ARCAPEX: ARCGIS INTERFACE FOR AGRICULTURAL POLICY ENVIRONMENTAL EXTENDER (APEX) HYDROLOGY/WATER QUALITY MODEL

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ABSTRACT

ArcAPEX is an ArcGIS-based user interface designed to automate the input parameterization of the Agricultural Policy Environmental eXtender (APEX) hydrologic/water quality model. The interface integrates topographic, land use, and soil spatial datasets and a built-in APEX-Parameters database that contains model parameter values required to simulate a wide range of plant growth, tillage, fertilizer, and pesticide applications over a farm/field to basin scale drainage area. Other key features of ArcAPEX include its ability to build and save alternative crop management operation schedules and options for integration directly with the Soil and Water Assessment Tool (SWAT) for large watershed simulations. The major components for the ArcAPEX interface are presented, including watershed delineation, analysis of land use and soils, weather data, input parameter definition, model run management, and SWAT model integration. An application of ArcAPEX, conducted to evaluate various agricultural best management practices for a subwatershed of Bosque River Watershed in central Texas, is described to provide a demonstration of ArcAPEX. The software also provides possibilities for watershed-scale assessments of agroforestry systems in Southeast Asia and other regions.

Keywords: *Watershed, geographical information system, hydrologic modeling, water quality, best management practice.* © 2009 AAAE

1. INTRODUCTION

The Agricultural Policy Environmental eXtender (APEX) model (Williams et al., 2008a; b) is a distributed, continuous, daily time-step farm or small watershed-scale hydrologic/water quality model. It is an extension of Environmental Policy Integrated Climate (EPIC) (Williams, 1990). The model is capable of detailed field scale modeling and routing, connecting farm/field sized subareas within a watershed. The EPIC/APEX models have been tested widely for their ability to simulate different agricultural management practices at both field and watershed scales (Gassman et al., 2005; 2009).

The use of spatial datasets and geographic information system (GIS) software to parameterize hydrologic and water quality models has been in practice for well over a decade. The GIS platforms provide functionality that enables efficient integration and analysis of critical landscape physiographic data layers, such as elevation, land use, soils, and hydrography required to characterize a watershed scale model. Properly designed GIS interfaces can automate watershed delineation and hydrologic network identification, calculation of parameters that describe subbasin geometric and topographic characteristics, channel dimensions, as well as land use, soils, and slope area distributions. An excellent example is the Soil and Water Assessment Tool (SWAT) watershed model (Arnold et al., 1998; Gassman et al., 2007) which has experienced significant integration with GIS interfaces over the last 15 years, including a RASS platform (SWAT/GRASS) interface (Srinivasan and Arnold, 1994), an ArcView 3.x (AVSWAT) interface (DiLuzio et. al., 2004), and an ArcGIS (ArcSWAT) interface (Olivera et al., 2006; Winchell et al., 2008).

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The APEX model has seen a rapid progression in user interfaces within the past five years. Several non-GIS-enabled interfaces have included a DOS-based Universal Text Integration Language (UTIL) interface (Williams et al., 2004; Taylor and Bryant, 1994), and two Windows based interfaces, WinAPEX (Magre et al., 2006) and i_APEX (Gassman et al., 2009). GIS-enabled interfaces for APEX have included an ArcView 3.x-based program referred to as SWAPP to convert SWAT files to and from APEX format and simulate SWAT and APEX simultaneously (Saleh and Gallego, 2007). In addition, a modeling system combining ArcGIS and WinAPEX called WinAPEX-GIS has also been recently developed (Gassman et al., 2009). This system utilizes ArcGIS (ESRI, Redlands, California) to calculate all the GIS-based input data such as soil, land use, and topographic characteristics of the landscape. These data are stored in Access tables that are exported to WinAPEX for further defining management and other inputs.

