INVITED REVIEW ARTICLE:

THE AGRICULTURAL POLICY/ENVIRONMENTAL EXTENDER (APEX) MODEL: AN EMERGING TOOL FOR LANDSCAPE AND WATERSHED ENVIRONMENTAL ANALYSES

P. W. Gassman, J. R. Williams, X. Wang, A. Saleh, E. Osei,

L. M. Hauck, R. C. Izaurralde, J. D. Flowers

ABSTRACT. *The Agricultural Policy/Environmental eXtender (APEX) model was developed by the Blackland 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 uses 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 crop fields, intensive rotational grazing scenarios depicting movement of cows between paddocks, vegetated grassed waterways in combination with filter strip impacts, and land application of manure removed 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 the National Pilot Project for Livestock and the Environment (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 GIS-based or Windows-based interfaces are also described, as are forthcoming improvements and additional research needs for the model.*

Keywords. *APEX, Best management practices, Conservation practices, Farm and watershed simulations, Soil carbon, Water quality.*

Extensive hydrologic and environmental model development has been carried out over the past four decades by the USDA Agricultural Research Service (USDA-ARS) and Texas A&M University, Texas AgriLIFE research units located in Temple, Texas, at the Grassland, Soil and Water Research Laboratory (GSWRL) and Blackland Research and Extension Center, respectively (Williams et al., 2008a). Early model investigations 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 (EPIC) model (Williams et al., 1984; Williams, 1990, 1995; Gassman et al., 2005; Izaurralde et al., 2006) and the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Arnold and Fohrer, 2005; Gassman et al., 2007), which were designed to evaluate water quality and other agricultural environmental problems at the field scale and watershed scale, respectively.

Both the EPIC and SWAT models have experienced continuous evolution since their inceptions and have emerged as key tools that are used worldwide for analyzing a wide variety of environmental problems (Gassman et al., 2005, 2007). However, significant gaps in the ability to simulate key landscape processes at the farm or small watershed scale have persisted, despite the versatility of these and other models. This weakness was noted at the onset of the National Pilot Project for Livestock and the Environment (NPP), which was commissioned in the early 1990s to address water quality and other environmental problems associated with intensive livestock production (Jones et al., 1993; Osei et al., 2008c). A key objective of the NPP was to evaluate a wide range of alternative manure management scenarios that included relatively complex

Submitted for review in June 2009 as manuscript number SW 8060; approved for publication by the Soil & Water Division of ASABE in March 2010.

The authors are **Philip W. Gassman, ASABE Member Engineer,** Associate Scientist, Center for Agricultural and Rural Development, Department of Economics, Iowa State University, Ames, Iowa; **Jimmy R. Williams,** Senior Research Scientist, and **Xiuying Wang, ASABE Member Engineer,** Research Assistant Professor, Blackland Research and Extension Center, AgriLIFE Research, Texas A&M University System, Temple, Texas; **Ali Saleh, ASABE Member Engineer,** Associate Director, **Edward Osei,** Senior Research Economist, and **Larry M. Hauck,** Lead Scientist, Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas; **R. César Izaurralde,** Laboratory Fellow, Joint Global Change Research Institute, Pacific Northwest National Lab and University of Maryland, College Park, Maryland; and **Joan D. Flowers,** Senior Water Quality Scientist, Jacobs Engineering Group, Inc., Water Infrastructure, Fort Worth, Texas. **Corresponding author:** Philip W. Gassman, Center for Agricultural and Rural Development, 560A Heady Hall, Department of Economics, Iowa State University, Ames, IA 50011-1070; phone: 515-294-6313; fax: 515-294-6336; e-mail: pwgassma @iastate.edu.

  ISSN 2151-0032

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 and Izaurralde, 2006; Williams et al., 2006a; Williams et al., 2008a), 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 crop fields, intensive rotational grazing scenarios depicting movement of livestock between paddocks, vegetated grassed waterways in combination with filter strip impacts, and land application of manure removed from livestock feedlots or waste storage ponds. The routing of water, sediment, nutrients, and pesticides can be simulated between subareas and through channel systems in the model; these routing capabilities are some of the most comprehensive available in current landscape-scale models (Srivastava et al., 2007).

The objectives of this study are 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 Geographic Information System (GIS) and other interface tools that have been developed to facilitate APEX applications for watershed-scale 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 APEX, which included a description of the major components of the model, including the manure management component. An expanded qualitative description of the model was reported by Williams et al. (2006a), who provided overviews of the manure erosion and routing components, including some mathematical description. Williams and Izaurralde (2006) provided 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. (2008b) provided 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 by Williams et al. (2006a). 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 by Gassman et al. (2005).

Overview of APEX

The APEX code is written in FORTRAN and can be executed on both personal computer and UNIX platforms. 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 irrigation (sprinkler, drip, or furrow), 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 animal feeding operation (AFO) waste storage ponds or lagoons is a key component of the model. Stockpiling and subsequent land application of solid manure collected from feedlots 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 runoff, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow. Water quality in terms of soluble and organic nitrogen (N), soluble and organic phosphorus (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.

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 (Nicks et al., 1995). 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 are 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 can be intercepted by plant canopies, and then precipitation, snowmelt water, and/or irrigation input are 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 off-site water effects.

Surface runoff volume can be estimated with two different methods in APEX: a modification of the USDA, Natural Resources Conservation Service (NRCS) 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 was described by Kannan et al. (2008) and Wang et al. (2009) and can result in more accurate runoff estimations for some soil and land cover conditions.

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-NRCS Technical Release 55 (TR-55) method (USDA-NRCS, 1986) as a function of rainfall intensity and other factors. 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 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. 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 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 (Priestley and Taylor, 1972), Penman-Monteith (Monteith, 1965), and Baier-Robertson (Baier and 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. APEX computes evaporation from soils and plants separately, as described by Ritchie (1972).

Crop Growth

A single growth model is used in APEX for the simulation of crops, trees, and other plants that is based on the EPIC crop growth model (Williams et al., 1989). To date, unique input parameters have been developed for about 100 different crops and other vegetative species. APEX is capable of simulating growth for both annual and perennial crops. Phenological development of the crop is based on daily heat unit accumulation. Annual crops grow from planting date to harvest date or until the accumulated heat units equal the potential heat units for the crop. Perennial crops maintain their root systems throughout the year, although they may become dormant after frost. They start growing when the average daily air temperature exceeds their base temperature. The model is also capable of simulating mixed stands of up to ten crops or other plants in a competitive environment. The plant competition algorithms were originally developed for the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model (Kiniry et al., 1992) and account for competition between crops, weeds, and other plants for light, water, and nutrients.

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 (Williams et al., 2008b): 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); three MUSLE variants described by Williams (1995), which are referred to as MUST (theoretical version), MUSS (small watershed version), and MUSI (approach that uses input coefficients); the Revised USLE (RUSLE) method (Renard et al., 1997); and RUSLE2 (USDA-ARS, 2005). Multiple equations can be activated during a simulation, but only one interacts with other APEX components, as specified by the user. The eight 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 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; Cerri et al., 2004). These routines estimate soil carbon changes as a function of climatic conditions, soil properties, and management practices and simulate storage and transfers of carbon and nitrogen among pools (structural litter, metabolic litter, biomass, slow and passive). Inputs of carbon to the soil in a subarea occur via litter inputs (above and below ground), organic amendments (e.g., composted manure), and carbon in soil sediments. Losses of carbon occur via heterotrophic respiration (CO_2), water (particulate and soluble C) and wind (particulate C) erosion, and leaching processes (soluble C). Carbon and nitrogen transfers among these pools are regulated by soil moisture, temperature, tillage, and oxygen availability.

Nitrogen Cycling and Losses

The complete N cycle is simulated in APEX, including atmospheric N inputs, fertilizer and manure N applications, crop N uptake, mineralization, immobilization, nitrification, denitrification, 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 includes N^2 and nitrous oxide (N_2O), as products of denitrification, and ammonia volatilization. The N_2 and N_2O emissions are simulated in APEX by 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 concentration (Williams, 1995). The NO_3-N concentration in a soil layer decreases exponentially as a function of flow volume. The average loss during a day is obtained by integrating the exponential concentration function with respect to flow. The 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 a partitioning concept originally developed by Knisel (1980), who used it to partition 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 above for organic N transport. The P mineralization model developed by Jones et al. (1984) is a modification (Williams, 1995) of the Production of Arid Pastures Limited by Rainfall and Nitrogen (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 ten herds or groups of animals. Only one herd may occupy a subarea at any time. All livestock rotations among subareas are performed automatically by APEX within user constraints. 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. 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. Solid manure is scraped from the feeding area automatically at a user input interval in days and stockpiled for automatic application to designated 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 and its ingredients (mineral and organic N and P) are inputs.

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 (Williams, 1995), which provides direct estimates of organic nutrient and carbon losses. The simulated erosion can consist of essentially just manure or 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.

Routing Component

A watershed first has to be subdivided into multiple subareas, which are relatively homogeneous in terms of soil, slope, land use, management, and weather, prior to defining the routing structure for an APEX whole-farm or watershed simulation. The ArcGIS APEX (ArcAPEX) GIS interface (Tuppad et al., 2009) can be used to define the subarea boundaries, as described later in the APEX Interfaces section. The user may also manually define the subareas using the procedure described by Steglich and Williams (2008). A downstream subarea is identified if the distance from the subarea outlet to the most distant point of the subarea is greater than the routing reach length. Runoff hydrographs from subareas are then simulated and routed downstream to the watershed outlet.

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, then the daily time step method should produce realistic estimates and be computationally efficient. However, the complete flood routing method provides estimates of actual stream flow and potentially increases accuracy in estimating pollutant transport, especially when simulating larger watersheds.

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. 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. Runoff hydrographs are simulated with a variation of the VSC method called the storage depletion technique. Sediment is routed through the channel and floodplain separately. If daily time step routing is used, then 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, then 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. Mineral nutrient losses occur only if flow is lost within the reach. Organic N and P mineralization in the channels is not considered because, in general, the travel time is short. 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.

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 the enhanced carbon cycling routine, expanded reservoir component, and complete streamflow routing submodel. The first APEX user's manual was produced for APEX version 8190 (BREC, 1999); more recent user's manuals have been published for APEX versions 1310 (Williams et al., 2003), 2110 (Williams et al., 2006b), 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

Table 1. Overview of key APEX versions including available documentation.

Version	Release Date	Documentation	Comments
5140	May 1995	--	Original version. Included subarea, routing, and liquid manure routines, and export of output to SWAT. First comparisons with field measurements. Used for NPP UNBRW study in north central Texas.
7045	February 1997	--	Automatic feedlot manure removal routines introduced. First applications for rotational grazing. Used for NPP LFRW study in northeast Texas.
8190	April 1998	BREC (1999)	Testing with Iowa tile drainage data. Applied for NPP UMRW study in northeast Iowa.
1310	November 2001	Williams et al. (2003)	Improved reservoir (including playa lake applications) and forest hydrology subcomponents. Ability to simulate multiple livestock species introduced.
2110	April 2002	Williams et al. (2006b)	Introduction of Century-based carbon cycling submodel. Version used for the National Conservation Effects Assessment Project (CEAP) study (Duriancik et al., 2008).
0604	April 2006	Steglich and Williams (2008)	Most recent version. Includes complete streamflow routing submodel, additional reservoir component enhancements, and RUSLE2 erosion equation.
0806	June 2008[a]	--	64-bit version. Can simulate large numbers of subwatersheds. Being used for Bosque River application in Texas with 15,000 subwatersheds.

[a] Version 0806 has not been publicly released yet.

was used for in the NPP. Additional discussion is then focused on other applications of the model, including calibration and/or 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 of conditions in the U.S. and other regions (Gassman et al., 2005), provide a further validation foundation for APEX.

A range of graphical and statistical approaches have been used to evaluate the calibration and/or validation performance of APEX in previous studies. Two of the most frequently used statistics are the Nash-Sutcliffe model efficiency (NSE) described by Nash and Sutcliffe (1970) and the coefficient of determination (R^2). Values of NSE can range from -∞ to 1 and indicate how accurately simulated values fit the 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. The R^2 value 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 indicating 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. Description of NSE and R^2 results for specific studies is provided as appropriate in the remainder of this discussion.

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 central Iowa (Gassman et al., 2003), and the Duck Creek watershed (DCW) located in east central Texas (Gassman et al., 2001). The associated projects and characteristics of the three NPP watersheds are listed in table 2. Each of these watersheds was simulated within part or all of the Comprehensive Economic Environmental Optimization Tool (CEEOT), an integrated economic and environmental modeling system that was developed for the NPP assessments (Osei et al., 2000b, 2008c).

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-level 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 in either APEX or SWAT as appropriate. Output from SWAT could then be compared with economic indicators generated from FEM; alternatively, just 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), who

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

Watershed	Watershed Characteristics (at the time of the studies)
Upper North Bosque River (UNBRW)	North central Texas, 93,000 ha, including rangeland (43%), woodland (23%), forage fields (23%), and dairy waste application fields (7%); 95 dairies with over 34,500 cows (confined feedlots).
Lake Fork Reservoir (LFRW)	Northeast Texas, 127,048 ha, including improved pasture (44%), unimproved pasture (27%), water (9%), and woodland (8%); 205 dairies with nearly 32,000 cows.
Upper Maquoketa River (UMRW)	Northeast Iowa, 16,224 ha, including corn or soybeans (66%), woodland (9%), alfalfa (7.5%), Conservation Reserve Program (CRP) land (4%), and pasture (4%); 90 operations with dairy cows, feeder cattle, swine, beef cows, and calves.

described the CEEOT 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 were described in further detail by 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 that were distributed across the watershed (fig. 1). Actual herd sizes estimated at the time of the UNBRW study were used to test baseline conditions (referred to as the environmental baseline) for APEX simulations nested in SWAT, in order to represent as accurately as possible the true nutrient load from the dairies located in the watershed. However, permitted herd sizes obtained from dairy permits were used for the policy scenarios to reflect the potential total manure nutrient load that could be land-applied in the watershed. Representative farm models were developed in FEM for small (225 cows), medium (400 cows), and large (1,200 cows) dairies that represented the small (0 to 249), medium, (250 to 600), and large (>600) size classes used in the study.

