 different economic-based scenarios. The use of grass, shrub, and/or tree species in the draws resulted in predicted declines in sediment, sediment-bound N, and sediment-bound P ranging between 55% and 70%. The estimated reductions of N, P, atrazine, and metolachlor in the soluble runoff phase were between 13% and 24%.

Paudel et al. (2003) describe an application of APEX for the 162 ha Deep Hollow Lake watershed, which is located in LeFlore County, Mississippi, and was managed by a single operator. A farm economic model was interfaced with APEX as part of the study to assess the economic impacts of multiple scenarios. The watershed was subdivided into 22 subwatersheds for the APEX simulations that were each characterized by a unique soil type. The results of the 25-year APEX simulations showed that sediment loss decreased as tillage decreased but nitrogen runoff increased. The authors attributed this to reduced topsoil permeability and pointed out the need to consider trade-offs when evaluating different management practices. Related studies are described by Intarapapong and Hite (2003) and Intarapapong et al. (2002).

Willis (2008) reported an analysis of cropping and conservation practice effects on a playa lake system in the Texas High Plains (THP) region. Playa lakes are the primary wetlands in the THP region and provide a variety of ecoservices including wildlife habitat, floodwater containment, and groundwater recharge. The primary sources of water inputs to playa lakes are precipitation and irrigation runoff. Agricultural production trends have resulted in degraded hydrologic and environmental functionality of many playa lakes, with decreases in water storage capacity occurring due to increased sediment accumulation. This results in increased water storage in land adjacent to the playa, subsequent higher evaporation and seepage losses, and a reduced playa hydroperiod leading to a diminished time period that water can be held and increased negative environmental externalities.

Thus, APEX was used to investigate the effects of two key conservation practices, filter strips and furrow diking, in combination with either cotton, wheat, sorghum, or range production (sorghum results were not reported). Center-pivot irrigation was assumed for both the baseline and the scenarios. A schematic of a 259 ha playa lake watershed APEX simulation is shown in Figure 28. The 6.27 ha

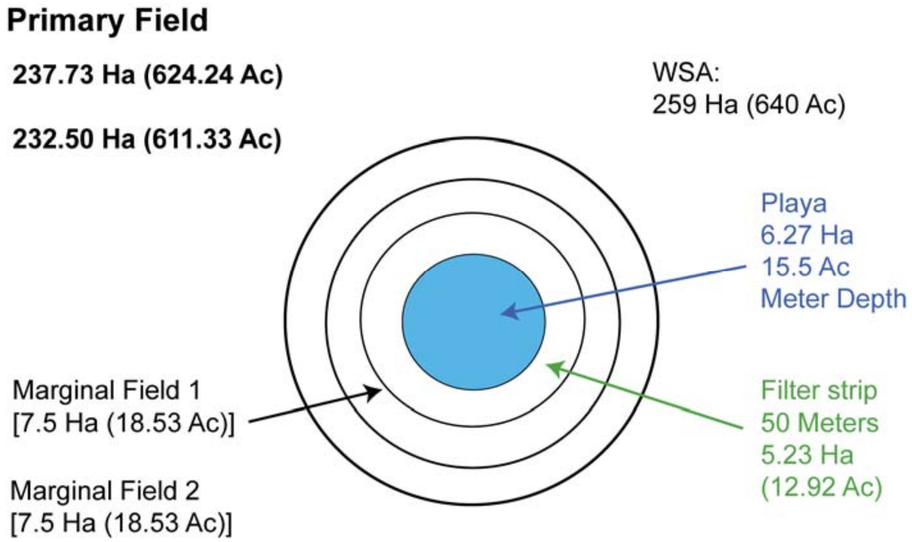


Figure 28. Schematic of the playa lake watershed scenario simulated in APEX (Source: Willis, 2008)

playa lake (assumed 1.0 m deep) was surrounded by a 50 m buffalo grass filter strip and two "marginal fields," which can be covered with backfilled water from the playa if the simulated lake begins to fill up with sediment. Subsequent crop yield damage can occur on the marginal fields because of the excess water. One hundred 50-year generated weather sequences were used in APEX for both the baseline and the scenarios, to isolate the effects of the conservation practices. The effects of introducing a 50 m buffer strip versus not using a buffer strip for a cropfield planted in cotton on an Amarillo soil are shown in Figure 29. The results show that the total number of wet days increased over the duration of the simulated time period with the addition of the buffer strip. The rate at which wet days were lost was reduced by about 10% and the number of years that the playa maintains some storage capacity is increased by around 20%. Additional impacts on the number of May through August playa wet days are shown in Figure 30, in which the effects of furrow dikes, with or without the 50 m buffers, are accounted for versus using no conservation practices.

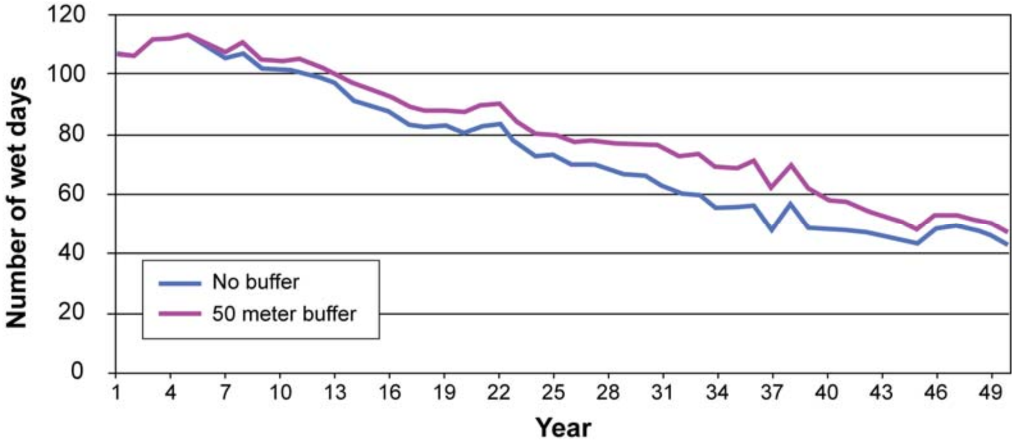


Figure 29. Impacts of a 50 m buffer strip versus no buffer strip (cotton; Amarillo soil) on playa lake storage during May through August in the THP region (Source: Willis, 2008)

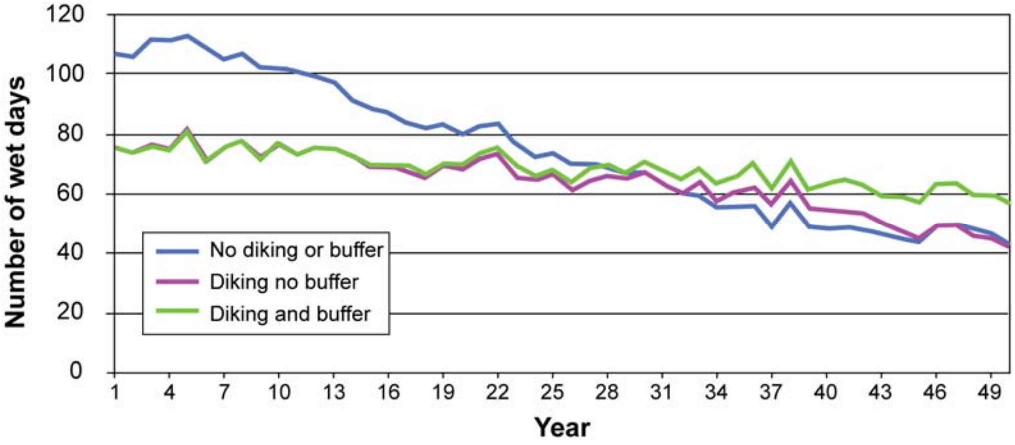


Figure 30. Impacts of no practices, furrow diking, or furrow diking and a 50 m buffer strip (cotton; Amarillo soil) on playa lake storage during May through August in the THP region (Source: Willis, 2008)

APEX Large Watershed Scenario Applications

Two studies reported by Azevedo et al. (2005a,b) used the enhanced APEX model (version 1310; Table 1) described by Saleh et al. (2004) to simulate the hydrologic and sediment loss impacts in response to hypothetical practices initiated within a Sustainable Forestry Initiative (SFI) program for either an 11.9 km^2 watershed (Azevedo et al., 2005a) or a 57.7 km^2 watershed (Azevedo et al., 2005b) located within the larger Shawanee Creek watershed in east Texas. A simulation program called HARVEST was used in both studies to simulate landscape management decisions such as harvest unit size, total area harvested, and rotation length. The watersheds were discretized into appropriately sized subwatersheds in order to perform routing of runoff and sediment yield to the watershed outlets in APEX. SFI practices incorporating 30 m wide buffers (previously described SMZs) were simulated in both studies. The effects of different tree species and/or silvicultural harvesting systems were also investigated. The results of both studies showed that the magnitude of the predicted surface runoff, water yields, and sediment yields at the watershed outlets were generally small, and that the introduction of SMZs resulted in reduced water and sediment yields at the watershed outlets. Similar SFI results using APEX were reported by Azevedo et al. (2008).