ArcAPEX is a GIS-based user interface that integrates enhanced GIS capabilities and algorithms based upon the ArcSWAT interface with APEX databases, input, and output management within a single interface. ArcAPEX is an extension to the ArcGIS software package that has been developed using ArcObjects and the Microsoft Visual Basic .NET software development kit. The interface has been developed for use with ArcGIS versions 9.2 and 9.3.x and is compatible with the Microsoft Windows operating systems. ArcAPEX was designed to automate the parameterization of APEX model using readily available topographic, hydrologic, land use, and soils spatial datasets. In addition to automated identification of model topographic and landscape characteristics, ArcAPEX features direct integration with an APEX-Parameters database that contains plant, tillage, fertilizer, pesticide, and weather characteristics required by the APEX model. Additionally, ArcAPEX has been designed to provide direct integration with SWAT model created using the ArcSWAT interface. This framework allows the development of watershed scale models that incorporate multiple scales into the simulation, and provides consistency between the two models for calculation of parameters as well as a similar series of processing steps for users to follow when developing their models with either interface. In this framework, APEX can be implemented for more detailed simulation of farms or small subwatersheds with complex agronomic systems, while SWAT is implemented for larger subwatersheds characterized by simple agricultural systems and non-agricultural landscapes, as well as for integrating constituent (runoff, sediment, nutrient, and pesticide) contributions from all subwatersheds and simulating in-stream channel processes. The ability of APEX to simulate multiple crop/plant species may also provide the potential in the future for simulating complex tropical agroforestry systems such as those used in Southeast Asia, as discussed by Johnson et al. (2009).

The specific objectives of this paper are to: (1) describe the features and functionality of ArcAPEX interface, and (2) demonstrate application of ArcAPEX to evaluate various agricultural best management practices for a subwatershed of Bosque River Watershed in central Texas.

2. METHODOLOGY

2.1 ArcAPEX Project Components

An ArcAPEX project is built around an ArcGIS ArcMap document, several ArcGIS personal geodatabases, and the APEX model executable program (APEX0604). The ArcMap document contains the user interfaces used to develop and run the APEX model for a particular project. It also provides all map visualization for the project and spatial analysis capabilities required to calculate APEX model parameters. The first geodatabase, the APEX Parameters geodatabase, is a database accessible to one or more APEX projects. This database contains parameters that describe various crops, tillage practices, fertilizers, pesticides, weather stations, and agricultural management schedules. In addition, the database serves as a repository for metadata on the content and structure of each APEX input file and parameter. This information is used directly by the ArcAPEX interface, providing data necessary to describe model parameters within the interface and dictating how APEX model input files are generated. The second database is referred to as the APEX Project database. As the name suggests, this database is associated with a single APEX project within the ArcMap document. The Project database stores all the spatial data layers associated with the project, including subareas, reaches, outlets, and longest flow paths. In addition, this database contains tables that store information on all of the APEX model parameters that are used to write the inputs necessary for the APEX0604 model. The APEX0604 executable reads the input files generated by the ArcAPEX interface, runs the APEX model, and generates the output files in a standard ascii text format. The ArcAPEX interface is designed to be

compatible with a specific version of the APEX0604 executable. The most recent and compatible version of APEX0604 is always included with the current ArcAPEX interface installation package. Documentation of the APEX0604 model is provided in Williams et al. (2008a, 2008b).

A new APEX project is initiated from within an empty ArcMap document which has the ArcAPEX extension activated. When a new project is created, the necessary directory structure and databases are generated and associated with the ArcMap document. The steps required to build an APEX simulation begin with analysis of GIS data layers, including delineation of watersheds and subareas, analysis of subarea land use and soils characteristics, and development of weather inputs. Model input tables are then built and edited by the user, if needed. These steps are described in more detail in the sections that follow.

2.2 APEX Subarea Delineation

The APEX model divides a watershed into one or more subareas. A subarea is conceptually equivalent to a field or landscape unit with homogeneous weather inputs, land cover, vegetation, soils, and agronomic practices. In this respect, an APEX subarea is functionally equivalent to a SWAT Hydrologic Response Unit (HRU). In addition, each subarea is associated with a channel for routing runoff, sediment, nutrients, and pesticides from one subarea to another. With respect to defining watershed connectivity, APEX subareas are functionally equivalent to subbasins in the SWAT model. Delineation of APEX subareas, channels, and subarea connectivity is the first step in the development of an APEX model project.