The development and execution of the APEX manure application scenarios were based on specific data available for the majority of these dairies from Texas Natural Resource Conservation Commission (TNRCC) permits, which must be filed for dairies with 250 or more cows. The permitted dairies

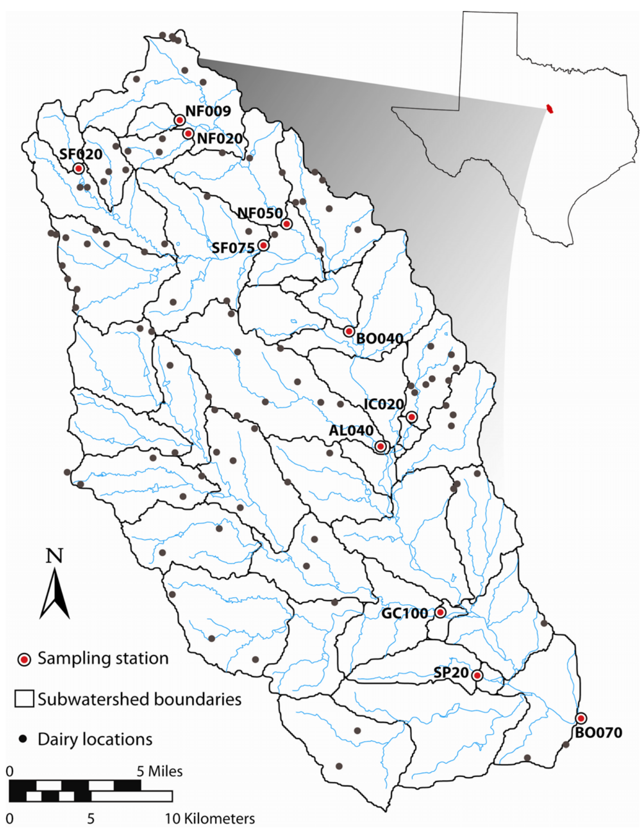

Figure 1. The Upper North Bosque River watershed (UNBRW) located in north central Texas, showing location of the SWAT subbasins, dairy operations, and sampling sites.

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 simulations due to several reasons, as discussed by Gassman (1997). The dairy manure application rates were simulated on an N basis for the policy baseline, which was determined as a function of TNRCC manure N availability and volatilization loss assumptions, as described further by Flowers et al. (1998) and Gassman et al. (2002); both studies also describe 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 included comparisons with measured data collected from field plots and indirect validation at the watershed level with APEX simulations embedded within SWAT. The first phase compared the model output with surface runoff, sediment loss, and N and P 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 2 through 4 show comparisons of simulated cumulative surface runoff, total N losses, and total P losses versus corresponding measured values reported by Flowers et al. (1996) for the eight test plots. These results show that the APEX predictions 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 indicators for the array of several hundred dairy waste application fields located in the UNBRW. Gassman (1997) reported additional UNBRW field-scale calibration and sensitivity analyses of APEX crop yield and other estimates.

Indirect watershed-level testing of APEX 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

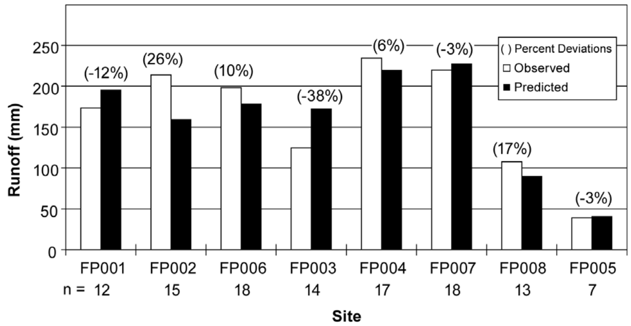

Figure 2. Comparison of predicted to observed cumulative runoff for UNBRW APEX plot-level testing (source: Flowers et al., 1996).

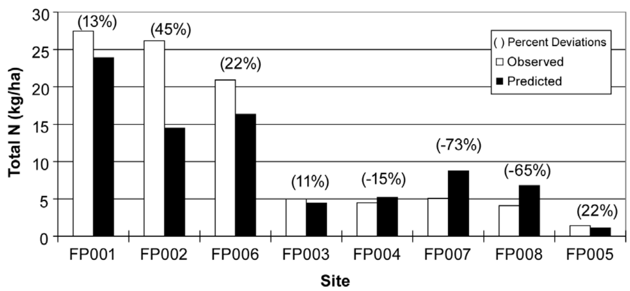

Figure 3. Comparison of predicted to observed cumulative total nitrogen loss for UNBRW APEX plot-level testing (source: Flowers et al., 1996).

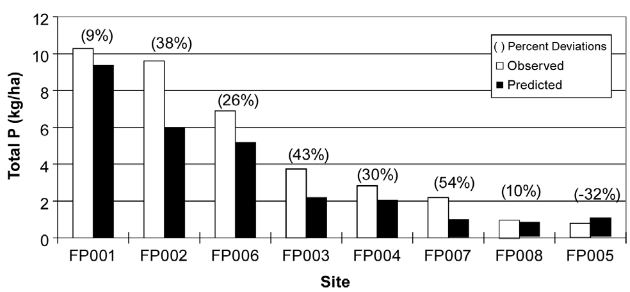

Figure 4. Comparison of predicted to observed cumulative total phosphorus loss for UNBRW APEX plot-level testing (source: Flowers et al., 1996; Osei et al., 2003a).

compared with measured data collected at 11 monitoring sites (fig. 1) 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 calibration and validation NSE statistics 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 replicated the measured streamflows and pollutant losses. Similar UNBRW APEX/SWAT testing results were reported for January 1994 to July 1999 by Saleh and Gallego (2007).

LFRW Baseline and Scenario Simulation Assumptions

Dairy production was also extensive in the LFRW, which was dominated by pasture-based dairies that were considerably smaller than the UNBRW dairy operations. The distribution of the 205 dairy operations across the LFRW at the time of the study is shown in figure 5, 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. Representative farm models were again developed in FEM for very small (95 cows), small (178 cows), medium (275 cows), and large (556 cows) dairies that represented the very small (<101), small (101 to 200), medium, (201 to 300), and large (>300) size classes used in the study.

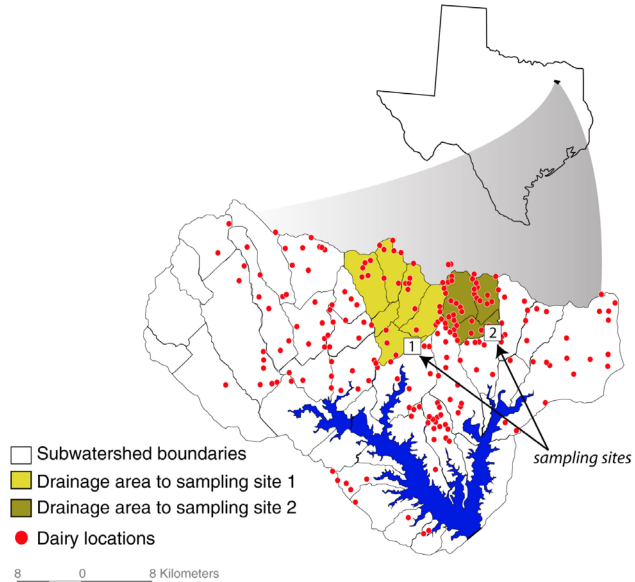

Figure 5. Location of the Lake Fork Reservoir watershed (LFRW) in northeast Texas, including sampling sites and dairy producer locations.

Typical LFRW dairy operations were managed with open-access grazing (OAG; fig. 6) 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 purchased fertilizer. Milking cows were assumed to split time between the milking parlor and milking herd pasture, as shown in figure 6; 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 (by a factor of 3) was 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 input 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 6 as described by Osei et al. (2000c). Adjustments of cow

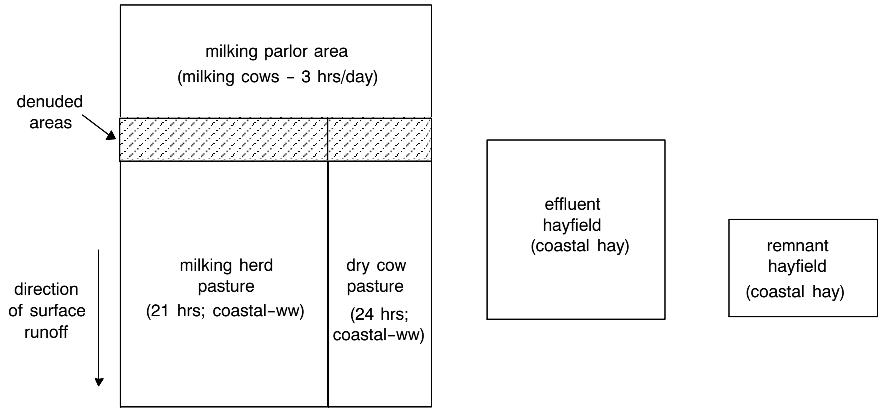

Figure 6. Baseline APEX scenario for each LFRW dairy showing milking cow and dry cow pastures (coastal bermuda overseeded with winter wheat) with associated denuded areas, the effluent hayfield (coastal bermuda hay) where the milking parlor waste water was applied, and the remnant or excess hayfield that was managed only with commercial fertilizer (source: Osei et al., 2000b).

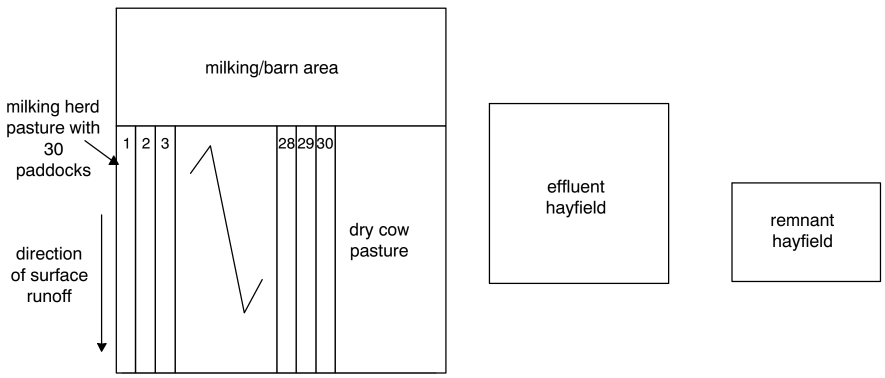

Figure 7. Schematic of the LFRW intensive rotational grazing (IRG) scenario simulated in APEX (source: Osei et al., 2000b).

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 scenarios were also performed with APEX for the LFRW study, including intensive rotational grazing (IRG). Each milking herd pasture was split into 30 paddocks for the APEX IRG scenario (fig. 7). The simulated milking cows grazed each paddock for one day before being rotated to the next paddock, to avoid overgrazing and associated denuded areas (fig. 7). Better grass management was also assumed for the dry cow pastures, which were simulated with the baseline OAG approach. In addition, higher forage production levels (due to increased fertilizer rates) and higher grazing rates were simulated for the IRG scenario to reflect that a much higher percentage of each cow's daily feed intake was obtained directly from the pasture. Management of the hayfields was identical to that simulated for baseline conditions. Further details regarding the IRG scenario as well as development of LFRW grassed loafing lots (GLL) and filter strip scenarios were reported by Osei et al. (2000b).

LFRW APEX Calibration Results

Streamflow data were available for the LFRW from 1978 to 1989 at sampling site 1 shown in figure 5. Limited sediment and/or nutrient data were collected at five sites in uneven intervals during 1994-1996, but only data collected at sampling site 2 (fig. 5) were 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 (Neitsch, 1998). Flow calibration was performed within the baseline simulation by comparing model output with measured streamflow values at sampling site 1 during the 1978 to 1989 period. The resulting annual NSE and R^2 values were 0.76 and 0.79, respectively, while corresponding values of 0.58 and 0.59 were computed for the monthly comparisons, indicating 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 during 1994 to 1996 at sampling site 2 showed that the model simulated the general pollutant loss trends well for most of the indicators except for sediment, which was underpredicted by a factor of almost 2 (Neitsch, 1998).

UMRW Baseline APEX Scenarios

The UMRW and MCW are both located in northeast Iowa in the larger Maquoketa River watershed (fig. 8). 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. 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

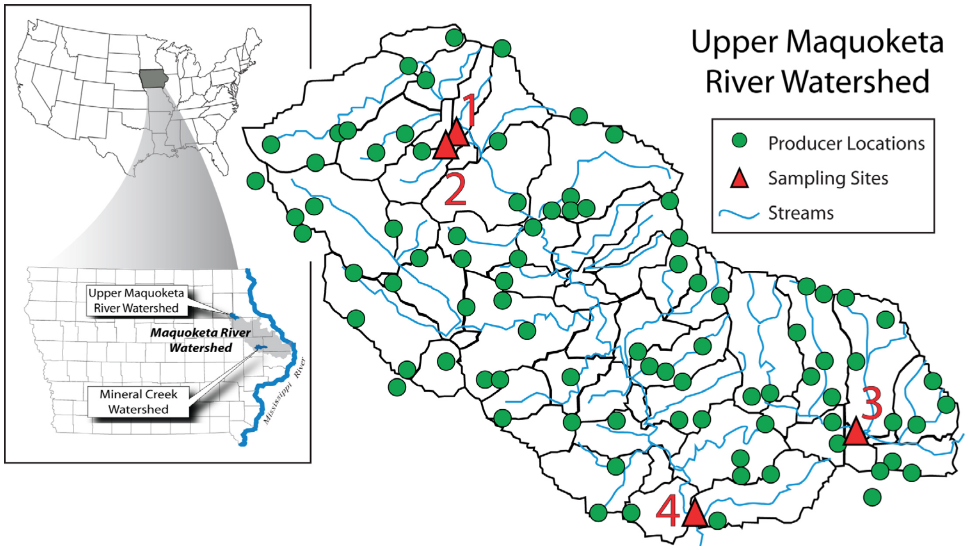

Figure 8. Locations of the Upper Maquoketa River watershed (UMRW) and Mineral Creek watershed (MCW) in northeast Iowa, including UMRW sampling sites, producer locations, and SWAT subwatershed boundaries.

livestock. The distribution of livestock operations and water quality sampling sites within the UMRW is shown in figure 8.