Three other studies (Harman et al., 2004; Wang et al., 2002; 2006a) describe similar types of simulation approaches for three different watersheds that differed roughly in one to two orders-of-magnitude in size from each other (Table 24). Key characteristics of each watershed are listed in Table 24, including brief summaries of the different types of scenarios evaluated for the respective study. A similar simulation approach was used in which each watershed was subdivided into subwatersheds, with subsequent simulated routing of flow and pollutant losses to the watershed outlets. Comparisons of simulated and observed crop yields for each study are shown in Table 25; the simulated yields accurately represented the observed crop yields for each watershed. Other APEX testing results reported in the studies were as follows: (1) simulated elemental N and P in surface runoff were 0.71 and 1.25 ppm versus measured counterparts of 0.71 and 1.20, for a single field in the TBC watershed (Wang et al., 2002); (2) average total loss of simulated atrazine applications for the Aquilla watershed study (Harman et al., 2004) was 1.98%, which was very close to observations of 2.03% for an atrazine runoff experiment at one site in the watershed; and (3) simulated annual surface runoff and sediment yield were within

Table 24. Characteristics of the watersheds analyzed in three different APEX studies

Watershed characteristics	Study		
	Wang et al. (2002)	Harman et al. (2004)	Wang et al. (2006a)
Name	Tierra Banco Creek (TBC)	Aquilla Creek	Zi-Fang-Gully (ZFG)
Region	Texas Panhandle & neighboring New Mexico	Hill country of central Texas	Shaanxi Province, Loess Plateau region, northwestern China
Area (km^2)	4,453	658	8.1
Total subwatersheds	94	44	29
Landuse Distribution (%)	cropland (86), & rangeland (14)	cropland (60), grassland (21), forest (13), & urban (6)	grassland (50), woodland (38), & cropland (12)
Cropland distribution (%)	irrigated wheat (19), corn (18) & sorghum (10); dryland wheat & sorghum (53%)	sorghum (36), corn (29), wheat (18), & cotton (17)	corn, soybean, pearl millet, proso millet, potato, sorghum, & buckwheat[a]
Key pollutant indicator(s)	sediment-bound N & P; soil P	Atrazine	Sediment loss and crop productivity
Length of simulation scenarios (years)	96	30 randomly generated weather sequences for 12 years each	30
Scenario summaries	4 scenarios: commercial fert. (baseline); 3 manure-based scenarios with or without commercial fertilizer	baseline & 8 scenarios including decreased atrazine appl. rates; incorporation; filter strips; wetlands or sediment reten. ponds; conservation- & no-till	baseline & 7 land-use scenarios, e.g.: partial grazing, all grain, all grass, all forest, 50% grass & 50% forest, all grain with reservoir effects
Other important characteristics	1 million cattle on feedlots; annual manure production equal 990,000 t; applied to irrigated cropland	Mixed crop and livestock production on clay & clay loam soils with slow infiltration & high runoff	Classified as a loess ravine hilly land zone, with undulating hills, deep gullies, & thick Yellow Earth soils

Table 25. Comparisons of average simulated and observed crop yields (mg/ha) for the three APEX studies described in Table 25

Indicator	Simulated	Observed
Wang et al. (2002); TBC watershed[a]		
Sorghum	5.6	5.51
Harman et al. (2004); Aquilla Creek watershed[b]		
Corn	6.25	6.28
Cotton	0.56	0.56
Sorghum	5.66	5.61
Wheat	3.15	3.03
Wang et al. (2006a); ZFG watershed[c]		
Corn	5.24	5.26
Soybean	1.13	1.14
Proso millet	1.77	1.87
Potato	2.53	2.54
Pearl millet	2.88	2.86
Sorghum	4.19	3.97
Buckwheat	1.59	1.53
Little bluestem grass	1.54	1.55
Gramagrass	1.00	1.00
Buffalograss	1.93	1.93
Black locust	10.00	12.86
Mesquite	30.00	29.43

[a] Based on a comparison for a single field.
[b] Observed Aquilla Creek watershed average yields based on local producer estimates.
[c] Average yields measured within ZFG watershed during 1997-2002 (extent of area not reported).

±15% of corresponding measured values for each year during 1997-2002 for the ZFG watershed (Wang et al., 2006a); the estimated six-year average surface runoff and sediment yield were 7.1% below and 2.4% higher than the observed averages.

The evaluation of three alternative scenarios (Table 24) by Wang et al. (2002) showed that objectives for the TBC watershed could best be achieved by using a reduced manure application rate in combination with commercial N fertilizer and conservation tillage, which resulted in eliminating fallowing. Harman et al. (2004) report that four of the evaluated eight scenarios proved most effective in terms of average atrazine loss relative to the total amount applied: (1) constructing sediment ponds, (2) establishing grass filter strips, (3) banding atrazine using an application rate that was 25% of the baseline rate, and (4) constructing wetlands. The scenario analysis by Wang et al. (2006a) found that reforestation was the best alternative among the eight scenarios evaluated regarding control of surface runoff and soil erosion. Installation of a reservoir was found to be the most effective practice in reducing the overall sediment yield for the watershed. They also found that expansion of crop production in the ZFG watershed resulted in increased environmental degradation and thus should not be encouraged.

An advanced APEX watershed application has been initiated for the Bosque River watershed (BRW), which covers 4,277 km^2 in central Texas (Dyke, 2008; Texas AgriLIFE, 2008). The watershed has been subdivided into 15,000 subwatersheds to perform detailed environmental impact assessments of BRW pollutants to Lake Waco, which serves as the drinking water supply for the city of Waco. The main focus of the project is to study in-depth the impact of dairy production in the UNBRW, which forms the upper reaches of the BRW, with corresponding detailed routing and potential attenuation of nutrient pollutants downstream from the dairy production areas. A 64-bit version of APEX (version 0806, Table 1) and a new ArcGIS-based interface, which is used in combination with the WinAPEX interface to build the APEX input files, are being used for the simulations (see the APEX Interface section for further description of these interfaces). The APEX framework is being used instead of SWAT to support scenario analyses requiring different and more detailed types of routing structures and to take advantage of the enhanced management simulation capabilities in APEX. The subwatershed delineations incorporate partitioning of floodplains from upland areas, to facilitate key scenarios such as landscaped-based filter strips in which livestock manure applications are eliminated from subareas that border stream segments. Several other scenarios will also be investigated in the study, including (1) no past practices, (2) likely future conditions (practices that have been approved but not implemented), and (3) possible future conditions that incorporate combinations of practices such as variations in cropping practices and lagoon management.

APEX Macro-Scale Applications

Osei et al. (2004) introduced the Comprehensive Economic and Environmental Optimization Tool – Macro Modeling System (CEEOT-MMS), which builds upon the previously described CEEOT-LP modeling system and is designed for macro-level policy assessments. CEEOT-MMS is an integrated modeling system that consists of APEX, FEM, supporting datasets, and an automated interface between the models and databases. However, the SWAT model is not used in CEEOT-MMS unlike the earlier developed CEEOT-LP. U.S. agricultural crop and livestock production census data have been incorporated into the system for the entire U.S. The user first selects the desired region that the analysis will be performed for (e.g., Corn Belt region). Subregions and representative farms are required for the respective analysis, using disaggregation and/or clustering processes. The economic and environmental analyses are performed at the micro-scale using the representative farms and then scaled up to provide overall impacts at the subregion, livestock type, or farm-size levels.

Osei et al. (2008a) describe an application of CEEOT-MMS for the state of Texas that incorporated six types of representative livestock farms distributed across 11 ecological subregions (Figure 31; Table 26). A multi-tiered clustering process was used to determine the subregions and representative livestock farms. The subregions were determined using a K-mains partitional clustering method. The representative farms were derived from 13,760 Texas farms (out of a total of 194,000 farms) that were identified as animal feeding operations (AFOs), based on having at least 35 animal units (Aus) present on-farm. A total of 780 representative farms were identified, based on a clustering analysis performed for each combination of six farm types and five farm sizes within each of the 11 subregions. The previously described N rate (baseline), high