Prior to beginning the subarea delineation process, a user must make the decision as to whether the APEX simulation being developed will be a standalone application or will be integrated with a larger-scale SWAT simulation. The standalone model option is intended for use when the entire watershed of interest will be simulated using the APEX model. In this case, the subarea delineation will define the subarea boundaries and hydrologic connectivity contributing to a user defined watershed outlet(s). Subarea boundaries may be delineated based upon a digital elevation model (DEM) or by importing user defined subarea boundaries and streams. The DEM-based subarea delineation implements the single flow direction algorithm used in ESRI software (Jenson and Domingue, 1988) to generate the required flow direction and flow accumulation raster datasets used

in watershed delineation. This method for subarea delineation defines subareas as essentially micro-watersheds. These micro-watersheds will often contain portions of multiple fields with different land uses or crops, however in the APEX model, the subarea must be characterized as a single land use or crop. An example DEM-based subarea delineation and underlying land cover is shown in figure 1. This shows how subareas can be made up of multiple fields, in this case, both corn and soybean.

In some situations, it may be desirable to define subareas to be closely associated with specific agricultural field boundaries. In this case, the option of importing user defined subarea boundaries and streams would be chosen in place of the DEM-based delineation of subareas. User defined subareas could easily be delineated from readily available aerial
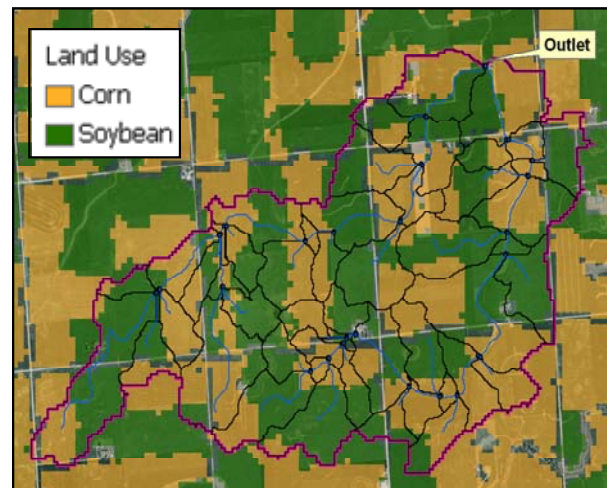

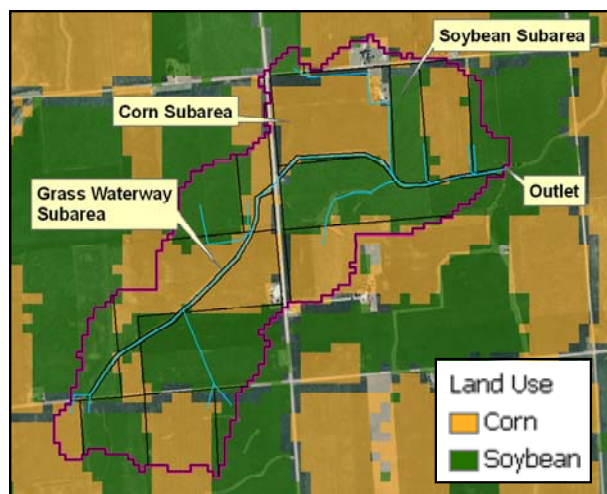Fig. 1: DEM-based APEX subarea delineation

Fig. 2: User-defined APEX subarea delineation

imagery; e.g., United States Department of Agriculture-National Agriculture Imagery Program (USDA, 2009b) or other remote sensing datasets. Figure 2 shows an example APEX subareas that were delineated using the NAIP aerial imagery to more accurately reflect field boundaries. Many BMPs can be represented in a more detailed way such as the grassed waterway shown in Figure 2.