Similar to the LFRW, generic APEX configurations and FEM farm models were developed for representative UMRW dairy, beef cattle, swine open lot, feeder cattle, swine confinement, and calf/heifer grazing operations, as described further by Osei et al. (2000b) and Gassman et al. (2002). 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 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. Additional details regarding the APEX generic livestock operations and modeling assumptions for the baseline and scenario simulations were given by Osei et al. (2000b, 2000c) and Gassman et al. (2002, 2006). Scenario applications performed for the MCW were performed with the same generic livestock operation configurations that were used for the UMRW (Gassman et al., 2003).

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 (fig. 9), 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 limited indirect testing of APEX was performed by comparing SWAT output (with nested APEX simulations) with measured data, as reported by Gassman et al. (2002). 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 of 0.79 and 0.74 for streamflow and nitrate, respectively, at the UMRW outlet, but weaker streamflow and nitrate R^2

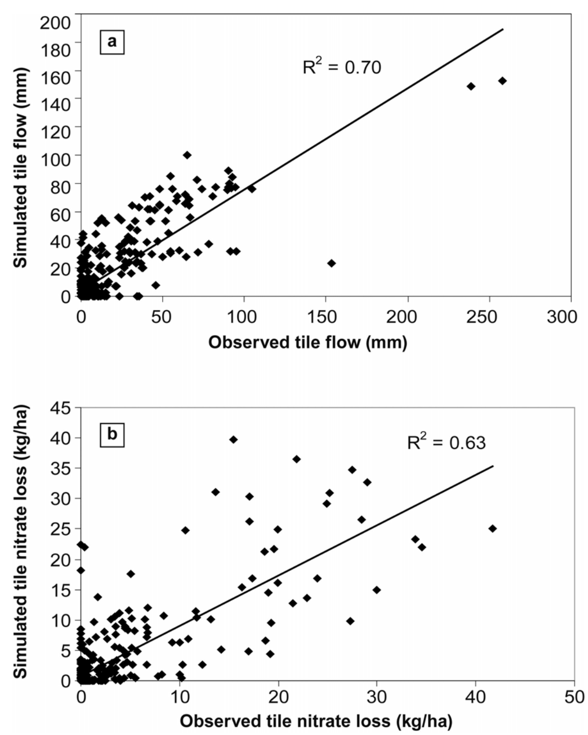

Figure 9. Comparisons of APEX output versus measured data for (a) subsurface tile drainage flows and (b) subsurface tile drain nitrate losses for 432 average monthly values for a range of cropping and/or tillage systems studied at two research sites near Nashua, Iowa, and Lamberton, Minnesota (source: Gassman et al., 2006).

statistics ranging from 0.39 to 0.51 and from 0.24 to 0.42, respectively, for the other three sampling sites (fig. 10). 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 were needed in order to obtain the best possible results for simulating streamflow and nitrate losses in the UMRW.

Scenario Results for NPP-Related Studies

A wide range of scenarios was performed for the three NPP watersheds (Osei et al., 2000b). Complete sets of scenario results were reported by Pratt et al. (1997), McNitt and Jones (1999), and Keith et al. (2000) for the UNBRW, LFRW, and UMRW, respectively. Additional description of NPP scenario results were reported in several other studies (Osei et al., 2000a, 2003a, 2003b; Gassman et al., 2002, 2003, 2006). Osei et al. (2000b) also presented a comprehensive table listing most of the scenarios that were performed for the three watershed studies. A brief summary of example results for selected scenarios is presented here.

NPP Study Results

Gassman et al. (2002) provided tabulated results of selected key scenarios (table 3) that were drawn from the overall suite of scenarios. 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) are compared versus the estimated net returns (figs. 10 and 11). Manure high P rate and low P rate scenarios were performed for all three watersheds. The 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, so that the total manure 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.

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,

Table 3. Selected policy scenarios from the NPP watershed studies (source: Gassman et al., 2002).

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

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

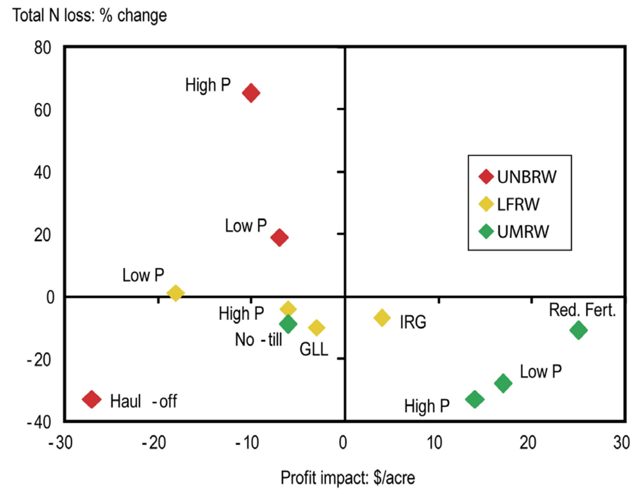

Figure 10. Comparison of total N losses versus aggregated net returns for selected UNBRW, LFRW, and UMRW scenarios listed in table 3 (% change from the baseline).

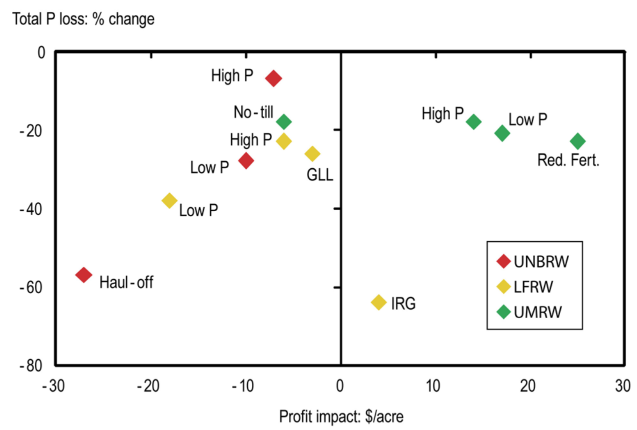

Figure 11. Comparison of total P losses versus aggregated net returns for selected UNBRW, LFRW, and UMRW scenarios listed in table 3 (% change from the baseline).

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 scenarios found to result in reduced P losses to the stream system and increased profits at the same time.

Further impacts of manure application scenarios are shown in figure 12 for the UNBRW, as reported by Osei et al. (2003a). These scenario results depict aggregate APEX edge-of-field predictions 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.

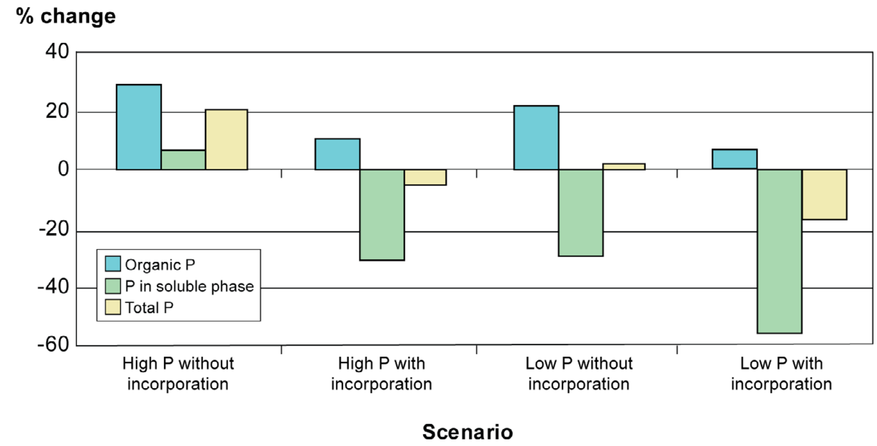

Figure 12. Impacts of P-based application rates with and without incorporation on aggregate organic P, soluble P, and total P for all UNBRW dairy waste application fields (source: Osei et al., 2003a).

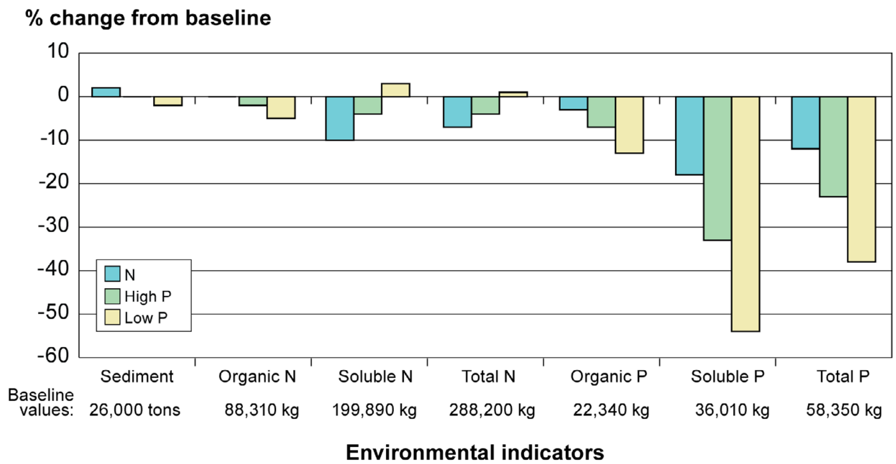

Figure 13. Environmental impacts predicted for the three LFRW stocking rate scenarios based on percent changes from baseline values (source: Osei et al., 2003b).

The APEX scenario results (fig. 12) 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.

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 this baseline scenario). 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 13. The results confirm the effectiveness of the P rate scenarios in reducing P losses, especially for 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.

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 the model with field data, although some of these studies also reported 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 and forestry applications. A brief overview of studies that focused principally on testing the model is given

Table 4. Summary of reported APEX surface runoff, sediment, and other calibration and validation results at the test plot, field, and watershed scales.

		Calibration						Validation					
		Daily		Monthly		Annual		Daily		Monthly		Annual	
Time Period[a]	Indicator	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE
Research test plots (Nashua, Iowa, and Lamberton, Minnesota) Gassman et al., 2006)													
432 total monthly comparisons	Tile Flow			0.70									
	Tile nitrate loss			0.63									
Goodwater Creek watershed (north central Missouri), 14 research plots, 0.270 km^2 (Mudgal et al., 2010)													
C: 1997-1999 V: 2000-2002	Surface runoff	0.52-0.93		0.46-0.67				0.62-0.98		0.52-0.94			
	Atrazine	0.52-0.91		0.45-0.68				0.53-0.97		0.45-0.86			
Nine forested watershed (eastern Texas), 0.026 to 0.027 km^2: Undisturbed control (CON), three watersheds (Saleh et al., 2004)[b]													
V: 1980-1985	Storm runoff								0.84-0.88				
	Sediment								0.12-0.33				
	Total N								0.58-0.84				
	Total P								0.55-0.67				
Nine forested watershed (eastern Texas), 0.026 to 0.027 km^2: Clearcutting, chopping, etc. (CHP), three watersheds (Saleh et al., 2004)[b]													
V: 1980-1985	Storm runoff								0.74-0.85				
	Sediment								-1.4-0.29				
	Total N								0.09-0.77				
	Total P								-1.1-0.69				
Nine forested watershed (eastern Texas), 0.026 to 0.027 km^2: Clearcutting, shearing, etc. (SHR), three watersheds (Saleh et al., 2004)[b]													
V: 1980-1985	Storm runoff								0.74-0.85				
	Sediment								0.26-0.78				
	Total N								0.32-0.77				
	Total P								0.14-0.82				
Tonk Creek and Wasp Creek watersheds (north central Texas), 104 km^2 (Tuppad et al., 2009)													
C: Oct. 1995-Dec. 1999; V: Jan. 1999-Mar. 2003	Stream flow			0.71	0.55					0.66	0.63		
	Sediment			0.68	0.68					0.17	0.02		
	Total N			0.75	0.57					0.38	0.30		
	Total P			0.65	0.60					0.27	0.16		

[a] C = calibration; V = validation.
[b] Additional statistics were reported by Saleh et al. (2004) for peak discharge, nitrate, organic N, orthophosphate, and organic P.

in the following 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. Table 4 contains a compilation of R^2 and NSE values for nine APEX studies for several different hydrologic and pollutant loss indicators. While these sets of statistics are not nearly as

Table 4 (continued). Summary of reported APEX surface runoff, sediment, and other calibration and validation results at the test plot, field, and watershed scales.