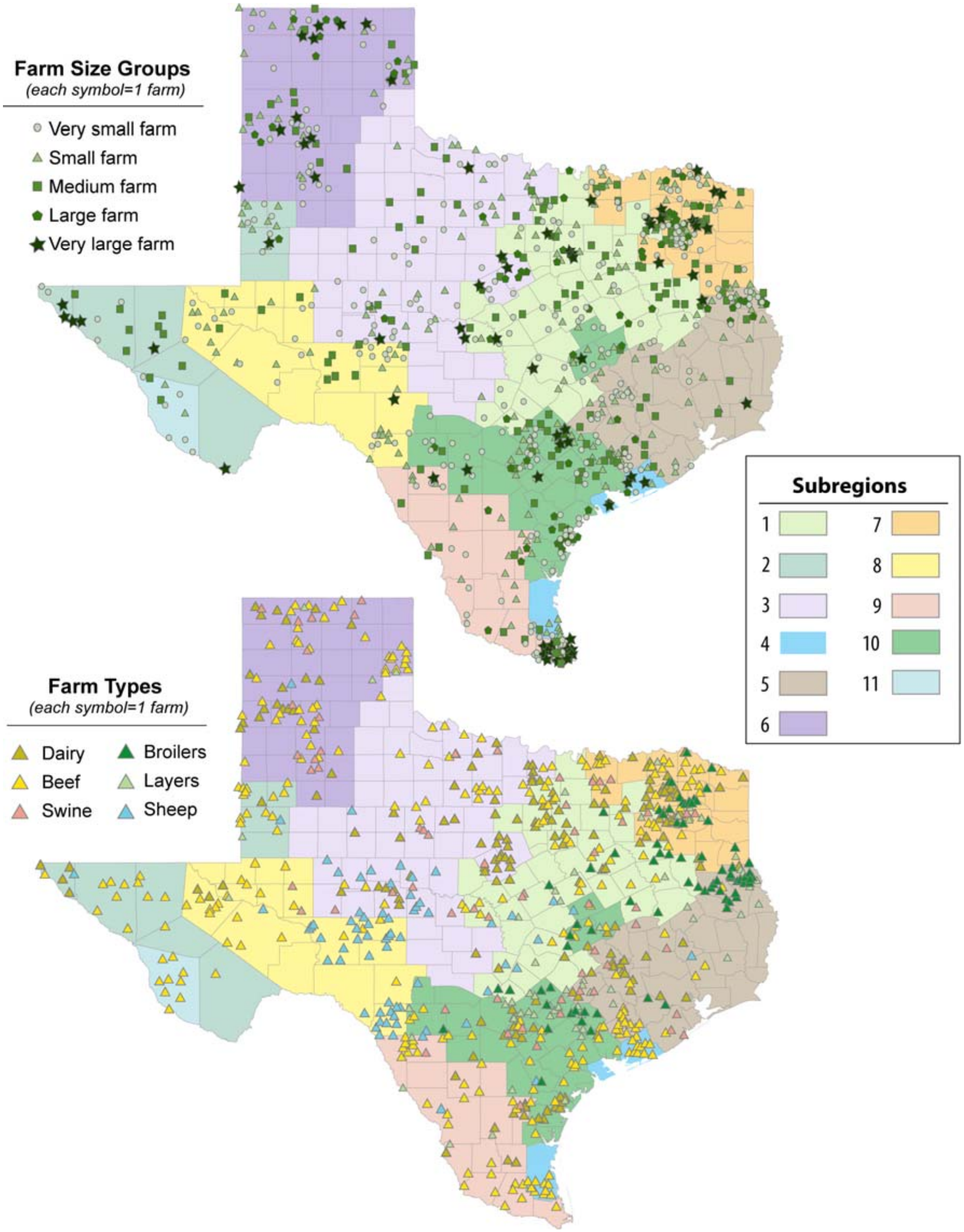


Figure 31. Distribution of the 780 representative livestock farms, by farm size or livestock farm type, across the 11 ecological subregions used in the Texas CEEOT-MMS study (Source: Osei et al., 2008a)

Table 26. Thirty-year (1971-2000) monthly averages of precipitation and temperature by subregion

Subregion	Precipitation	Maximum Temperature	Minimum Temperature
	mm	°C	°C
1	71.8	25.2	12.1
2	27.6	25.2	7.6
3	47.1	25.0	10.1
4	71.6	25.6	17.4
5	95.7	26.1	13.7
6	39.8	22.2	6.2
7	92.7	24.0	11.3
8	29.0	26.7	10.3
9	44.8	29.1	15.3
10	64.6	27.0	14.5
11	19.0	30.0	12.0

P, and low P rate scenarios were performed for both solid and liquid manure applications for the 780 representative farms. Changes in sediment, nitrogen, and phosphorus losses are presented by subregion, livestock farm type, and farm size for the two P scenarios, as compared to the N rate baseline. The impacts of the P scenarios varied greatly between the two scenarios, subregion, and farm types, with the greatest average reductions predicted for total P, in response to the low P scenario, of 14% across all subregions and 30% for dairy farms. Further results are presented in the study, including economic impacts. Additional assessments of Texas AFOs with CEEOT-MMS are reported by Osei et al. (2007).

Osei et al. (2008b) describe another CEEOT-MMS application in which comprehensive nutrient management plans (CNMPs) were analyzed for AFOs in the Ohio River Basin. Nearly 22,000 AFOs were identified in the region, which were categorized as dairy, beef, swine, broiler, layer, or sheep farms in one of three categories: small/very small, medium, or large/very large. A multi-tiered clustering analysis, similar to the one reported by Osei et al. (2008a), resulted in 757 representative farms distributed across 14 subregions (Figure 32; Table 27). The CNMP scenarios took into account feed management, manure wastewater handling and storage, nutrient management (N, high P, or low P rate), land treatment (no-till, contouring, and/or terraces), and

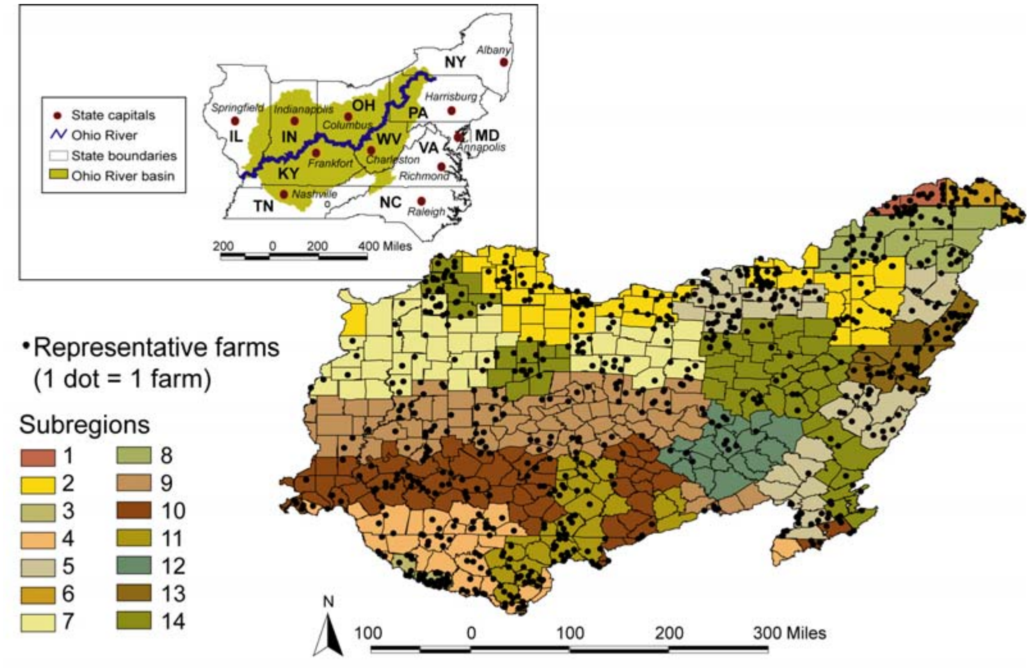


Figure 32. Distribution of the 14 ecoregions and 757 representative livestock farms that were used for the Ohio River Basin CEEOT-MMS study (Source: Osei et al., 2008b)

Table 27. Distribution of representative farms by type and subregion for the CEEOT-MMS Ohio River Basin study

Subregion	Dairy	Beef	Swine	Broilers	Layers	Sheep	Total
1	22	1	0	0	0	0	23
2	10	14	30	10	29	3	96
3	15	11	6	0	0	0	32
4	11	13	16	12	1	0	53
5	21	24	14	11	16	6	92
6	26	1	0	0	0	0	27
7	13	12	13	3	12	2	55
8	20	10	1	0	10	0	41
9	6	21	36	6	10	1	80
10	7	18	17	11	10	3	66
11	15	19	8	13	7	0	62
12	6	7	0	0	0	0	13
13	21	14	1	0	6	4	46
14	4	14	35	0	16	2	71
Total	197	179	177	66	117	21	757

Source: Osei et al., 2008b.

Table 28. Simulated impacts of CNMPs by subregion and corresponding distribution of key practices for the CEEOT-MMS Ohio River Basin study

Sub-region	Runoff	Sediment	Organic N	Organic P	Nitrate	Phos-phate	Ration	Low P rate	No-till	Contour	Terrace
------------------- % change from baseline values -----------------							- % of farms -		-------- % of area --------		
1	-2.3	-6.4	-6.1	-15.2	7.2	-30.8	93.8	100.0	1.0	0.2	0.0
2	-8.6	-13.0	-17.8	-21.3	6.7	-25.9	53.8	57.5	7.9	2.1	0.2
3	-1.0	-1.1	-14.7	-11.4	2.7	-11.4	15.0	15.0	0.8	0.8	00
4	4.4	0.9	4.7	-0.7	2.4	-3.3	35.0	40.0	4.6	2.8	0.3
5	-2.4	-4.7	-2.2	-10.1	3.6	-23.0	35.0	42.5	3.4	1.6	0.1
6	-7.1	-17.2	17.3	-7.5	2.8	-33.1	42.5	60.0	2.7	0.3	0.0
7	-2.6	-2.8	-8.5	-17.2	14.7	-22.0	27.5	30.0	5.1	0.3	0.2
8	-7.4	-15.6	21.3	-3.5	2.0	-32.4	51.6	61.3	3.1	0.2	2.3
9	-6.6	-8.6	-6.5	-9.0	2.0	-5.1	41.3	45.0	6.5	6.7	0.5
10	-8.9	-14.7	-5.7	-18.2	6.6	-24.5	33.8	41.3	4.1	3.3	0.2
11	-6.2	-8.2	-14.3	-19.9	2.0	-21.3	38.8	42.5	3.8	3.0	0.7
12	-1.6	-4.4	-0.3	-3.6	1.2	-4.2	5.0	5.0	1.7	1.1	0.4
13	2.1	-8.6	-9.3	-18.1	-8.6	-24.4	45.7	62.9	0.3	4.4	0.1
14	-2.5	-1.2	-12.5	-17.2	6.5	-29.2	23.8	33.8	13.3	3.7	0.5
Average	-2.9	-5.8	-9.4	-14.3	4.6	-18.8	38.9	45.5	5.7	2.9	0.4

Source: Osei et al., 2008b.

other utilization options. The impact of the CNMP scenarios on surface runoff, sediment, and selected nutrient indicators are shown in Table 28. Relatively large reductions in organic P (14%) and ortho-P (19%) were predicted, mainly because of the combinations of ration, nutrient, and land management CNMP treatments, including the use of the low P rate. Nitrate, on the other hand, was predicted to increase in every subregion.