The SWAT-Integrated option is applicable when APEX will be used to simulate one or more subbasins in an existing SWAT model. This option would typically be chosen when simulation of a complex agricultural system is necessary to properly represent certain areas within a larger watershed. In this case, a user will be required to identify an existing SWAT model and choose which subbasins will be modeled with APEX. Once users have selected SWAT subbasins, the interface provides the option of importing the SWAT DEM and derived datasets or incorporating a new, usually more refined, DEM from which to base the APEX subarea delineation and calculation of subarea parameters. Both the standalone APEX model and SWAT-Integrated subarea delineations provide users a range of options when defining the size and location of subareas. Usage of the DEM-based delineation allows users to define the size of their subareas based upon a threshold drainage area that constrains the minimum size of a subarea in the watershed. Threshold drainage area is the minimum area required to begin a stream. The size of a subarea typically range from 1 to 100 ha or more depending on the geographic location. It is limited only by the degree of details to be incorporated in the model setup and the variability in the landscape. The number of subareas is limited by the computing resources and ease of data handling and analysis. Point source inputs can also be added directly to user specified subareas through an interactive tool. Users have the option of adding additional subarea outlets through a table of latitude and longitude coordinates, or by interactively specifying a location along the channel network using the GIS functionality of the interface. Reservoirs within the watershed can also be added into the model structure through the same interactive approach. Once the subarea and channel structure definition has been completed, the subarea topographic and physical characteristics, including area, slope, overland flow slope length, channel length, and channel slope are calculated by the interface.

The outputs of the APEX subarea delineation include subarea and stream spatial datasets, which are stored as feature classes within an ArcGIS geodatabase. The format of the geodatabase data model is consistent with the ArcSWAT data model (Olivera et al., 2006) and uses the watershed feature class to store subareas and the reach feature class to store streams. The attribute tables of these feature classes are used by the ArcAPEX interface to define subarea connectivity and parameters for each subarea input file. In some cases, multiple watershed outlets will be defined within a single ArcAPEX project. The APEX model refers to watersheds draining to a single outlet as "sites". The ArcAPEX database keeps tracks of which subareas are associated with which APEX site, allowing many sites to be simulated concurrently.

2.3 Subarea Analysis

Subarea analysis characterizes the land use/land cover, soils, and slope distributions within each delineated subarea. These characteristics are critical in determining the hydrologic and agronomic response within a watershed. The two steps in the subarea analysis are the definition of land use, soils and slope input datasets, and then the selection of the most appropriate of these characteristics for each subarea.

The land use/soils/slope definition in ArcAPEX combines these three landscape properties to generate areas representing unique hydrology within each subarea. The slope data layer is a direct outcome of the subarea delineation step. The land use data layer must be provided by the user, which can be either a vector or a raster layer. The soil data layer can be extracted from the U.S. STATSGO soils database for U.S. watersheds, which is packaged and integrated with the ArcAPEX interface. Loading and defining soil properties based on the STATSGO soil database (USDA, 1994; 2006) is currently automated in ArcAPEX. Depending on the specific purpose and nature of soil variability in the location of their interest, users can either use STATSGO or import a table of soils properties into the APEX Parameters database from any other soil database, such as the U.S. SSURGO database (USDA, 1995; 2009a).

Consistent formats are maintained between the ArcAPEX and ArcSWAT soil properties database tables. Once all required input data layers and lookup tables are defined, a spatial overlay is performed to calculate the areas represented by each unique combination of characteristics within each subarea.

The ArcAPEX subarea definition step assigns a single land use, soil class, and slope class to each subarea. This is conceptually different than ArcSWAT, where multiple HRUs can be defined within each subbasin. By design, APEX subareas are

intended to be smaller than a SWAT subbasin, and as previously discussed, have conceptual similarities to individual HRUs. There are three options for assigning a land use, soil, and slope class to each subarea: 1) the most dominant of each of the three landscape characteristic, 2) the most dominant unique combination of the three landscape characteristics, and 3) the user specified land use, soil, and slope class to a particular subarea.