		Calibration						Validation					
		Daily		Monthly		Annual		Daily		Monthly		Annual	
Time Period[a]	Indicator	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE
Nine forested watersheds (eastern Texas), 0.026 to 0.027 km^2: Undisturbed control, three watersheds (Wang et al., 2007)													
V: 1999-2004	Stream flow									0.70-0.84	0.65-0.80	0.69-0.90	0.68-0.80
	Sediment									0.87-0.99	0.85-0.97	0.94-0.99	0.86-0.97
	Organic N									0.02-0.91		0.01-0.92	
	Mineral N									0.44-0.70		0.83-0.95	
	Organic P									0.70-0.95		0.40-0.99	
	Soluble P									0.85-0.88		0.92-0.97	
Nine forested watersheds (eastern Texas), 0.026 to 0.027 km^2: Conventional clear cut, three watersheds (Wang et al., 2007)													
V: 1999-2004	Stream flow									0.71-0.91	0.71-0.86	0.93-0.97	0.88-0.94
	Sediment									0.34-0.99	0.10-0.97	0.84-0.99	0.83-0.99
	Organic N									0.14-0.65		0.08-0.58	
	Mineral N									0.14-0.61		0.09-0.90	
	Organic P									0.18-0.31		0.0-0.17	
	Soluble P									0.64-0.72		0.53-0.96	
Two herbicides (Wang et al., 2007)													
V: 2002-2004	Herbicide									0.11-0.96			
Nine forested watersheds (eastern Texas), 0.026 to 0.027 km^2: Intensive clear cut, three watersheds (Wang et al., 2007)													
V: 1999-2004	Stream flow									0.54-0.76	0.44-0.81	0.79-0.95	0.74-0.85
	Sediment									0.43-0.88	0.32-0.80	0.68-0.85	0.60-0.85
	Organic N									0.27-0.85		0.42-0.81	
	Mineral N									0.31-0.62		0.02-0.80	
	Organic P									0.34-0.44		0.23-0.46	
	Soluble P									0.27-0.81		0.05-0.71	
Two herbicides (Wang et al., 2007)													
V: 2002-2004	Herbicide									0.04-0.99			
Conventional and intensive watersheds (two herbicides) (Wang et al., 2007)													
V: 2002-2004	Herbicide											0.68-0.74	0.65-0.73

[a] C = calibration; V = validation.

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. These authors further suggested that their NSE and other statistical criteria be relaxed or tightened as appropriate for shorter or

Table 4 (continued). Summary of reported APEX surface runoff, sediment, and other calibration and validation results at the test plot, field, and watershed scales.

Time Period[a]	Indicator	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
Treynor W2 (southwest Iowa), 0.344 km^2 (Wang et al., 2008a)													
C: 1976-1987 V: 1988-1995	Surface runoff			0.51	0.41					0.68	0.62	0.97	0.95
	Sediment			0.43	0.36					0.76	0.72	0.98	0.96
Treynor W3 (southwest Iowa), 0.433 km^2 (Wang et al., 2008a)													
C: 1976-1987 V: 1988-1995	Surface runoff			0.38	0.35					0.63	0.62	0.90	0.89
	Sediment			0.35	0.32					0.41	0.41	0.66	0.65
Shoal Creek (Fort Hood, Texas), 22.5 km^2: Pre-BMP (Wang et al., 2009)													
C: April 1997-April 2000; V: March 2002-April 2004	Stream flow	0.76	0.73					0.60	0.33				
	Sediment	0.80	0.77					0.62	0.61				
Shoal Creek (Fort Hood, Texas), 22.5 km^2: Post-BMP (Wang et al., 2009)													
C: April 1997-April 2000; V: March 2002-April 2004	Stream flow	0.78	0.61					0.77	0.75				
	Sediment	0.64	0.63					0.61	0.58				
Bison feedlot (North Dakota), 462 m^2: CN = 93 (Williams et al., 2006a)													
2001-2002	Surface runoff	0.72											
Bison feedlot (North Dakota), 462 m^2: CN = 95 (Williams et al., 2006a)													
2001-2002	Surface runoff	0.73											
Three test plots, Middle Huaihe River watershed (Henan Province, China): Plot EHC1, 0.10 ha (Yin et al., (2009)													
C: 1982 V: 1983-1986	Surface runoff	0.56	0.52					0.77	0.41				
	Sediment	0.88	0.83					0.81	0.73				
Three test plots, Middle Huaihe River watershed (Henan Province, China): Plot EHC2, 0.14 ha (Yin et al., (2009)													
C: 1982 V: 1983-1986	Surface runoff	0.71	0.70					0.72	0.52				
	Sediment	0.68	0.67					0.85	0.84				
Three test plots, Middle Huaihe River watershed (Henan Province, China): Plot EHC4, 0.06 ha (Yin et al., (2009)													
C: 1982 V: 1983-1986	Surface runoff	0.98	0.89					0.72	0.50				
	Sediment	0.66	0.48					0.55	0.49				

[a] C = calibration; V = validation.

longer time steps. Based on their NSE criteria (and assuming it is also appropriate for R^2 values), the majority of the studies listed in table 4 reported satisfactory NSE and R^2 values. Poor results were reported for some of the studies, particularly statistics reported by Saleh et al. (2004) and Tuppad et al. (2009); the authors of both studies provide further insights about those results, as discussed below. Further discussion of the other statistics shown in table 4 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 fig. 9).

Williams et al. (2006a) reported a test of the APEX feedlot submodel using data collected for feedlots located near Bushland, Texas, and Carrington, North Dakota (table 5). The assessment focused on tests of both the hydrologic balance and the manure erosion subcomponents of the model. The North Dakota feedlot test resulted in R^2 statistics of 0.72 and 0.73 for surface runoff (table 4), 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 6. 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. (2006a) and accounted for different filter strip lengths and other factors downslope of a hypothetical feedlot.

Table 5. Characteristics of feedlots used to test the APEX feedlot submodel (source: Williams et al., 2006a).

Characteristic	Bushland, Texas	Carrington, North Dakota
Livestock type	Beef cattle	Bison
Feedlot size (ha)	4	0.462
Slope (%)	2	4
Stocking rate (m^2)	13.3	46.2
Monitoring years	1971-1973	2001-2002
Average rainfall (mm)	429	440[a]
Soil hydrologic group	C[a]	B

[a] Not reported by Williams et al. (2006a).

Table 6. Comparisons of average simulated and observed surface runoff and/or pollutant indicators for two feedlots (source: Williams et al., 2006a).

Indicator	Simulated	Observed
Bushland, Texas		
Surface runoff (mm $year^{-1}$)	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

Mudgal et al. (2010) reported testing 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. Thirty 0.34 km^2 (189 × 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. Atrazine data collected for 14 of the research plots managed with different cropping/tillage systems during 1997 to 2001 were used to test the model. The APEX calibration and validation results (table 4) 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.

Tests of APEX were reported by Wang et al. (2008a) for two small watersheds called W2 and W3 (table 7) that were part of the former USDA Deep Loess Research Station that was located near Treynor in southwestern Iowa (fig. 14). 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 between -4.2% and 0.3% across the two watersheds. The validation statistics were stronger, with the majority of R^2 and NSE values exceeding 0.6 (table 4). There are several reported examples of validation statistics exceeding calibration statistics, as reviewed by Gassman et al. (2007). Differences in data quality, length, and nature of climate data (wet/dry years, etc.) may contribute to this phenomenon. APEX-predicted corn yields and soil organic carbon also compared well with counterpart measured values (table 8).

Table 7. Characteristics of the two watersheds located near Treynor, Iowa (source: Wang et al., 2008a).

Watershed	Area (ha)	Cropping System	Precipitation[a] (mm)	Tillage Type
W2	34.4	Continuous corn	808	Conventional
W3	43.2	Continuous corn	772	Ridge

[a] Average annual precipitation for 1976 to 1995.

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.

Yin et al. (2009) described APEX testing results for three small research plots located in the Middle Hauihe River watershed in China (fig. 15) 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 9. 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 had the greatest influence on the surface runoff and sediment outputs. The simulated daily surface runoff and sediment values compared favorably with the corresponding observed values for each plot, as evidenced by the R^2 and NSE statistics in table 4. Long-term scenarios were also reported and indicated that adoption of mixed wood-grass or woodland with corresponding conservation practices (as listed in table 9) resulted in surface runoff reductions of 35% to 37% and sediment yield reductions as compared to a fallow baseline.

Saleh et al. (2004) described 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 (fig. 16) 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 (fig. 16): 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 occurred in stream management zones (SMZs) that were preserved in all nine watersheds (stream corridor filter strip areas with

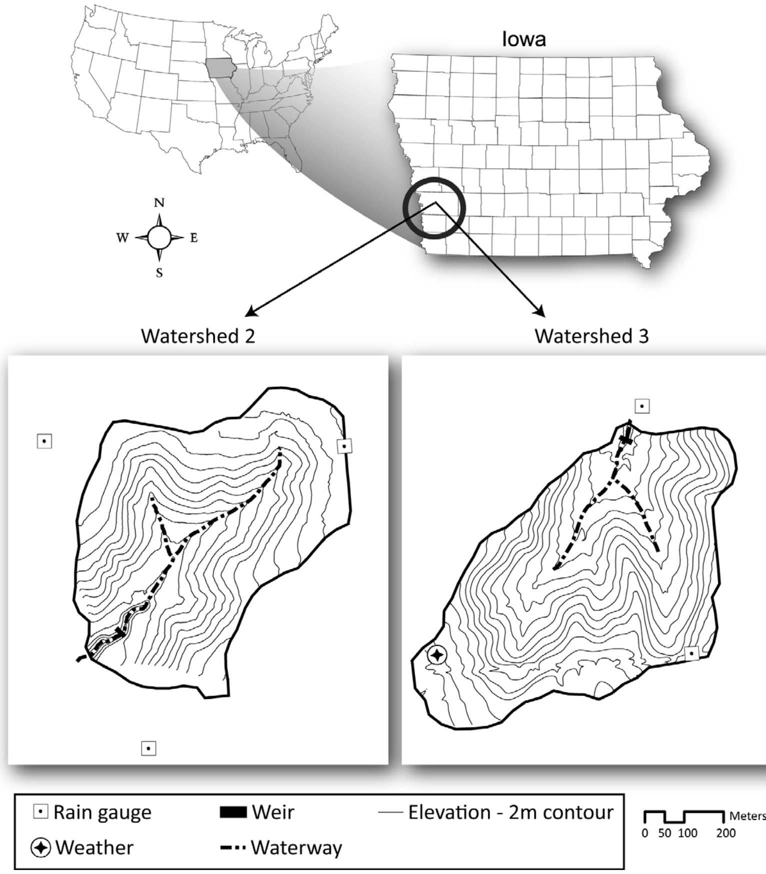

Figure 14. Watersheds W2 and W3 of the Deep Loess Research Station located near Treynor in southwestern Iowa (source: Wang et al., 2008a).

Table 8. Observed and predicted corn grain yield and soil organic carbon in the top 0.15 m soil (source: Wang et al., 2008a).

		Watershed W2			Watershed 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[a]	29.1	9.2	34.7[a]	36.4	5.0

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

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 4). 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 (fig. 16). The subareas, SMZ depiction, and other simulation assumptions were essentially the same as reported by 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 4 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 article provide additional evidence that the model accurately tracked the measured surface runoff and pollutant losses.

Wang et al. (2009) 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 (fig. 17). 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

Figure 15. Location of the Hauihe River watershed in China, and location of the study site within the Middle Huaihe River watershed (source: Yin et al., 2009).

Table 9. Characteristics and management practices of the three plots at the study site in the Middle Hauihe River watershed, China (source: Yin et al., 2009).

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 and 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

[a] Management practices performed in numerical order for plots EHC1 and EHC2.

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. Best management practice (BMP) strategies have been introduced to mitigate these negative externalities, including the implementation of contour ripping across 26% of the Shoal Creek watershed during the last two months of 2001, and the installation of 211 gulley plugs from 2002 to 2004 (fig. 17). 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 4) 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.

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 performed for 20 representative crop fields 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 crop field. 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 and draw area is assumed cropped (baseline scenario); (2) the upland field is cropped and the draw is managed with either switchgrass (grass), curly willow (shrub), or cottonwood (trees); or (3) the upland field is cropped and the draw is managed with a mixed buffer of switchgrass, curly willow, and cottonwood. Fifteen 12-year APEX simulations were performed for each field,

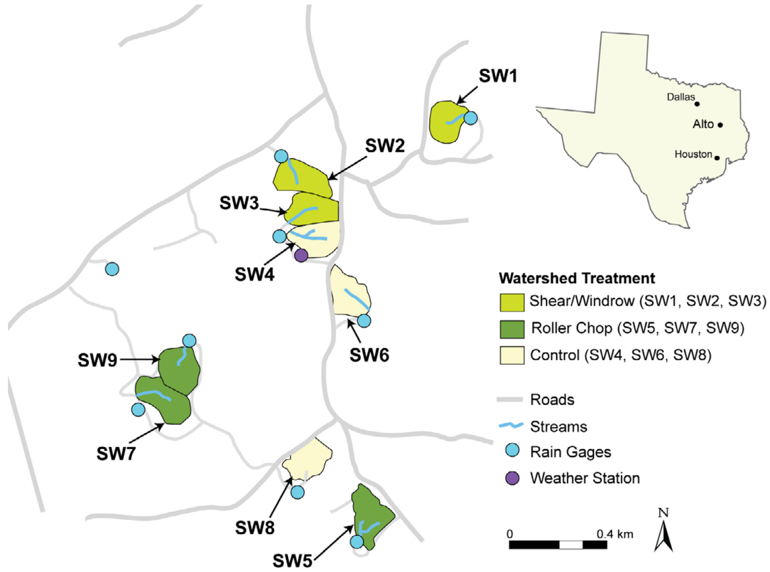

Figure 16. Location of the nine forested watersheds near Alto, Texas (source: Saleh et al., 2004).