FAPRI-UMC (2008) describes an economic and environmental analysis of conservation programs funded by the Missouri Parks, Soil and Water Tax (MO – PS&W – Sales Tax) of the Missouri Department of Natural Resources (MODNR). The study was performed by partitioning the state into seven regions, as shown in Figure 33. A review of the MO-PS&W-Sales Tax conservation programs claims database showed that 70%-80% of the revenue was used to fund cost-share investments for sediment retention structures, water impoundment ponds, surface-drained terraces, and tile-drained terraces. Thus, FAPRI-UMC (2008) analyzed the environmental impact of these structural practices, using the assumption that sediment retention structures and water impoundment ponds had essentially the same impacts (referred to as just ponds). The surface-drained terraces are characterized by surface waterways that typically have vegetation cover (similar to a grassed waterway) while the tile-drained terraces are drained by subsurface tile drains to the edge of the respective field, thus eliminating the need for grassed waterways and allowing the entire field to be cropped.

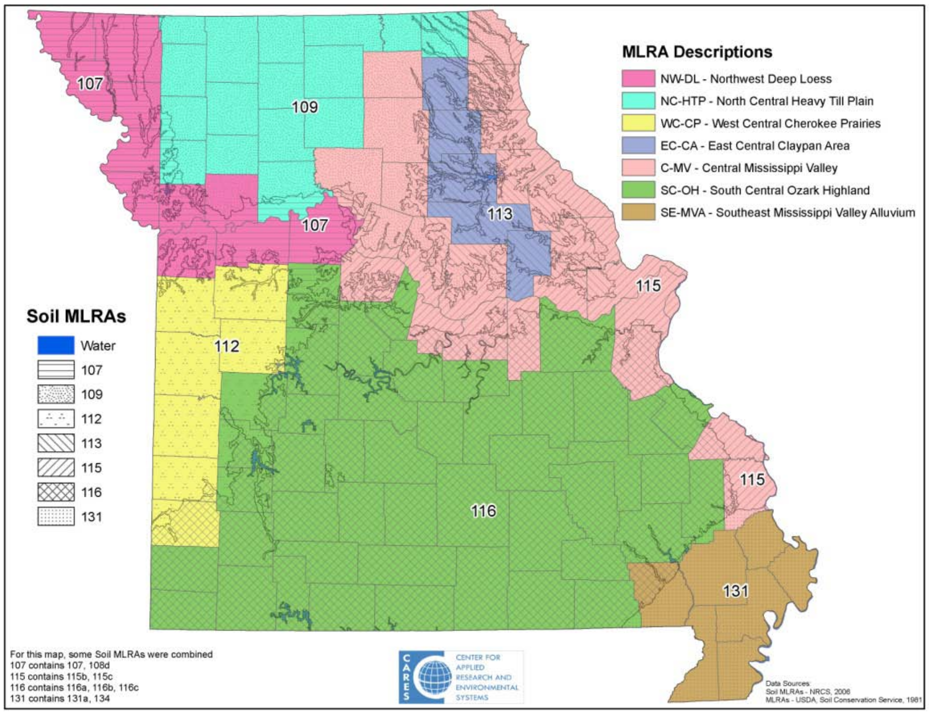


Figure 33. Study regions delineated for evaluation of the Missouri Park, Soil and Water Tax effects on conservation practice benefits using APEX (Source: FAPRI-UMC, 2008)

The average water quality impacts of the ponds and terraces for each region were determined on the basis of 44 representative APEX pond simulations and 24 representative APEX terrace simulations distributed across the seven regions as described in FAPRI-UMC (2008). The same representative terraces were used for both the surface-drained terraces and the tile-drained terraces. The estimated average reductions of surface runoff, N and P in the solution phase, sediment, sediment-bound N, P, and carbon are shown by practice and study region in

Figures 34 to 36 (manure and manure-P impacts are also shown for the pond results). All three practices were predicted to have large impacts on sediment, sediment-bound nutrients, and soil terraces. The impact on surface runoff and soluble-phase nutrients was much less than expected, because these practices are designed for erosion control.

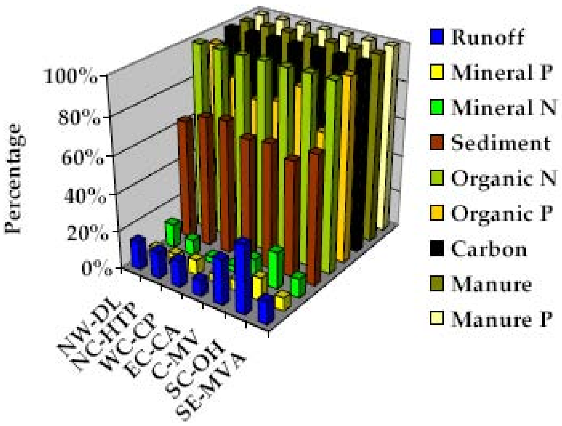


Figure 34. Predicted percentage of runoff and selected pollutants trapped by ponds using APEX for Missouri sales tax study (Source: FAPRI-UMC, 2008)

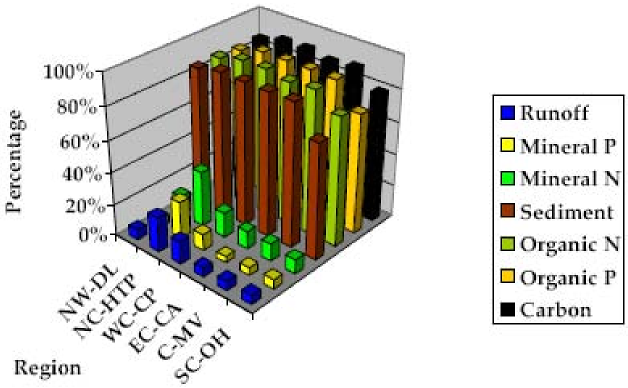


Figure 35. Predicted percentage of runoff and selected pollutants trapped by surface-drained terraces using APEX for Missouri sales tax study (Source: FAPRI-UMC, 2008)

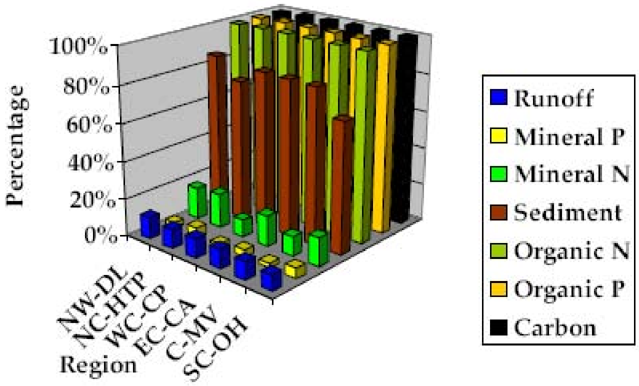
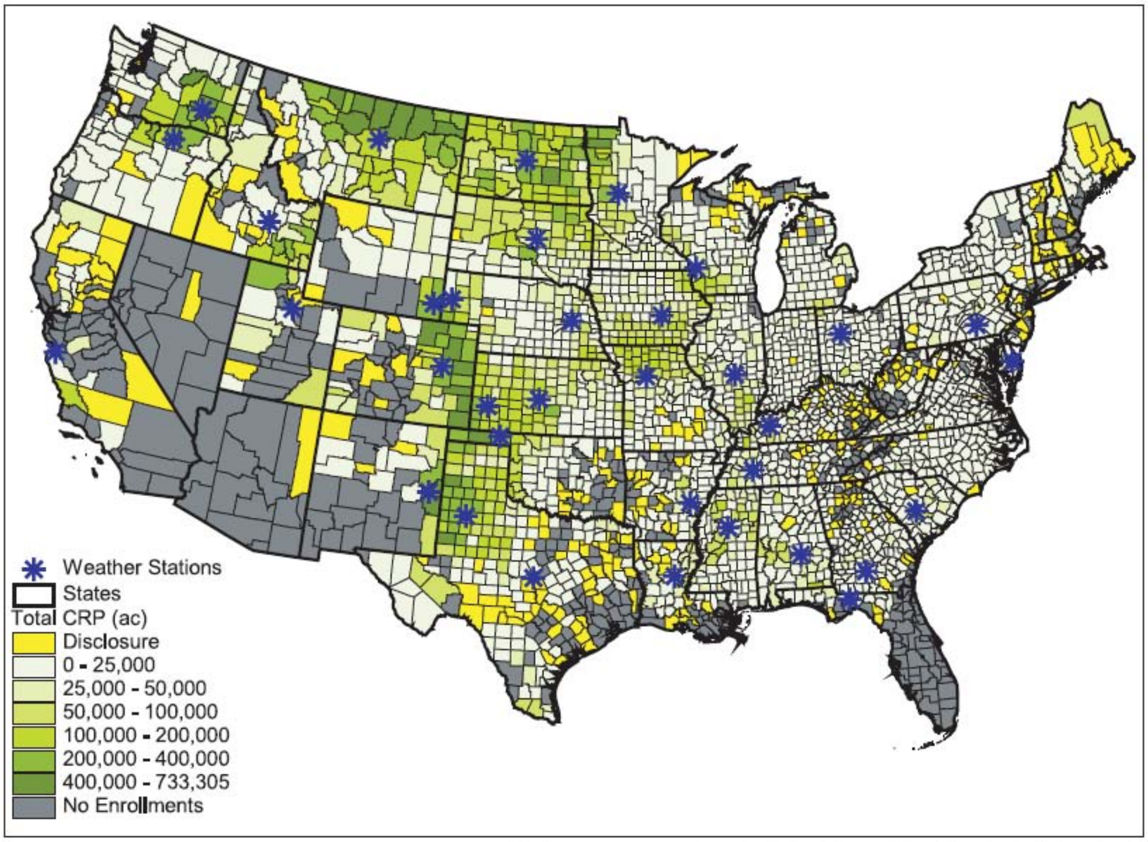


Figure 36. Predicted percentage of runoff and selected pollutants trapped by tile-drained terraces using APEX for Missouri sales tax study (Source: FAPRI-UMC, 2008)

FAPRI-UMC (2007) reports a national assessment of the environmental benefits of Conservation Reserve Program (CRP) land, in which EPIC was used to assess the impact of converting crop fields into CRP (conservation grasses or trees) and APEX was used to simulate the effect of CRP buffers on cropland sediment and nutrient losses. The CRP impacts estimated with both EPIC and APEX were performed by comparing environmental indicators for the CRP scenario versus baseline conditions without CRP. The density of CRP acreage across the 48 conterminous states is shown in Figure 37. Ten-year sequences of generated weather were used to forecast the CRP impacts, using a single weather station (Figure 37) for most of the state – CRP scenario run combinations. The EPIC and APEX simulations were performed for the 363 most dominant soils associated with CRP production; five representative soils from Maryland and Pennsylvania were used for the northeast region, due to a lack of discernible dominant soils. The regional and national impacts were determined using area-weighted estimates of the predicted CRP benefits in each region. The estimated average annual water erosion and soluble phase N and P are shown in Table 29 on both the basis of reductions per acre of buffer and per acre of fields treated with downslope buffers. The results underscore that the use of CRP buffers can be a very effective conservation practice throughout the U.S.



disclosure – acres not reported when the number of contracts is too few to protect confidentiality of program participants

Figure 37. Distribution of CRP land across the conterminous U.S. and location of the weather stations

Table 29. Estimated annual average impact of CRP buffers simulated with APEX for the conterminous U.S.

Pollutant Indicator	Reductions per acre of buffer[a]	Reductions per acre of field affected by a buffer
Water erosion (tons)	96	2.5
Soluble phase N loss (lbs)	247.2	6.4
Soluble phase P loss (lbs)	41.6	1.1

Source: FAPRI-UMC, 2007.

[a] Reductions per acre of buffer are strongly related to the size of watershed filtered by the buffer.

CEAP National Assessment

The Conservation Effects Assessment Project (CEAP) was established by multiple branches of the USDA to investigate in-depth how effective different conservation practices have been in delivering desired environmental benefits (Duriancik et al., 2008; USDA-NRCS, 2008). Much of the CEAP effort has focused on watershed-level analyses, including several that have relied on SWAT (Richardson et al., 2008; Lerch et al., 2008; Heathman et al., 2008). A National CEAP assessment is also being performed to estimate the overall impact of conservation practices that have been established on cropland areas nationwide and to estimate what conservation treatments would be further needed to meet remaining conservation resource goals (Duriancik et al., 2008; Lemunyon and Kellogg, 2008). APEX version 2110 (Table 1) is being used in the National CEAP study to estimate sediment, nutrient, and other nonpoint source pollution impacts from agricultural landscapes in cropped regions of the country, which are then routed in SWAT to provide overall water quality impacts at the Major Water Resource Region (MWRR) level and corresponding subwatersheds (Figure 38). Conservation practices are accounted for in the APEX simulations based on cropping, management and other information reported in a National CEAP survey, which was collected from 2003 to 2006 at 20,000 National Resource Inventory (NRI) sampling points that represent approximately 98% of the U.S. cropland area (Duriancik et al., 2008; Lemunyon and Kellogg, 2008). APEX 2110 has also been modified for the National CEAP study to make more efficient use of the National CEAP survey data and to provide an improved interface between APEX and SWAT.

The initial phase of applying APEX within the National CEAP analysis by Wang et al. (2006c) focused on conducting a sensitivity analysis of key parameters used in the model for approximately 90 sites located across the conterminous U.S. (Figure 39). The test sites spanned a wide range of soil types and climatic conditions and included cropping systems consisting of

Figure 38. The 18 Major Water Resource Regions (MWRRs) that comprise the conterminous U.S., and the distribution of subwatersheds within each MWRR (Source: Gassman et al., 2007)

corn, soybeans, and wheat and three tillage systems: no-till, mulch, and conventional. The sensitivity analysis was conducted for 15 APEX parameters (Table 30) that influence hydrologic, sediment loss by water or wind, nutrient losses, soil organic carbon change, and crop yield. A variance-based sensitivity analysis was performed for the selected set of parameters using an extended Fourier amplitude sensitivity test and an enhanced Morris method, which was applied to calculate the total and interaction effects of the parameters. The dominant parameters for the 10 key APEX outputs are shown in Figure 40, which were determined based on the sensitivity analysis; additional results of the sensitivity analysis are reported in the study. These results were used to guide APEX calibration procedures for the National CEAP study.

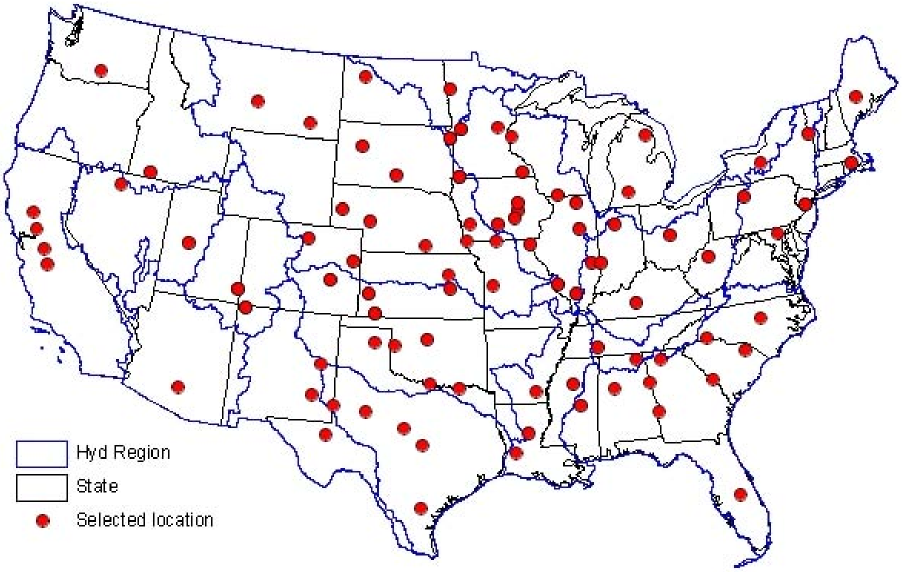


Figure 39. Distribution of APEX testing sites across the conterminous U.S. that were used in the CEAP APEX sensitivity analysis

Table 30. The APEX parameters used in the National CEAP sensitivity analysis

Input File	Parameter	Description	Lower range	Upper Range
PARM				
	parm2 (RGSS)	Root growth soil strength	1	2
	parm5 (SWLL)	Soil water lower limit; top 0.5 m soil depth	0.3	0.7
	parm7 (NFIX)	N fixation	0	1
	parm8 (SPRC)	Soluble P runoff coefficient	10	20
	parm11 (MFSG)	Moisture fraction required for seed germination	0.4	0.7
	parm29 (BMEF)	Biological mixing efficiency	0.1	0.5
	parm31 (BMMD)	Maximum depth for biological mixing (m)	0.1	0.3
	parm34 (HPETE)	Hargreaves PET equation exponent	0.5	0.6
	parm42 (CNIC)	NRCS curve number index coefficient	0.5	5
	parm46 (RCFC)	RUSLE C factor coefficient	0.5	5
	Parm52 (TERD)	Exponential coefficient of tillage effect on residue decay rate	5	15
OPS				
	PHU	Potential heat units (ºC)	800	2400
SOIL				
	FHP	Fraction of HUMUS in passive pool	0.3	0.9
APEXCONT				
	UXP	Power parameter of modified exponential distribution of wind speed	0.1	0.6
	RFP	Return flow ratio	0.4	0.95

Source: Wang et al., 2006c.