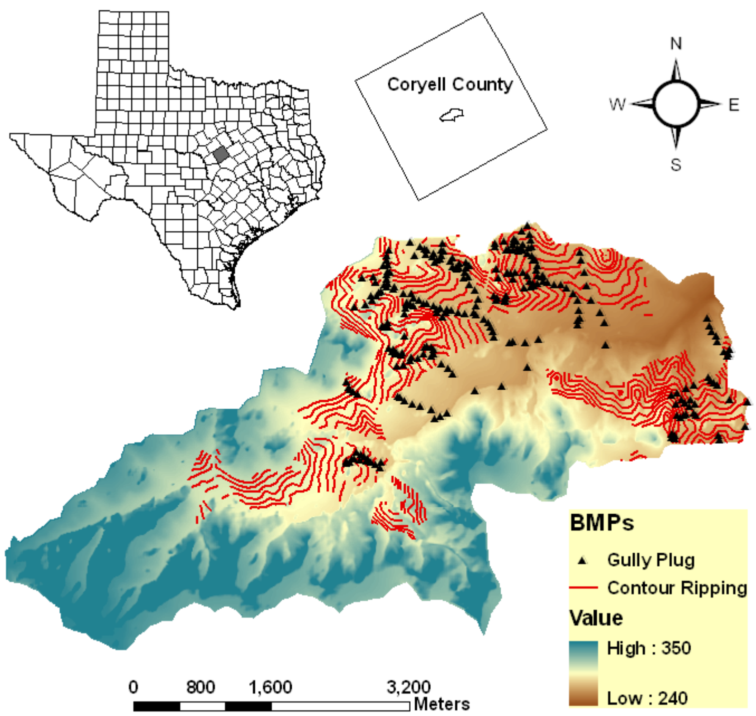

Figure 17. Location of the Shoal Creek watershed in Coryell County, Texas, and the distribution of contour ripping and gully plug conservation practices installed in 2001 and in 2002 to 2004, respectively (source: Wang et al., 2009).

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) described 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 results of the 25-year APEX simulations showed that sediment loss decreased as tillage decreased, but nitrogen runoff increased. 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 region. Playa lakes are the primary wetlands in the Texas High Plains region and provide a variety of ecosystem services, including wildlife habitat, floodwater containment, and groundwater recharge. 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, resulting 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) for a representative 259 ha playa lake system in the Texas Panhandle region. Center-pivot irrigation was assumed for both the baseline and the scenarios. The results showed 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 maintained some storage capacity was increased by around 20%. Additional applications of APEX for playa lake management problems in the Texas Panhandle region were described by Peabody (2005).

APEX Large Watershed Scenario Applications

Two studies reported by Azevedo et al. (2005a, 2005b) 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) described similar simulation approaches for three different watersheds that differed roughly by one to two orders of magnitude in size. Key characteristics of each watershed are listed in table 10, 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 11; the simulated yields accurately represented the observed crop yields for each watershed. Other APEX testing results reported in the studies included: (1) simulated elemental N and P in surface runoff were 0.71 and 1.25 ppm, versus measured levels of 0.71 and 1.20, for a single field in the Tierra Banco Creek watershed (Wang et al., 2002); (2) average total loss of simulated atrazine applications for the Aquilla Creek 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 ±15% of corresponding measured values for each year during 1997-2002 for the Zi-Fang-Gully 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.

Table 10. 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	Aquilla Creek	Zi-Fang-Gully
Region	Texas Panhandle and neighboring New Mexico	Hill country of central Texas	Shaanxi Province, Loess Plateau region, northwestern China
Area	4,453 km^2	658 km^2	8.1 km^2
Total subwatersheds	94	44	29
Land use distribution	Cropland (86%) and rangeland (14%)	Cropland (60%), grassland (21%), forest (13%), and urban (6%)	Grassland (50%), woodland (38%), and cropland (12%)
Cropland distribution	Irrigated wheat (19%), corn (18%), and sorghum (10%); dryland wheat and sorghum (53%)	Sorghum (36%), corn (29%), wheat (18%), and cotton (17%)	Corn, soybean, pearl millet, proso millet, potato, sorghum, and buckwheat.
Key pollutant indicators	Sediment-bound N and P; soil P	Atrazine	Sediment loss and crop productivity
Length of simulation scenarios	96 years	30 randomly generated weather sequences for 12 years each	30 years
Scenario summaries	Four scenarios: commercial fertilizer (baseline); three manure-based scenarios with or without commercial fertilizer	Baseline and eight scenarios including decreased atrazine application rates, incorporation, filter strips, wetlands or sediment retention ponds, conservation till, and no-till.	Baseline and seven land-use scenarios, e.g., partial grazing, all grain, all grass, all forest, 50% grass and 50% forest, and 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 and clay loam soils with slow infiltration and high runoff.	Classified as a loess ravine hilly land zone, with undulating hills, deep gullies, and thick Yellow Earth soils.

Table 11. Comparisons of average simulated and observed crop yields (mg ha^{-1}) for the three APEX studies described in table 10.

Indicator	Simulated	Observed
Tierra Banco Creek watershed (Wang et al., 2002)[a]		
Sorghum	5.6	5.51
Aquilla Creek watershed (Harman et al., 2004)[b]		
Corn	6.25	6.28
Cotton	0.56	0.56
Sorghum	5.66	5.61
Wheat	3.15	3.03
Zi-Fang-Gully watershed (Wang et al., 2006a)[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 average yields based on local producer estimates.
[c] Average yields measured within the Zi-Fang-Gully watershed during 1997-2002 (extent of area not reported).

The evaluation of three alternative scenarios (table 10) by Wang et al. (2002) showed that objectives for the Tierra Banco Creek 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) reported 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 Zi-Fang-Gully watershed resulted in increased environmental degradation and thus should not be encouraged.

Tuppad et al. (2009) described an application of APEX for the 104 km^2 combined Tonk Creek and Wasp Creek watersheds in north central Texas. The application was performed using the ArcAPEX interface, which is described in more detail later in the APEX Interfaces section. Calibration and validation statistics were reported for streamflow, sediment, total nitrogen, and total phosphorus (table 4). The resulting R^2 and NSE values reflected strong calibration results for streamflow and the three pollutant indicators. However, the validation R^2 and NSE results were only adequate for streamflow. The authors discussed several reasons for the poor sediment and nutrient validation results and indicated a need for further investigation to improve simulation of the combined watershed area. They also described the impacts of an APEX BMP scenario executed within the ArcAPEX interface that resulted in reduced surface runoff, sediment loss, and nutrient losses due to increased use of no-till, furrow dikes, and contouring.

An advanced APEX watershed application has been initiated for the Bosque River watershed (BRW), which covers 4,277 km^2 in central Texas (P. Dyke, personal communication, 2008. Temple, Tex.: Texas AgriLIFE Research and Extension, Blackland Research and Extension Center). 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 subwatershed delineations incorporate partitioning of floodplains from upland areas to facilitate key scenarios such as landscape-based filter strips in which livestock manure applications are eliminated from subareas that border stream segments.

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 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. 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 for which the analysis will be performed for (e.g., Corn Belt). Subregions and representative farms are required for the respective analyses, 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) described an application of CEEOT-MMS for the state of Texas that incorporated six types of representative livestock farms distributed across 11 ecological subregions (fig. 18). A multi-tiered clustering process was used to determine the subregions and representative livestock farms. The subregions were determined using a *k*-means 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 AFOs based on having at least 35 animal units present on-farm. A total of 780 representative farms were identified, based in part 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 P rate, and low P rate scenarios were

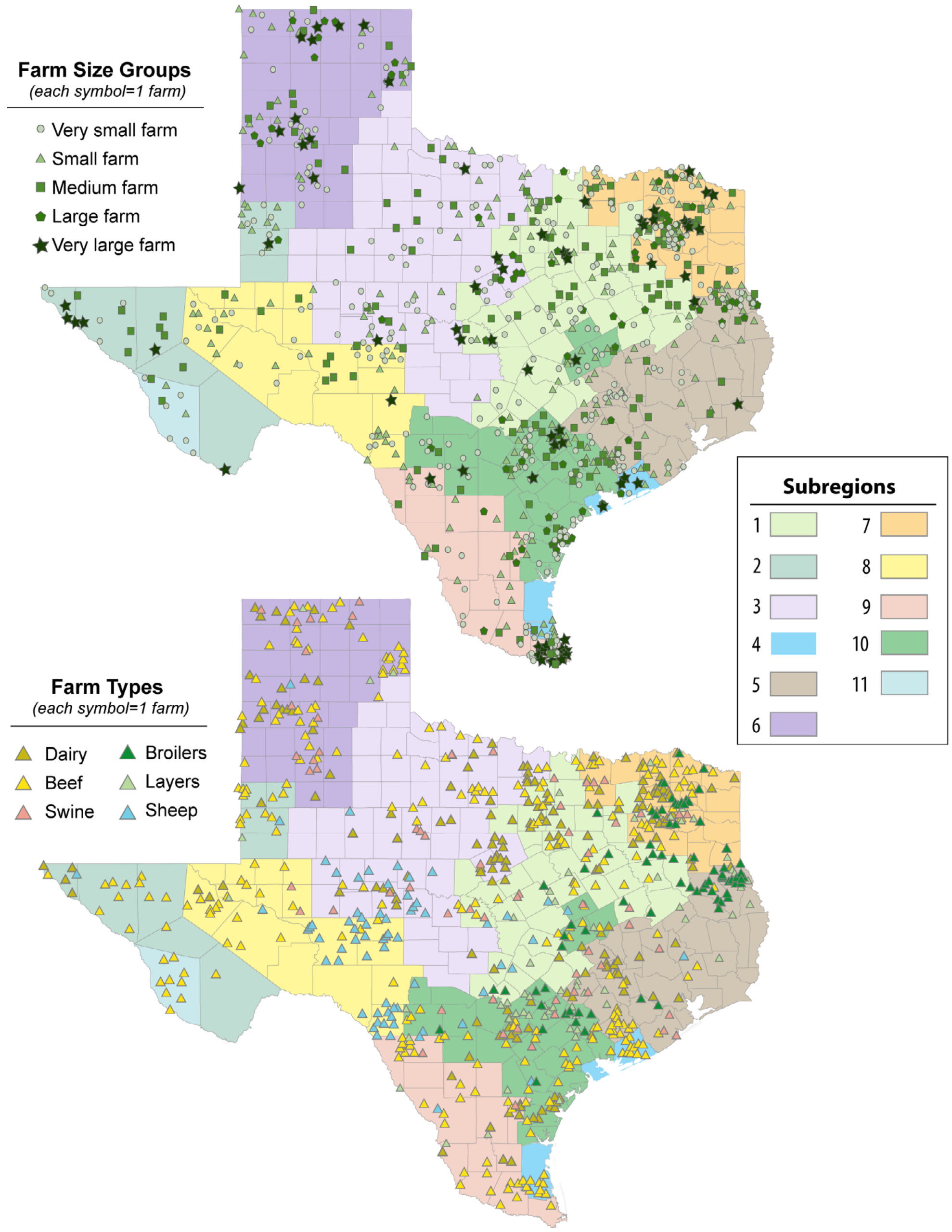

Figure 18. Distribution of the 780 representative livestock farms, by farm size or livestock farm type, across the 11 ecological subregions used in the Texas CEEOT-MMS study (source: Osei et al., 2008a).

performed for both solid and liquid manure applications for the 780 representative farms. Changes in sediment, nitrogen, and phosphorus losses were 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 were presented in the study, including economic impacts. Additional assessments of Texas AFOs with CEEOT-MMS were reported by Osei et al. (2007).

Osei et al. (2008b) described another CEEOT-MMS application in which comprehensive nutrient management plans were analyzed for nearly 22,000 AFOs in the Ohio River basin. Other large-scale assessments using APEX have been reported, including an assessment of the impacts of sediment retention structures, water impoundment ponds, surface-drained terraces, and tile-drained terraces on water quality indicators and soil carbon in Missouri (FAPRI-UMC, 2008) and an assessment of CRP buffers on cropland sediment and nutrient losses for the conterminous U.S. (FAPRI-UMC, 2007).

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, 2009a). A CEAP National Cropland Assessment is being performed to estimate the overall impact of conservation practices that

Table 12. APEX parameters determined to have the highest sensitivity in the national CEAP sensitivity analysis (source: Wang et al., 2006b).

Input File	Parameter	Description	Lower Range	Upper Range
PARM	parm2 (RGSS)	Root growth soil strength	1	2
	parm8 (SPRC)	Soluble P runoff coefficient	10	20
	parm11 (MFSG)	Moisture fraction required for seed germination	0.4	0.7
	parm42 (CNIC)	NRCS curve number index coefficient	0.5	5
	parm46 (RCFC)	RUSLE C factor coefficient	0.5	5
OPS	PHU	Potential heat units (°C)	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

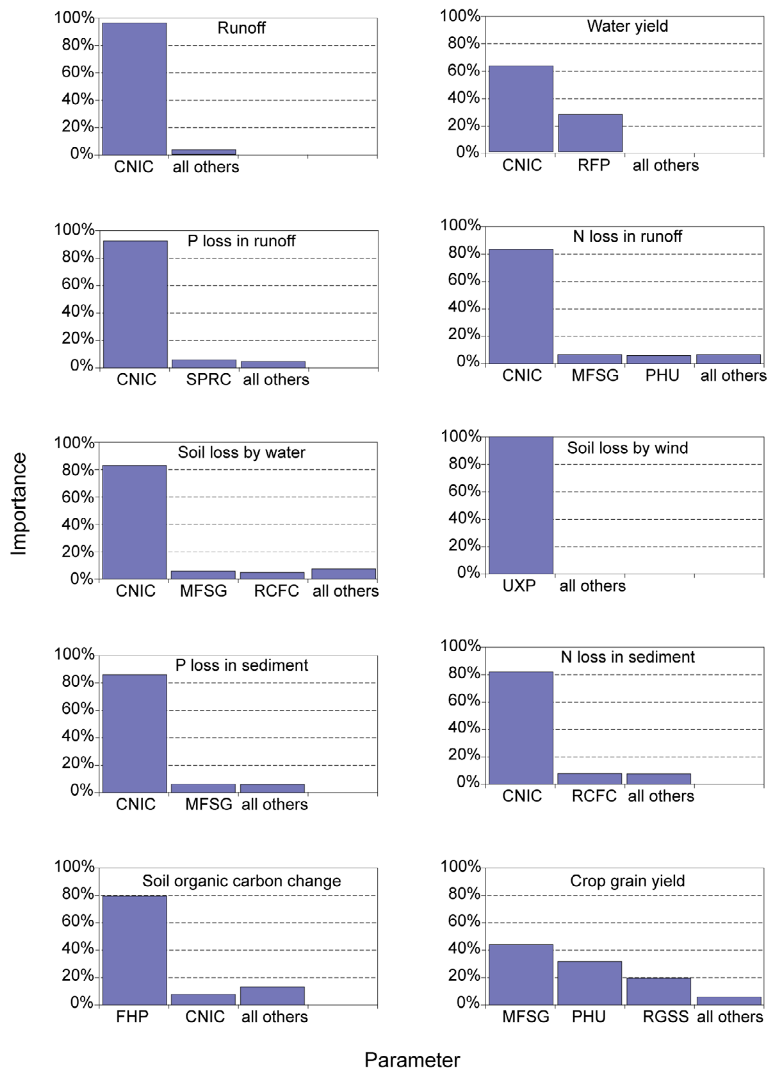

Figure 19. "Percentage of importance" of APEX input parameters that were ranked first in the sensitivity analysis for ten key APEX output indicators; plotted are the dominant input parameters for which the percentage of importance was calculated to be >5% and the total percentage for all the remaining parameters analyzed based on the sensitivity analysis results (source: Wang et al., 2006b).

have been established on cultivated cropland nationwide and to estimate what further conservation treatments would be 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 nonpoint-source pollution impacts from cultivated cropland, which are then routed in SWAT to provide overall water quality impacts at the major water resource region (MWRR) level. Conservation practices are accounted for in the APEX simulations based on information obtained from several sources, including a national CEAP survey, 1997 and 2003 National Resource Inventory (NRI) data (USDA-NRCS, 2009b), USDA-NRCS field offices, and the USDA Farm Service Administration (FSA). The national CEAP survey was collected from 2003 to 2006 at 20,000 NRI sampling points that represent approximately 98% of the U.S. cropland area (Duriancik et al., 2008; Lemunyon and Kellogg, 2008). APEX version 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.