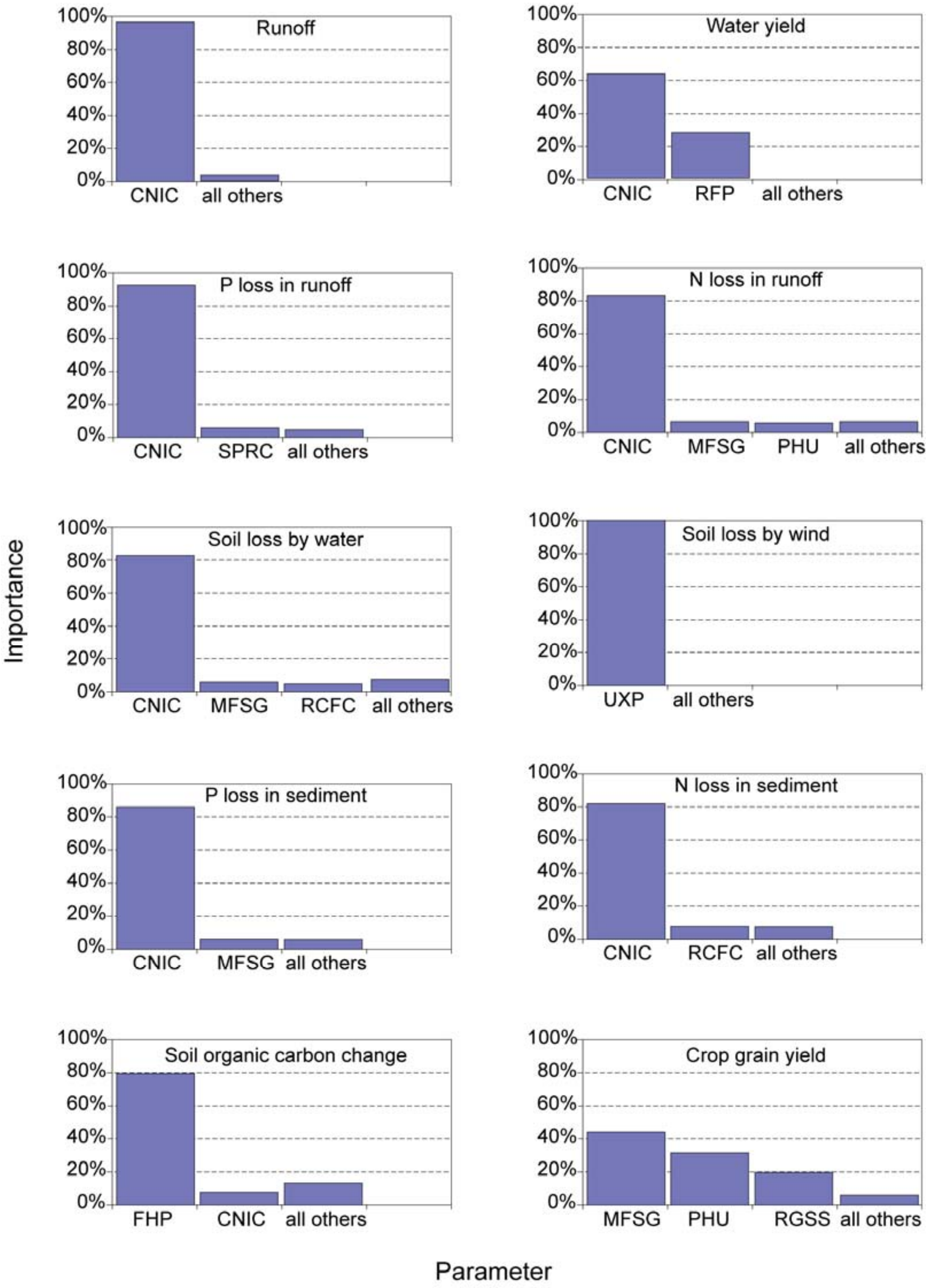


Figure 40. The "percentage of importance" of APEX input parameters that were ranked first in the sensitivity analysis for 10 key APEX output indicators, plus comparisons of the dominant input parameters versus other parameters that were determined to rank at least 5% in importance based on the sensitivity analysis results (Source: Wang et al., 2006c)

APEX simulations are being performed for a wide range of cultural and structural conservation practices in the national CEAP study as described by BREC (2008), in support of two primary scenarios being performed with the modeling system for the national CEAP study: (1) a baseline scenario that incorporated conservation practice and CRP data from the CEAP surveys conducted from 2003 to 2006, and (2) a no-practices scenario that assumed that conservation practices were not implemented on any U.S. cropland. The no practices scenario provides a basis for determining the environmental benefits of the conservation practices that were simulated in the baseline. Conservation practices were grouped together according to similar functionality; representative practices were determined for each grouping and simulated in the baseline scenario where appropriate.

The APEX scenarios were constructed based on standard configuration that represented a 16 ha (40 ac) crop field and tillage in the same direction of the slope (Figure 41). The standard field configuration was used to represent baseline CEAP survey points that either had no conservation practices or reported structural or cultural practices that could be simulated using just one subarea in APEX. Other APEX configurations were developed to represent more complex practices that required multiple subarea simulations such as forest riparian buffers (Figure 42) and grassed waterways (Figure 43). The forest riparian buffer is depicted in APEX as consisting of both a thinner grass filter strip 10 m in width upslope from the 30 m wide forest buffer, along with contoured tillage performed on the cropped area (Figure 42). The grassed waterway is represented with a vegetated channel in the second APEX subarea, which buffers surface runoff and potential soil erosion that could occur from the runoff in the channel (Figure 43). The methodology and assumptions used to perform these and other simulations are discussed in more detail in BREC, 2008.

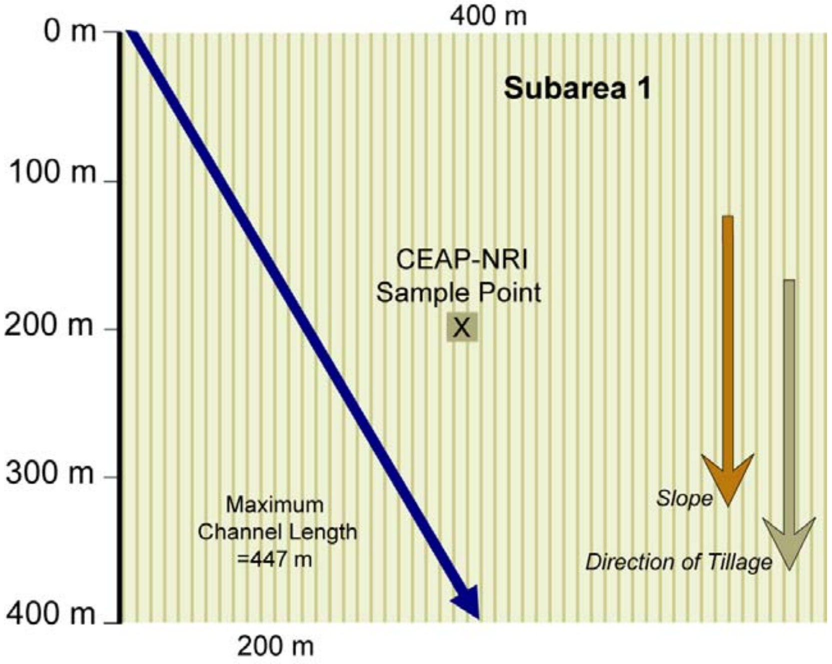


Figure 41. Standard APEX field configuration used for the CEAP National Assessment (Source: BREC, 2008)

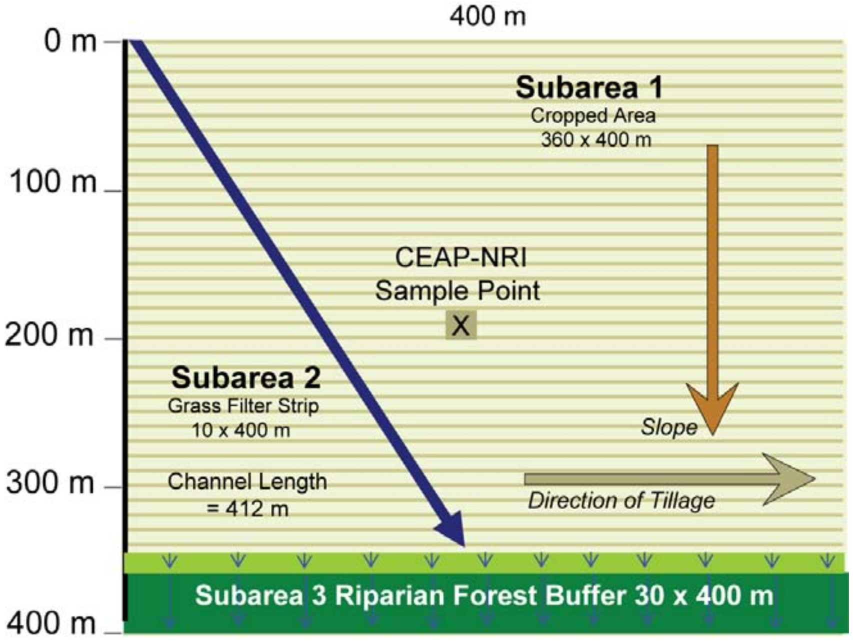


Figure 42. APEX field configuration used to represent a riparian buffer for CEAP National Assessment, shown with tillage performed on the contour (Source: BREC, 2008)

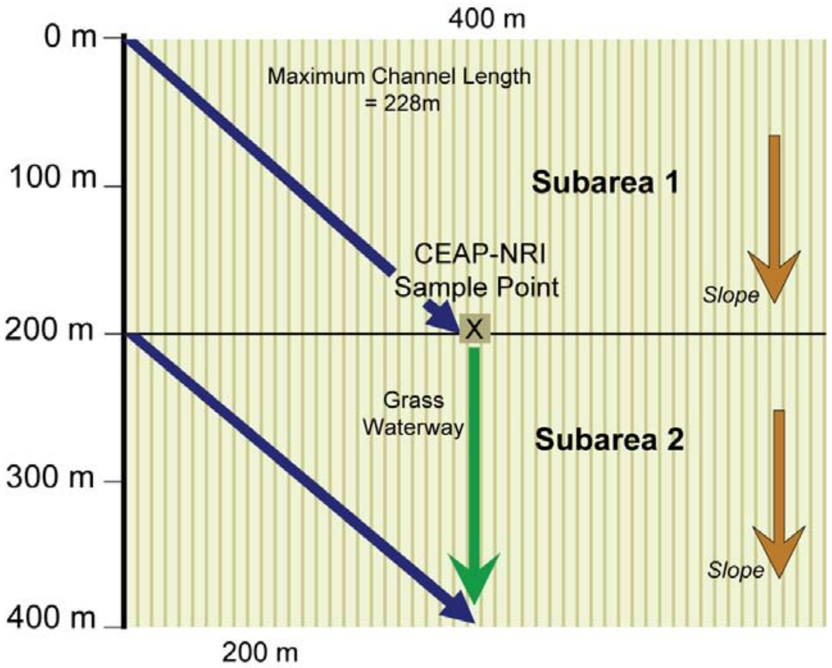


Figure 43. APEX field configuration used to represent a grade stabilization structure or grass waterway for the CEAP National Assessment (Source: BREC, 2008)

A detailed summary of complete national CEAP study results obtained for the Upper Mississippi River Basin (UMRB) MWRR (Figure 38) is forthcoming in early 2009. Results for other MWRRs will be described in forthcoming reports that will be released in the near future.