Wang et al. (2006b) conducted a sensitivity analysis of 15 key APEX parameters for 159 sites located across the conterminous U.S. that spanned a wide range of soil types and climatic conditions and included cropping systems consisting of corn, soybeans, and wheat and three tillage systems: no-till, mulch, and conventional. The sensitivity analysis was conducted for parameters that influence hydrology, sediment loss by water or wind, nutrient losses, soil organic carbon change, and crop yield. The nine most sensitive parameters are listed in table 12. The relative sensitivities of these dominant parameters for ten key APEX outputs, as determined by the sensitivity analysis, are shown in figure 19; additional results of the sensitivity analysis are reported in the study. These results were used to guide APEX calibration procedures and ultimately support the conservation practice scenarios required for the national CEAP study. APEX simulations are being performed for a wide range of cultural and structural conservation practices in the national CEAP study, as described by Potter et al. (2009), in support of two primary scenarios being performed with the modeling system for the national CEAP study: (1) a baseline scenario that incorporates conservation practice and CRP data from the CEAP surveys conducted from 2003 to 2006, and (2) a no-practices scenario that assumes that conservation practices were not implemented on any U.S. cropland. National CEAP results for the Upper Mississippi River basin MWRR are reported by the USDA-NRCS (2010).

APEX Interfaces

Several interfaces and other tools have been developed to support APEX applications since the first versions of the model were released. The first such software was an automatic input file builder and execution program used to support NPP APEX applications (Osei et al., 2000b); this has been superseded by several other interface programs described below.

Interactive Apex (i_APEX)

The Interactive APEX (i_APEX) software package, which functions in a PC Windows environment, is similar to other interactive software developed by the Center for Agricultural and Rural Development (CARD) for EPIC, Century, and SWAT (CARD, 2010; Williams et al., 2008a). The i_APEX software performs automatic management of the input data, execution of each APEX run, and storage of selected model outputs using a single database to manage both the input and output data of all of the required APEX simulations. Documentation of the i_APEX structure and software downloads are provided on the i_APEX website (CARD, 2010). 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 study performed by Yin et al. (2009).

WinAPEX and WinAPEX-GIS

The WinAPEX software is a Windows interface developed by the Blackland Research and Extension Center (Magre et al., 2006; Steglich and Williams, 2008; Williams et al., 2008a) 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 and provides editing tools that support assessments of the impacts of alternative scenarios. The output of APEX simulations performed in WinAPEX are stored in several ACCESS tables, which 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 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.

SWAT-APEX (SWAPP)

Saleh and Gallego (2007) described 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 for performing nested APEX simulations on the field, whole-farm, or small watershed scale within a SWAT watershed application. The program is executed in four phases and is initiated with SWAT GIS input data layers created by the ArcView SWAT (AVSWAT) interface (Di Luzio et al., 2004) for the respective watershed of interest. 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.

Saleh et al. (2008) presented 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 were reported by Saleh et al. (2008) for a UNBRW haul-off scenario as well as environmental impacts based on combined APEX and SWAT simulations.

ArcGIS APEX (ArcAPEX)

Olivera et al. (2006) developed an ArcGIS SWAT interface (ArcSWAT) that has been accessible by the SWAT user community since early 2007. An ArcGIS APEX (ArcAPEX) interface has recently become available that supports creation of both stand-alone APEX and SWAT simulations as well as integrated APEX-SWAT scenarios (Tuppad et al., 2009). It provides overall modeling support similar to that in SWAPP and takes advantage of improved options included in the ArcGIS platform. Integrated applications initially require user identification of a pre-existing SWAT dataset. The subbasin boundaries and hydrologic connectivity between subareas are based on a digital elevation model (DEM) or by importing user pre-defined subarea boundaries and streams that are closely associated with specific agricultural field boundaries. See Tuppad et al. (2009) for additional application details.

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:

- 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.
- A new water table fluctuation routine is also being developed for APEX that uses the drainage volume and 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 and water table depth relationship can be determined from estimated drainable porosities of each soil layer, as described by Skaggs (2007) for the DRAINMOD subsurface drainage model.
- 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, again similar to the approach used in the DRAINMOD model (Skaggs, 2007), which would allow for a broader range of tile drainage scenarios to be performed with APEX.
- 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 such as those reported by Wang et al. (2008b) and White et al. (2008).
- 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).
- 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 has indicated that they provide more accurate estimates of key soil water parameters versus the routines that have traditionally been used in EPIC.
- 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. In addition, manure production and content will be affected by forage and feed intake and quality.
- Ephemeral and classic gully erosion will be simulated using GIS and physically based erosion equations as an addition to the APEX erosion/sedimentation component.
- 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.
- The incorporation of an autocalibration routine within APEX and/or an APEX interface would provide greatly enhanced calibration and validation capabilities for future users of the model, as is currently available for users of the SWAT model (EAWAG, 2009).
- Improvement of the structure of APEX to interface with land and Earth systems models would be useful. For example, a current weakness of APEX is lack of detail on plant carbon pools needed to construct ecosystem carbon and energy balances. This improvement would be important as well for calculating carbon and energy exchanges between the land and atmosphere. For example, global climate models describe well the exchange of mass (carbon, water) and energy between the land and the atmosphere but lack detail on land manipulations (e.g., agricultural crops and their management, erosion, and other effects). Conversely, APEX is one of the most explicit models in terms of representing land manipulations and their effects integrated within watershed environments. However, its algorithms cannot be used efficiently to interact with input from and provide feedback to (global or regional) general circulation models. This modification would require the development and adaptation of algorithms for more mechanistic description of processes such as photo-

synthesis, autotrophic respiration, as well as energy and water balances.

Conclusions

The Agricultural Policy Environmental 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 of simulating field-level 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.

Acknowledgements

This study was funded in part from support provided by the USDA Natural Resources Conservation Service (Project No. Q683H753122#33) and US DOE Office of Science (Contract No. DE-AC06-76RLO 1830). Copyright permissions granted for figures and/or tables used in article report are also acknowledged as follows for the respective sources: (1) from ASABE for Gassman et al. (2001, 2003), Saleh et al. (2004), Wang et al. (2006b), Osei et al. (2008b), and Yin et al. (2009); (2) from Rangeland Ecology and Management, Allen Press Publishing Services, for Osei et al. (2003b); and (3) from Elsevier Science, Ltd., via License Numbers 2106611169022, 2106610765202, and 21005-11130045 issued by Copyright Clearance Center, Inc., Rightslink for Osei et al. (2003a), Gassman et al. (2006), and Wang et al. (2008a), respectively. Acknowledgement is also given to Mr. Matthew McBroom, Geographic Information Systems Laboratory, Arthur Temple College of Forestry and Agriculture, Stephen F. Austin University, as the creator of the original version of figure 16.

References

Arnold, J. G., and N. Fohrer. 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modeling. *Hydrol. Proc*. 19(3): 563-572.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large-area modeling and assessment: Part I. Model development. *J. American Water Resour. Assoc*. 34(1): 73-89.

Azevedo, J. C., J. R. Williams, M. G. Messina, and R. F. Fisher. 2005a. Impacts of the sustainable forestry initiative landscape level measures on hydrological processes. *Water Resour. Mgmt*. 19(2): 95-110.

Azevedo, J. C., X. B. Wu, M. G. Messina, and R. F. Fisher. 2005b. Assessment of sustainability in intensively managed forested landscapes: A case study in eastern Texas. *Soc. American Foresters* 51(4): 321-333.

Azevedo, J. C., X. B. Wu, M. G. Messina, J. R. Williams, and R. F. Fisher. 2008. The role of the sustainable forestry initiative in forest landscape changes in Texas, USA. In *Patterns and Processes in Forest Landscapes*, 273-295. R. Lafortezza, J. Chen, G. Sanesi, T. R. Crow, eds. Berlin, Germany: Springer Verlag.

Bagnold, R. A. 1977. Bed-load transport by natural rivers. *Water Resour. Research* 13(2): 303-312.

Baier, W., and G. W. Robertson. 1965. Estimation of latent evaporation from simple weather observations. *Canadian J. Plant Sci*. 45: 276-284.

Borah, D. K., J. G. Arnold, M. Bera, E. C. Krug, and X. Liang. 2007. Storm event and continuous hydrologic modeling for comprehensive and efficient watershed simulations. *J. Hydrol. Eng*. 12(6): 605-616.

BREC. 1999. *APEX User's Guide and Technical Documentation*. Version 8190. Temple, Tex.: Texas A&M University, Texas Agricultural Experiment Station, Blackland Research and Extension Center.

Cambardella, C. A., T. B. Moorman, S. S. Andrews, and D. L. Karlen. 2004. Watershed-scale assessment of soil quality in the loess hills of southwest Iowa. *Soil Tillage Res.* 78(2): 237-247.

CARD. 2010. CARD interactive software programs. Ames, Iowa: Iowa State University, Center for Agricultural and Rural Development. Available at: www.card.iastate.edu/environment/interactive_programs.aspx. Accessed 1 May 2010.

Cerri, C. E. P., K. Paustian, M. Bernoux, R. L. Victoria, J. M. Melillos, and C. C. Cerri. 2004. Modeling changes in soil organic matter in Amazon forest to pasture conversion with the Century model. *Global Change Biol*. 10(5): 815-832.

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

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

Di Luzio, M., R. Srinivasan, and J. G. Arnold. 2004. A GIS-coupled hydrological model system for the watershed assessment of agricultural nonpoint and point sources of pollution. *Trans. GIS* 8(1): 113-136.

Duriancik, L. F., D. Bucks, J. P. Dobrowski, T. Drewes, S. D. Eckles, L. Jolley, R. L. Kellogg, D. Lund, J. R. Makuch, M. P. O'Neill, C. A. Rewa, M. R. Walbridge, R. Parry, and M. A. Weltz. 2008. The first five years of the Conservation Effects Assessment Project. *J. Soil Water Conserv.* 63(6): 185A-197A.

EAWAG. 2009. SWAT-CUP. Dübendorf, Switzerland: Swiss Federal Institute of Aquatic Science and Technology. Available at: www.eawag.ch/organisation/abteilungen/siam/software/swat/index_EN.

Eckhardt, K., and U. Ulbrich. 2003. Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. *J. Hydrol*. 284(1-4): 244-252.

FAPRI-UMC. 2007. Estimating water quality, air quality, and soil carbon benefits of the Conservation Reserve Program. FAPRI-UMC Report 01-07. Columbia, Mo.: University of Missouri, Food and Agricultural Policy Research Institute. Available at: www.fapri.missouri.edu/outreach/publications/2007/FAPRI_UMC_Report_01_07.pdf. Accessed 5 June 2009.

FAPRI-UMC. 2008. Evaluating economic and environmental benefits of soil and water conservation measures applied in Missouri. FAPRI-MU Report 31-07. Columbia, Mo.: University of Missouri, Food and Agricultural Policy Research Institute. Available at: www.fapri.missouri.edu/outreach/publications/2007/FAPRI_MU_Report_31_07.pdf. Accessed 5 June 2009.

Flowers, J. D., J. R. Williams, and L. M. Hauck. 1996. Livestock and the environment: A national pilot project. NPP integrated modeling system: Calibration of the APEX model for dairy waste application fields in Erath County, Texas. TIAER Report No. PR9607. Stephenville, Tex.: Tarleton State University, Texas Institute for Applied Environmental Research. Available at: http://tiaer.tarleton.edu/pdf/PR9607.pdf. Accessed 2 February 2010.

Flowers, J., E. Osei, L. Hauck, P. Gassman, and A. McFarland. 1998. Livestock and the environment: A national pilot project: Manure nutrient application rates and other assumptions underlying APEX runs. TIAER Information Bulletin 9803. Stephenville, Tex.: Tarleton State University, Texas Institute for Applied Environmental Research.