APEX INTERFACES

Several interface and other tools have been developed to support APEX applications since the first versions of the model were released. One of the first software programs developed to support APEX simulations was an automatic input file builder and execution program called run_apex (Figure 44); three separate versions of the software were used to create and execute specific APEX simulations required for the NPP UNBRW, LFRW, and UMRW applications. Each run_apex software performed similar tasks of integrating required soil, livestock operation, and manure characteristics; management practices; climate data; and standard APEX data files

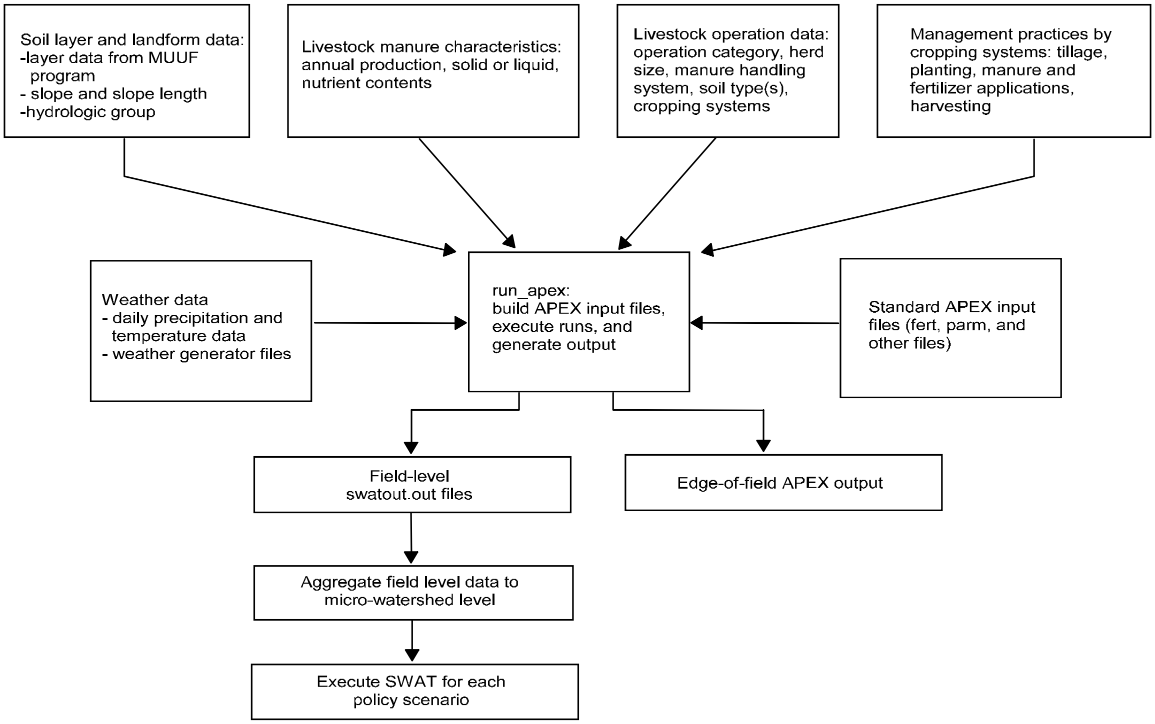


Figure 44. Schematic of the automatic APEX input file builder and execution (run_apex) programs developed for the NPP, and the required steps to link APEX with SWAT (adapted from Osei et al., 2000b)

into a set of APEX scenario simulations for the respective watershed of interest. Execution of APEX was also performed within each run_apex code for every simulation required for a given scenario, with corresponding outputs of both edge-of-field indicators and output data that were subsequently routed through SWAT. Further post-processing of the data designed for input into SWAT was performed by an additional software program, as described in Gassman and Hauck, 1996. The original run_apex codes were designed to operate on UNIX platforms but were later ported to a Disk Operating System (DOS) environment supported by standard PCs.

Interactive APEX (i_APEX)

The original run_apex programs have been superseded by the Interactive APEX (i_APEX) software package, which functions in a PC Windows environment and is similar to other interactive software developed by the Center for Agricultural and Rural Development (CARD) for EPIC, Century, and SWAT (CARD, 2008). The i_APEX software performs essentially the same functions as the predecessor run_apex programs for a user-defined set of APEX simulations, including automatic management of the input data, execution of each APEX run, and storage of selected model outputs. A single Access database is used to manage both the input and output data of all APEX simulations performed for an i_APEX application. An initial preprocessing step is required to fill the Access database input data tables, which typically requires conversion of existing input data from ASCII files and other file formats. An import function is also provided that allows users to import previously existing APEX datasets into the i_APEX environment. Modifications of input values can be performed in Access using query functions and other tools provided in Access. Analysis of output can also be performed in the databases using various functions provided in Access, and Access export options to Excel and other software can also be used. Documentation for the structure of the data tables is provided on the i_APEX website (CARD, 2008); the i_APEX executable file can also be downloaded from the i_APEX website, along with a sample Access database.

To date, the most extensive use of the i_APEX software has been to manage the thousands of APEX simulations required for the national CEAP study. The software has also been used to support other APEX-based studies, including the one performed by Yin et al. (2008).

WinAPEX and WinAPEX-GIS

The WinAPEX software is a Windows interface developed by the BREC (Magre et al., 2006; Steglich and Williams, 2008) to provide APEX users with a user-friendly environment for executing APEX version 0604, the latest version of the model (Table 1). The program provides a watershed builder subroutine that takes the user through a series of screens in order to construct the input data for individual subareas that will be incorporated into an APEX field, landscape, whole farm, or watershed simulation. These attributes include soil layer inputs, landscape characteristics, climate data, management practices, cropping systems, and other data. WinAPEX also provides editing tools that allow for assessments of the impacts of alternative scenarios, such as changes in management or cropping systems, on APEX output indicators such as the hydrologic balance or sediment, nutrient, and other pollutant losses. The output of APEX simulations performed in WinAPEX are stored in several ACCESS tables, which again provide post-processing or export options similar to what was described for i_APEX above.

A combined ArcGIS and WinAPEX modeling system called WinAPEX-GIS has also been developed (Dyke, 2008) and is being used to build the input files and execute APEX version 0806 (64-bit; see Table 1) for the BRW application requiring over 15,000 subwatersheds, as described above in the APEX Large Watershed Scenario Applications section. The system first utilizes the capabilities of ArcGIS to calculate all the GIS-based input data such as soil distributions and attributes, landscape characteristics, land use, and topographic variation. These data are stored in Access tables that are ported to WinAPEX, where management data required for the BRW simulations are then constructed. The APEX simulations are executed in WinAPEX and the output data are stored back in Access. These final Access tables can then be read back into ArcGIS to create different map displays of interest.

SWAT-APEX (SWAPP) Program

Saleh and Gallego (2007) describe an innovative SWAT-APEX (SWAPP) interface that has been constructed within an ArcView GIS platform. The SWAPP program was developed to provide an automated method of performing nested APEX simulations on the field, whole farm, or small watershed scale within a SWAT watershed application. The approach builds on the previously described NPP APEX-SWAT simulations and provides an improved and more consistent methodology as compared to the earlier NPP interfaces of the two models.

The SWAPP program is executed in four phases (Figure 45) and is initiated with SWAT GIS input data layers created by the ArcView SWAT (AVSWAT) interface (Di Luzio et al., 2004a,b) for the respective watershed of interest. Additional steps in Phase I include input of standard data files (crop parameters, farm machinery, etc.) and generation of the required APEX

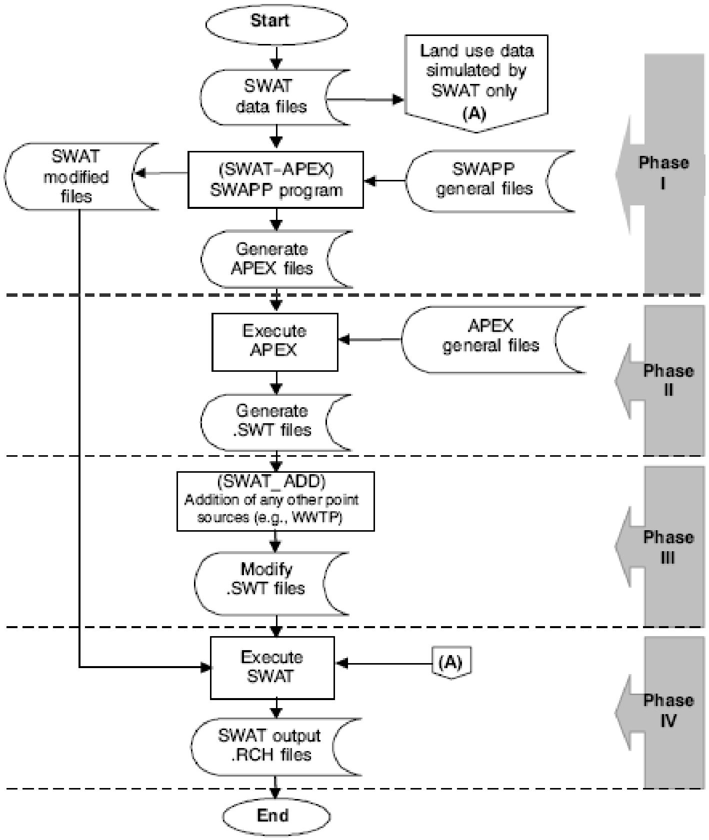


Figure 45. Schematic showing the four main phases of a SWAT-APEX (SWAPP) program application (Source: Saleh and Gallego, 2007)

and modified SWAT input files. Determination of the land parcels simulated in APEX versus those simulated in SWAT is based on user-supplied criteria in SWAPP. Execution of the APEX simulations is performed in phase II, including creation of output files (.SWT files) that contain flow and pollutant exports from the APEX simulations that are input into SWAT at the subwatershed level. These .SWT files are further modified in phase III if point sources such as wastewater treatment plants (WWTP) are present in the watershed. The watershed-level SWAT simulation is then performed in phase IV, which incorporates output from all APEX simulations that were performed in phase II of the SWAPP application.

Saleh et al. (2008) present an enhanced version of SWAPP called CEEOT-SWAPP, which supports an expanded interface between the previously described FEM economic model and APEX and/or SWAT. The incorporation of FEM into the software provides the ability to estimate net farm returns and other economic indicators for different representative farms. Net farm returns are reported by Saleh et al. (2008) for a UNBRW haul-off scenario as well as environmental impacts based on combined APEX and SWAT simulations. Saleh and Gallego (2007) also report UNBRW environmental impacts that are briefly summarized in the UNBRW APEX Calibration/Validation Studies subsection.

ArcGIS APEX-SWAT Interface

Olivera et al. (2006) developed an ArcGIS SWAT interface (ArcSWAT) that has been accessible by the SWAT user community since early 2007. A new software package has since been developed that interfaces SWAT with APEX within ArcGIS. It provides overall modeling support similar to that in SWAPP and takes advantage of improved options included in the ArcGIS platform. The APEX-SWAT ArcGIS interface allows the creation of both stand-alone APEX and SWAT simulations, as well as integrated APEX-SWAT scenarios. Integrated applications initially require user identification of a pre-existing SWAT dataset. The user then selects which subbasins will be modeled with APEX, including the option of choosing higher resolution topographic data (Digital Elevation Model or DEM) to facilitate more detailed terrain modeling for the APEX areas. The APEX model interface automatically generates time series of model outputs that can be incorporated directly back into the SWAT model. A complete watershed simulation can then be performed with SWAT, including the hydrologic and pollutant loss levels generated with APEX for specific areas of the watershed.

FUTURE IMPROVEMENTS AND RESEARCH NEEDS

The APEX model has continually evolved since its inception, and the process of adaptation and modification will likely continue as use of the model expands for an ever-increasing range of environmental problems and conditions. Several improvements to specific model subroutines have already been initiated, while other potential improvements have been identified that will require future research and code modification efforts. Some of these forthcoming or identified potential enhancements are as follows.

1. A more mechanistic denitrification routine is currently being developed that will be incorporated into future versions of APEX. This new submodel will incorporate more comprehensive approaches to estimate CO_2, O_2, and N_2O fluxes in the soil-plant-atmosphere system than are currently used in APEX.

2. A new water table fluctuation routine is also being developed for APEX that uses the drainage volume–water table depth relationship to determine how far the water table falls or rises when a given amount of water is removed or added. The drainage volume–water table depth relationship can be determined from estimated drainable porosities of each soil layer as described by Skaggs (2007).

3. An improved subsurface tile drainage routine is also being developed for APEX that simulates the volume of water removed from the soil profile through the subsurface drains by calculating subsurface drainage flux based on Houghoudt's steady-state equation (Bouwer and van Schilfgaarde, 1963). This is the same approach that is used in the DRAINMOD subsurface drainage model as described by Skaggs (2007). This approach would allow for a broader range of tile drainage scenarios to be performed with APEX for both subsurface flow and nitrate loss (e.g., see Brevé et al., 1997; Singh et al., 2007).

4. Improvements to the APEX hydrologic interface could be obtained via modifications to the RCN technique and/or adaptation of more complex physically based routines, similar to the concepts discussed by Gassman et al. (2007) for the SWAT model. Several viable proposed or actual modifications have been reported in the literature for SWAT that could be incorporated into APEX, including the potential to incorporate a kinematic wave methodology into SWAT as discussed by Borah et al. (2007) and specific SWAT curve number modifications reported by Easton et al. (2008), Wang et al. (2008c), and Kim and Lee (2008).

5. To date, there are no reported applications of climate change impacts on crop yields using APEX, although the model can be readily applied for such scenarios in a manner similar to that of many studies reported for EPIC (Gassman et al., 2005). Improvements in evaluating atmospheric CO_2 effects on crop yield could be incorporated in both models, based on the methods developed by Eckhardt and Ulbrich (2003) for the SWAT-Germany (SWAT-G) model in which the effects of CO_2 on plant growth are accounted for via varying stomatal conductance and leaf area response as a function of plant species, rather than using the same response functions across all plant species as currently assumed in EPIC and APEX (and the standard SWAT model). There is also a need to investigate further the response of CO_2 on crop yield in general in APEX and related models, per the debate that has emerged between Long et al. (2006) and Tubiello et al. (2007).

6. An optional method based on the nearest-neighbor concept for estimating hydraulic conductivity, field capacity, and wilting point computed as a function of soil texture and organic C has been developed and inserted in the latest versions of EPIC and APEX. Initial testing of these functions indicate that they provide more accurate estimates of key soil water parameters versus the routines that have traditionally been used in EPIC.

7. The APEX grazing component will be improved to include preferential grazing and weight gain and loss. Range conditions will be simulated so that plant populations and mixes change as a function of management. Also, manure production and content will be affected by forage and feed intake and quality.

8. Ephemeral and classic gully erosion will be simulated using GIS and physically based erosion equations as an addition to the APEX erosion/sedimentation component.

9. From their origin the EPIC/APEX models have removed eroded soil and attached nutrients and pesticides from the soil profile as part of the emphasis on erosion-productivity. In a similar manner, eroded soil and attachments will be deposited and added to downstream subarea soil profiles as dictated by the APEX sediment routing component.

CONCLUSIONS

The Agricultural Environmental Policy EXtender (APEX) model has proven to be a versatile and useful tool for evaluating complex landscape and management scenarios, as demonstrated by the review of applications reported here. The multi-subarea capabilities of the model greatly expand the simulation strengths inherent in the predecessor model EPIC and provide a platform for performing a much wider array of hydrologic and/or environmental impact scenarios than previously possible. The model also complements the strengths of SWAT well by providing a means to simulate field- or landscape-level cropping systems, field operations, conservation practices, and silvicultural practices in much more detail than possible in SWAT. The output from the APEX simulations can then be incorporated into a larger SWAT watershed application, which preserves the accuracy of the APEX simulations in the overall watershed-level assessment as described for several studies. The advent of GIS interfaces such as SWAPP, CEEOT-SWAPP, and ArcGIS APEX-SWAT point to even greater flexibility in future applications that incorporate the combined modeling approach with APEX simulations nested within SWAT.

The calibration and validation results reported from several studies reviewed here further underscore the strength of APEX and indicate that the model can provide accurate accounting of different scenario impacts, especially when used to generate relative comparisons of different cropping and management system impacts. However, ongoing testing of APEX is needed to further improve its accuracy and to expand the overall simulation domain to which the model can be applied. It is anticipated that the types of environmental problems to which APEX can be applied will increase in the future, particularly for evaluation of different cropping systems and conservation practices on varied landscapes that require the multi-subarea capabilities of the APEX approach to be properly evaluated.

ACKNOWLEDGMENTS

This study was funded in part from support provided by the U.S. Department of Agriculture, Natural Resources Conservation Service (Project No. Q683H753122#33). Copyright permissions granted for figures and/or tables used in this report are also acknowledged as follows for the respective sources: (1) from the American Society of Agricultural Engineers for Gassman et al. (2001; 2003), Saleh et al. (2004), Wang et al. (2006c), Saleh and Gallego (2007), Osei et al. (2008b), and Yin et al. (2008); (2) from the Soil and Water Conservation Society for Osei et al. (2000a); (3) from Rangeland Ecology & Management, Allen Press Publishing Services, for Osei et al. (2003b); (4) from Elsevier Science Ltd. via License Numbers 2106611169022, 2106610765202, and 2100511130045 issued by Copyright Clearance Center, Inc. Rightslink for Osei et al. (2003a), Gassman et al. (2006), and Wang et al. (2008), respectively.

We also acknowledge permissions granted by Dr. Verel Benson of the University of Missouri (retired) to use figures and/or tables taken from FAPRI-UMC (2007 and 2008), and to Dr. David Willis of Clemson University for use of figures from Willis (2008). And we acknowledge Mr. Matthew McBroom, Geographic Information Systems Laboratory, Arthur Temple College of Forestry & Agriculture, Stephen F. Austin University, as the creator of the original version of Figure 26.

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