Gassman, P. W. 1997. The national pilot program integrated modeling system: Environmental baseline assumptions and results for the APEX model (Livestock Series Report 9). Staff Report 97-SR 85. Ames, Iowa: Iowa State University, Center for Agricultural and Rural Development. Available at: www.card.iastate.edu/publications/synopsis.aspx?id=205. Accessed 2 February 2010.

Gassman, P. W., and L. Hauck. 1996. The environmental component of the national pilot program integrated modeling system (Livestock Series Report 8). Staff Report 96-SR 84. Ames, Iowa: Iowa State University, Center for Agricultural and Rural Development. Available at: www.card.iastate.edu/publications/synopsis.aspx?id=172. Accessed 2 February 2010.

Gassman, P. W., J. Abraham, L. Hauck, A. Saleh, and K. Keplinger. 2001. Simulation of nutrient losses from chicken litter applications in east central Texas with APEX and SWAT. ASAE Paper No. 012004. Presented at the 2001 ASAE Annual International Meeting. St. Joseph, Mich.: ASAE.

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

Gassman, P. W., A. Saleh, E. Osei, J. Abraham, and J. Rodecap. 2003. Environmental and economic impacts of alternative management scenarios for the Mineral Creek watershed. In *Proc. Total Maximum Daily Load (TMDL) Environmental Regulations II*, 323-331. St. Joseph, Mich.: ASAE.

Gassman, P. W., J. R. Williams, V. W. Benson, R. C. Izaurralde, L. Hauck, C. A. Jones, J. D. Atwood, J. Kiniry, and J. D. Flowers. 2005. Historical development and applications of the EPIC and APEX models. Working Paper 05-WP 397. Ames, Iowa: Iowa State University, Center for Agricultural and Rural Development. Available at: www.card.iastate.edu/publications/synopsis.aspx?id=763. Accessed 5 June 2009.

Gassman, P. W., E. Osei, A. Saleh, J. Rodecap, S. Norvell, and J. R. Williams. 2006. Alternative practices for sediment and nutrient loss control on livestock farms. *Agric. Ecosys. and Environ*. 117(2-3): 135-144.

Gassman, P. W., M. Reyes, C. H. Green, and J. G. Arnold. 2007. The Soil and Water Assessment Tool: Historical development, applications, and future directions. *Trans. ASABE* 50(4): 1211-1250.

Godwin, D. C., C. A. Jones, J. T. Ritchie, P. L. G. Vlek, and L. G. Youngdahl. 1984. The water and nitrogen components of the CERES models. In *Proc. Intl. Symp. on Minimum Data Sets for Agrotechnology Transfer*, 95-100. Patancheru, India: International Crops Research Institute for the Semi-Arid Tropics.

Green, W. H., and G. A. Ampt. 1911. Studies on soil physics: 1. Flow of air and water through soils. *J. Agric. Sci*. 4: 1-24.

Hargreaves, G. H., and Z. A. Samani. 1985. Reference crop evapotranspiration from temperature. *Applied Eng. in Agric*. 1(2): 96-99.

Harman, W. L., E. Wang, and J. R. Williams. 2004. Reducing atrazine losses: Water quality implications of alternative runoff control practices. *J. Environ. Qual*. 33(1): 7-12.

Intarapapong, W., and D. Hite. 2003. Watershed-level policies to implement best management practices under environmental risk. Paper presented at the Southern Agricultural Economics Association Annual Meeting. Available at: http://purl.umn.edu/35007. Accessed 2 February 2010.

Intarapapong, W., D. Hite, and A. Renck. 2002. Environmental risk assessment under environmental standard and safety-first constraints. Paper presented at the Western Agricultural Economics Association Annual Meeting. Available at: http://purl.umn.edu/36673. Accessed 2 February 2010.

Izaurralde, R. C., J. R. Williams, W. B. McGill, N. J. Rosenberg, and M. C. Quiroga Jakas. 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. *Ecol. Model*. 192(3-4): 362-384.

Jones, C. A., C. V. Cole, A. N. Sharpley, and J. R. Williams. 1984. A simplified soil and plant phosphorus model: I. Documentation. *SSSA J*. 48(4): 800-805.

Jones, R., L. Frarey, A. Bouzaher, S. Johnson, and S. Neibergs. 1993. Livestock and the environment: A national pilot project: Detailed problem statement. Stephenville, Texas: Tarleton State University, Texas Institute for Applied Environmental Research. Available at: http://tiaer.tarleton.edu/pdf/PR9304.pdf. Accessed 22 December 2009.

Kannan, N., C. Santhi, J. R. Williams, and J. G. Arnold. 2008. Development of a continuous soil moisture accounting procedure for curve number methodology and its behaviour with different evapotranspiration methods. *Hydrol. Proc*. 22(13): 2114-2121.

Keith, G., S. Norvell, R. Jones, C. Maguire, E. Osei, A. Saleh, P. Gassman, and J. Rodecap. 2000. Livestock and the environment: A national pilot project: CEEOT-LP modeling for the Upper Maquoketa River watershed, Iowa: Final report. TIAER Report No. PR003. Stephenville, Tex.: Tarleton State University, Texas Institute for Applied Environmental Research. Available at: http://tiaer.tarleton.edu/pdf/PR0003.pdf. Accessed 2 February 2010.

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

Knisel, W. G. 1980. CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems. Conservation Research Report No. 26. Washington, D.C.: USDA National Resources Conservation Service.

Krause, P., D. P. Boyle, and F. Bäse. 2005. Comparison of different efficiency criteria for hydrological model assessment. *Adv. Geosci.* 5: 89-97.

Lemunyon, J. L., and R. L. Kellogg. 2008. Assessment of conservation benefits derived from conservation practices in the United States. In *Proc. 21st Century Watershed Technology Conf.: Improving Water Quality and Environment*. E. W. Tollner and A. Saleh, eds. St. Joseph, Mich.: ASABE.

Long, S. P., E. A. Ainsworth, A. D. B. Leakey, J. Nösberger, and D. R. Ott. 2006. Food for thought: Lower-than-expected crop yield

stimulation with rising CO_2 concentrations. *Science* 312(5782): 1918-1921.
Magre, M., J. R. Williams, W. L. Harman, T. Gerik, J. Greiner, L. Francis, E. Steglich, and A. Meinardus. 2006. *WinAPEX Users Guide.* Version 1.0. Temple, Tex.: Texas A&M University, Texas Agricultural Experiment Station, Blackland Research and Extension Center. Available at: http://winapex.brc.tamus.edu/downloads/user-manuals.aspx. Accessed 5 June 2009.
McElroy, A. D., S. Y. Chiu, J. W. Nebgen, A. Aleti, and F. W. Bennett. 1976. Loading functions for assessment of water pollution from nonpoint sources. EPA 600/2-76-151. Washington, D.C.: U.S. Environmental Protection Agency.
McNitt, J., and R. Jones. 1999. Livestock and the environment: Precedents for runoff policy. Stephenville, Tex.: Tarleton State University, Texas Institute for Applied Environmental Research.
Monteith, J. L. 1965. Evaporation and environment. *Symp. Soc. Exp. Biol.* 19: 205-234.
Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Binger, R. D. Harmel, and T. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* 50(3): 885-900.
Mudgal, A., C. Baffaut, S. H. Anderson, E. J. Sadler, and A. L. Thompson. 2010. APEX model assessment of variable landscapes on runoff and dissolved herbicides. *Trans. ASABE* 53(4) (accepted).
Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part I. A discussion of principles. *J. Hydrol*. 10(3): 282-290.
Neitsch, S. 1998. Environmental impacts of dairy operations in the Lake Fork Reservoir watershed: SWAT baseline modeling results. Temple, Tex.: Texas A&M University, Texas Agricultural Experiment Station, Blackland Research and Extension Center.
Nicks, A. D. 1974. Stochastic generation of the occurrence, pattern, and location of maximum amount of daily rainfall. Misc. Publ. No. 1275. In *Proc. Symp. on Statistical Hydrology*, 154-171. Washington, D.C.: USDA.
Nicks, A. D., L. J. Lane, and G. A. Gander. 1995. Chapter 2. Weather generator. In *USDA Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation*. D. C. Flanagan and M. A. Nearing, eds. NSERL Report No. 10. West Lafayette, Ind.: USDA-ARS National Soil Erosion Research Laboratory. Available at: www.ars.usda.gov/Research/docs.htm?docid=18073. Accessed 22 December 2009.
Olivera, F., M. Valenzuela, R. Srinivasan, J. Choi, H. Cho, S. Koka, and A. Agrawal. 2006. ArcGIS-SWAT: A geodata model and GIS interface for SWAT. *J. American Water Resour. Assoc*. 42(2): 295-309.
Onstad, C. A., and G. R. Foster. 1975. Erosion modeling on a watershed. *Trans. ASAE* 18(2): 288-292.
Osei, E., P. W. Gassman, R. Jones, S. Pratt, L. Hauck, L. Beran, W. Rosenthal, and J. R. Williams. 2000a. Economic and environmental impacts of alternative practices on dairy farms in an agricultural watershed. *J. Soil and Water Conserv.* 55(4): 466-472.
Osei, E., P. Gassman, and A. Saleh. 2000b. Livestock and the environment: A national pilot project: Economic and environmental modeling using CEEOT. TIAER Report No. PR0002. Stephenville, Tex.: Tarleton State University, Texas Institute for Applied Environmental Research. Available at: http://tiaer.tarleton.edu/pdf/PR0002.pdf. Accessed 2 February 2010.
Osei, E., P. Gassman, and A. Saleh. 2000c. Livestock and the environment: A national pilot project: Upper Maquoketa River watershed, Iowa, modeling assumptions. TIAER Report No. RR0001. Stephenville, Tex.: Tarleton State University, Texas Institute for Applied Environmental Research. Available at: http://tiaer.tarleton.edu/pdf/RR0001.pdf. Accessed 2 February 2010.
Osei, E., P. W. Gassman, L. M. Hauck, R. Jones, L. Beran, P. T. Dyke, D. W. Goss, J. D. Flowers, and A. M. S. McFarland. 2003a. Economic costs and environmental benefits of manure incorporation on dairy waste application fields. *J. Environ. Mgmt*. 68(1): 1-11.
Osei, E., P. W. Gassman, L. M. Hauck, S. Neitsch, R. D. Jones, J. McNitt, and H. Jones. 2003b. Economic and environmental impacts of pasture nutrient management. *J. Range Mgmt*. 56(3): 218-226.
Osei, E., B. Du, A. Bekele, L. Hauck, A. Saleh, and A. Tanter. 2004. CEEOT-MMS: A macro modeling system for environmental assessment. TIAER Report No. TR0409. Stephenville, Tex.: Tarleton State University, Texas Institute for Applied Environmental Research. Available at: http://tiaer.tarleton.edu/pdf/TR0303.pdf. Accessed 2 February 2010.
Osei, E., B. Du, and L. M. Hauck. 2007. Impacts of changing herd sizes on the effects of manure application rates. In *Proc. 4th Conf.: Watershed Management to Meet Water Quality Standards and TMDLs*, 59-66. A. McFarland and A. Saleh, eds. St. Joseph, Mich.: ASABE.
Osei, E., B. Du, A. Bekele, L. Hauck, A. Saleh, and A. Tanter. 2008a. Impacts of alternative manure application rates on Texas animal feeding operations: A macro-level analysis. *J. American Water Resour. Assoc*. 44(3): 1-15.
Osei, E., B. Du, L. M. Hauck, A. Saleh, and A. Tanter. 2008b. Macro-level analysis of CNMPs in the Ohio River basin. In *Proc. 21st Century Watershed Technology Conf.: Improving Water Quality and Environment*. E. W. Tollner and A. Saleh, eds. St. Joseph, Mich.: ASABE.
Osei, E. L. Hauck, R. Jones, C. Ogg, and K. Keplinger. 2008c. Livestock and the environment: Lessons from a national pilot project. TIAER Report No. PR0801. Stephenville, Tex.: Tarleton State University, Texas Institute for Applied Environmental Research. Available at: http://tiaer.tarleton.edu/pdf/PR0801.pdf. Accessed 22 December 2009.
Parton, W. J., D. S. Schimel, C. V. Cole, and D. S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *SSSA J*. 51(5): 1173-1179.
Peabody, P. J. 2005. Agricultural cost of maintaining playa lake hydroperiod to preserve playa lake ecosystems in the Texas High Plains. MS thesis. Lubbock, Tex.: Texas Tech University, Department of Agriculture and Applied Economics. Available at: http://repositories.tdl.org/tdl/handle/2346/1275?show=full. Accessed 14 May 2009.
Paudel, K. P., D. Hite, W. Intarapapong, and D. Susanto. 2003. A watershed-based economic model of alternative management practices in southern agricultural systems. *J. Agric. Applied Econ*. 35(2): 381-389.
Penman, H. L. 1948. Natural evaporation from open water, bare soil, and grass. *Proc. Royal Soc. London A* 193(1032): 120-145.
Potter, K. N., J. R. Williams, F. J. Larney, and M. S. Bullock. 1998. Evaluation of EPIC's wind erosion submodel using data from southern Alberta. *Canadian J. Soil Sci.* 78(3): 485-492.
Potter, S., S. Wang, and A. King. 2009. Modeling structural conservation practices: Cropland component of the National Conservation Effects Assessment Project. Temple, Tex.: Texas A&M University, Texas Agricultural Experiment Station, Blackland Research and Extension Center. Available at: www.nrcs.usda.gov/technical/NRI/ceap/umrbdocumentation/. Accessed 1 February 2010.
Pratt, S., R. Jones, and C. A. Jones. 1997. Livestock and the environment: Expanding the focus: Policy options: CEEOT-LP. TIAER Report No. PR9603. Stephenville, Tex.: Tarleton State University, Texas Institute for Applied Environmental Research.

Priestley, C. H. B., and R. J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Rev.* 100(2): 81-92.

Qiu, Z., T. Prato, L. Godsey, and V. Benson. 2002. Integrated assessment of uses of woody draws in agricultural landscapes. *J. American Water Resour. Assoc.* 38(5): 1255-1269.

Reddy, K. R., R. Khaleel, M. R. Overcash, and P. W. Westerman. 1979. A nonpoint-source model for land areas receiving animal wastes: II. Ammonia volatilization. *Trans. ASAE* 22(6): 1398-1404.

Renard, K. G., G. R. Foster, G. A. Weesies, D. K. McCool, and D. C. Yoder. 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook No. 703. Washington, D.C.: USDA Agricultural Research Service.

Reungsang, P., R. S. Kanwar, M. Jha, P. W. Gassman, K. Ahmad, and A. Saleh. 2007. Calibration and validation of SWAT for the Upper Maquoketa River watershed. *Intl. Agric. Eng. J.* 169(1-2): 35-48.

Richardson, C. W. 1981. Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water Resour. Res.* 17(1): 182-190.

Ritchie, J. T. 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* 8(5): 1204-1213.

Saleh, A., and O. Gallego. 2007. Application of SWAT and APEX using the SWAPP (SWAT-APEX) program for the Upper North Bosque River watershed in Texas. *Trans. ASABE* 50(4): 1177-1187.

Saleh, A., J. G. Arnold, P. W. Gassman, L. M. Hauck, W. D. Rosenthal, J. R. Williams, and A. M. S. McFarland. 2000. Application of SWAT for the Upper North Bosque River watershed. *Trans. ASAE* 45(3): 1077-1087.

Saleh, A., P. W. Gassman, J. Abraham, and J. Rodecap. 2003. Application of SWAT and APEX models for Upper Maquoketa River watershed in northeast Iowa. ASAE Paper No. 032063. Presented at the 2003 ASAE Annual International Meeting. St. Joseph, Mich.: ASAE.

Saleh, A., J. R. Williams, J. C. Wood, L. M. Hauck, and W. H. Blackburn. 2004. Application of APEX for forestry. *Trans. ASAE* 47(3): 751-765.

Saleh, A., E. Osei, and O. Gallego. 2008. Use of CEEOT-SWAPP modeling system for targeting and evaluating environmental pollutants. In *Proc. 21st Century Watershed Technology Conf.: Improving Water Quality and Environment*. E. W. Tollner and A. Saleh, eds. St. Joseph, Mich.: ASABE.

Seligman, N. G., and H. van Keulen. 1981. PAPRAN: A simulation model of annual pasture production limited by rainfall and nitrogen. In *Proc. Workshop: Simulation of Nitrogen Behaviour of Soil-Plant Systems*, 192-221. M. J. Frissel and J. A. van Veen, eds. Wageningen, The Netherlands: Centre for Agricultural Publishing and Documentation.

Skaggs, R. W. 2007. Criteria for calculating drain spacing and depth. *Trans. ASABE* 50(5): 1657-1662.

Srivastava, P., K. W. Migliaccio, and J. Šimůnek. 2007. Landscape models for simulating water quality at point, field, and watershed scales. *Trans. ASABE* 50(5): 1683-1693.

Steglich, E. M., and J. R. Williams. 2008. *Agricultural Policy/Environmental Extender Model: User's Manual*. Version 0604 DOS and WINAPEX interface. BREC Report 2008-16. Temple, Tex.: Texas A&M University, Texas AgriLIFE Research, Blackland Research and Extension Center. Available at: http://epicapex.brc.tamus.edu/downloads/user-manuals.aspx. Accessed 31 January 2010.

Tubiello, F. N., J. S. Amthor, K. J. Boote, M. Donatelli, W. Easterling, G. Fischer, R. M. Gifford. M. Howden, J. Reilly, and C. Rosenzweig. 2007. Crop response to elevated CO_2 and world food supply: A comment on "Food for Thought..." by Long et al., *Science* 312: 1918-1921, 2006. *European J. Agron*. 26(3): 215-223.

Tuppad, P., M. F. Winchall, X. Wang, R. Srinivasan, and J. R. Williams. 2009. ARCAPEX: ARCGIS interface for Agricultural Policy Environmental Extender (APEX) hydrology/water quality model. *Intl. Agric. Eng. J*. 18(1-2): 59-71.

USDA-ARS. 2005. Revised Universal Soil Loss Equation 2: Overview of RUSLE2. Oxford, Miss.: USDA-ARS National Sedimentation Laboratory, Watershed Research Physical Processes Unit. Available at: www.ars.usda.gov/Research/ docs.htm?docid=6010. Accessed 2 February 2010.

USDA-NRCS. 1986. Urban hydrology for small watersheds. Technical Release 55. Washington, D.C.: USDA National Resource Conservation Service. Available at: www.hydrocad.net/pdf/TR-55%20Manual.pdf. Accessed 31 January 2010.

USDA-NRCS. 2004. Chapter 10: Estimation of direct runoff from storm rainfall. In *NRCS National Engineering Handbook*, Part 630: Hydrology, 10.1-10.22. Washington, D.C.: USDA National Resource Conservation Service. Available at: http://directives.sc.egov.usda.gov/viewerFS.aspx?hid=21422. Accessed 5 June 2009.

USDA-NRCS. 2009a. Conservation Effects Assessment Project (CEAP). Washington, D.C.: USDA National Resources Conservation Service. Available at: www.nrcs.usda.gov/technical/NRI/ceap/.

USDA-NRCS. 2009b. National Resource Inventory: A statistical survey of land use and natural resource conditions and trends on U.S. non-federal lands. Washington, D.C.: USDA National Resources Conservation Service. Available at: www.nrcs.usda.gov/technical/NRI/.

USDA-NRCS. 2010. Assessment of the effects of conservation practices on cultivated cropland in the Upper Mississippi River basin. Washington, D.C.: USDA Natural Resources Conservation Service. Available at: www.nrcs.usda.gov/technical/nri/ceap/cropland.html.

Wang, E., W. L. Harman, M. Magre, J. R. Williams and J. M. Sweeten. 2002. Profitability and nutrient losses of alternative manure application strategies with conservation tillage. *J. Soil and Water Conserv.* 57(4): 221-228.

Wang, E., C. Xin, J. R. Williams, and C. Xu. 2006a. Predicting soil erosion for alternative land uses. *J. Environ. Qual*. 35(2): 459-467.

Wang, X., S. R. Potter, J. R. Williams, J. D. Atwood, and T. Pitts. 2006b. Sensitivity analysis of APEX for national assessment. *Trans. ASABE* 49(3): 679-688.

Wang, X., A. Saleh, M. W. McBroom, J. R. Williams, and L. Yin. 2007. Test of APEX for nine forested watersheds in east Texas. *J. Environ. Qual.* 36(4): 983-995.

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

Wang, X., S. Shang, and W. Yang. 2008b. Simulation of an agricultural watershed using an improved curve number method in SWAT. *Trans. ASABE* 51(4): 1323-1339.

Wang, X., D. W. Hoffman, J. E. Wolfe, J. R. Williams, and W. E. Fox. 2009. Modeling the effectiveness of conservation practices at Shoal Creek watershed, Texas, using APEX. *Trans. ASABE* 52(4): 1181-1192.

White, E. D., G. W. Feyereisen, T. L. Veith, and D. D. Bosch. 2008. Improving daily water yield estimates in the Little River watershed: SWAT adjustments. *Trans. ASABE* 52(1): 69-79.

Williams, J. R. 1975. Sediment yield prediction with universal equation using runoff energy factor. ARS-S-40. Washington, D.C.: USDA Agricultural Research Service.

Williams, J. R. 1990. The erosion productivity impact calculator (EPIC) model: A case history. *Phil. Trans. Royal Soc. London* 329(1255): 421-428.

Williams, J. R. 1995. The EPIC model. In *Computer Models of Watershed Hydrology*, 909-1000. V. P. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Williams, J. R., and R. W. Hann. 1978. Optimal operation of large agricultural watersheds with water quality constraints. Tech. Report No. 96. College Station, Tex.: Texas A&M University, Texas Water Resources Institute.

Williams, J. R., and R. C. Izaurralde. 2005. The APEX model. BREC Report No. 2005-02. Temple, Tex.: Texas A&M University, Texas

Agricultural Experiment Station, Blackland Research and Extension Center.
Williams, J. R., and R. C. Izaurralde. 2006. The APEX model. In *Watershed Models*, 437-482. V. P. Singh and D. K. Frevert, eds. Boca Raton, Fla.: CRC Press.
Williams, J. R., C. A. Jones, and P. T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Trans. ASAE* 27(1): 129-144.
Williams, J. R., C. A. Jones, J. R. Kiniry, and D. A. Spanel. 1989. The EPIC crop growth model. *Trans. ASAE* 32(2): 497-511.
Williams, J. R., C. A. Jones, P. W. Gassman, and L. M. Hauck. 1995. Simulation of animal waste management with APEX. In *Innovations and New Horizons in Livestock and Poultry Manure Management*, 22-26. J. McFarland, ed. Austin, Tex.: Texas A&M University, Texas Agricultural Extension Service.
Williams, J. R., J. G. Arnold, and R. Srinivasan. 2000. The APEX model. BREC Report No. 00-06. Temple, Tex.: Texas A&M University, Texas Agricultural Experiment Station, Blackland Research and Extension Center.
Williams, J. R., E. Wang, A. Meinardus, and W. L. Harman. 2003. *APEX Users Guide*. Version 1310. Temple, Tex.: Texas A&M University, Texas Agricultural Experiment Station, Blackland Research and Extension Center.
Williams, J. R., W. L. Harman, M. Magre, U. Kizil, J. A. Lindley, G. Padmanabhan, and E. Wang. 2006a. APEX feedlot water quality simulation. *Trans. ASAE* 49(1): 61-73.
Williams, J. R., E. Wang, A. Meinardus, W. L. Harman, M. Siemers, and J. D. Atwood. 2006b. *APEX Users Guide*. Version 2110. Temple, Tex.: Texas A&M University, Texas Agricultural Experiment Station, Blackland Research and Extension Center.
Williams, J. R., J. G. Arnold, J. R. Kiniry, P. W. Gassman, and C. H. Green. 2008a. History of model development at Temple, Texas. *Hydrol. Sci. J.* 53(5): 948-960.
Williams, J. R., R. C. Izaurralde, and E. M. Steglich. 2008b. *Agricultural Policy/Environmental Extender model: Theoretical Documentation*. Version 0604. BREC Report 2008-17. Temple, Tex.: Texas A&M University, Texas AgriLIFE Research, Blackland Research and Extension Center. Available at: http://epicapex.brc.tamus.edu/downloads/user-manuals.aspx. Accessed 31 January 2010.
Willis, D. B. 2008. Cost-effectiveness of on-farm conservation practices to protect playa lake hydroperiod in the Texas High Plains. Paper presented at the Southern Agricultural Economics Association Annual Meeting. Available at: http://purl.umn.edu /6753. Accessed 2 February 2010.
Wischmeier, W. H., and D. D. Smith. 1978. Predicting rainfall erosion losses: A guide to conservation planning. Agric. Handbook No. 537. Washington, D.C.: USDA. Available at: http://naldr.nal.usda.gov. Accessed 2 February 2010.
Yin, L., X. Wang, J. Pan, and P. W. Gassman. 2009. Evaluation of APEX for daily runoff and sediment yield from three plots in the Upland Huaihe River watershed, China. *Trans. ASABE* 52(6): 1833-1845.

NOMENCLATURE

AFO = animal feeding operation
ALMANAC = Agricultural Land Management Alternatives with Numerical Assessment Criteria model
APEX = Agricultural Policy Environmental Extender model
ArcAPEX = ArcGIS APEX interface
ArcSWAT = ArcGIS SWAT interface
AVSWAT = ArcView SWAT interface
BMP = best management practice
BRW = Bosque River watershed
CARD = Center for Agricultural and Rural Development
CEAP = Conservation Effects Assessment Project
CEEOT = Comprehensive Economic Environmental Optimization Tool
CEEOT-MMS = Comprehensive Economic Environmental Optimization Tool - Macro Modeling System
CHP = clearcutting followed by roller chopping and burning
CON = undisturbed control
CRP = Conservation Reserve Program
DCW = Duck Creek watershed
DEM = digital elevation model
EPIC = Environmental Policy Impact Climate model (originally Erosion Productivity Impact Calculator model; see Gassman et al., 2005)
FEM = farm-level economic model
GLL = grass loafing lots
GSWR = Grassland, Soil and Water Research Laboratory
i_APEX = interactive APEX interface
IRG = intensive rotational grazing
LFRW = Lake Fork Reservoir watershed
MCW = Mineral Creek watershed
MLRA = major land resource area
MSEA = Missouri Management Systems Evaluation Area
MUSI = MUSLE approach that uses input coefficients
MUSLE = Modified Universal Soil Loss Equation
MUSS = MUSLE small watershed version
MUST = MUSLE theoretical version
MWRR = major water resource region
NPP = National Pilot Project for Livestock and the Environment
NRI = National Resources Inventory
NSE = Nash-Sutcliffe model efficiency
OAG = open-access grazing
PAPRAN = Production of Arid Pastures Limited by Rainfall and Nitrogen
RCN = runoff curve number technique
RUSLE/RUSLE2 = Revised Universal Soil Loss Equation
SFI = Sustainable Forestry Initiative
SHR = clearcutting by shearing, windrowing, and burning
SMZ = stream management zone
SWAPP = SWAT-APEX interface
SWAT = Soil and Water Assessment Tool
TNRCC = Texas Natural Resource Conservation Commission
TR-55 = Technical Release 55
UMRW = Upper Maquoketa River watershed
UNBRW = Upper North Bosque River watershed
USLE: Universal Soil Loss Equation
VSC = Variable Storage Coefficient flood routing method
WECS = Wind Erosion Continuous Simulation
WEQ = Wind Erosion Equation