2.4 Weather

The APEX model requires daily time series of precipitation, temperature, relative humidity, solar radiation, and wind speed. The ArcAPEX interface provides the user three options for supplying weather information: 1) Daily time series for all weather parameters provided by the user, 2) Daily time series for all weather parameters generated by APEX, and 3) Daily time series provided by the user for some parameters and generated by APEX for other parameters. The daily weather time series generated by the APEX model use station-specific monthly weather statistics and account for the interdependence among weather parameters to generate synthetic daily time series. The APEX Parameters geodatabase contains monthly weather and wind statistics for 975 stations across the United States. APEX users in countries other than the United States can import monthly weather statistics data for local weather stations directly into the ArcAPEX weather stations database, in the required format. The weather generator algorithms in APEX are also used to fill in missing data within user provided observed daily time series.

The ArcAPEX interface will identify the closest station to each subarea. The monthly weather generator stations and the user provided daily stations associated with each subarea are then written to a table contained in the APEX Project geodatabase. These data are then used to populate the APEX input files with the appropriate weather information.

2.5 APEX Input Files

The ArcAPEX interface will generate a set of initial input parameters based upon the subarea delineation, subarea land use/soils/slope analysis, and the weather data. These parameters are stored in tables within the ArcAPEX Project geodatabase. The structure of the APEX Project geodatabase has been designed so that there is generally one table that represents each of the main APEX0604 input files.

The exceptions to this rule are the APEX soils input files, which are represented by two tables in the APEX Project geodatabase; one for the component level attributes and one for the layer level attributes. In addition to project specific tables, APEX0604 input files will be extracted from tables stored in the APEX Parameters database. These tables, including operations schedules, are shared between multiple APEX projects. As with the inputs generated from the APEX Project geodatabase, the inputs generated from the Parameters geodatabase are generally represented as one table per APEX input file. The operations schedule input files are an exception to this, with one table storing operation schedules and a second table storing the related individual management operations. The APEX input files and associated geodatabase tables are listed in table 1.

The ArcAPEX interface includes a user interface for editing each of the input files listed in table 1, which are integrated with metadata tables stored in the APEX Parameter geodatabase. The metadata table for each APEX input table/file provides help to the user in terms of describing each parameter and constraining the allowable values for the parameters. In addition, the metadata tables describe the formatting necessary for writing the APEX0604 text input files from the geodatabase tables. This allows APEX parameters to be efficiently added, modified, or removed from the input files without requiring changes to the interface code that reads the database and prints the input files.

The user interfaces for the tables in the APEX Parameters geodatabase (Operation Schedules, Crop, Tillage, Fertilizer, Pesticide, Monthly Weather, and Wind) allow users to add new records to the database tables. This is necessary if a user would like to simulate, for example, a crop or pesticide that is not included in the APEX Parameters database provided with ArcAPEX. These interfaces allow the user to choose an existing record (crop, pesticide, etc.) in the database upon which to base the new record, greatly simplifying the process of defining new entries in the APEX databases. The Operations Schedules database interface, one of the more complex interfaces in ArcAPEX, provides functionality for creating new operation schedules, adding, deleting, and editing operations from those schedules, and also provides the ability to upload properly formatted APEX0604 operations files (*.OPC files) into the APEX Parameters database.

2.6 APEX Model Run and Output Files

ArcAPEX contains a simple interface for running the APEX model. In cases where an APEX project contains multiple watersheds, the user may elect to run the model for one or more of the watersheds in a single APEX run. With the advent of ArcAPEX, APEX0604 was modified to generate output files in the same format generated by the SWAT model. At the conclusion of an APEX model run, users may use a built-in tool to import the output files into a Microsoft Access or Excel database for analyzing the output for individual reaches or subareas. APEX will also generate an output file containing all the flow, sediment, and nutrient time series for the outlet of APEX watershed(s) in the same format as a SWAT point source input file. It is this output file that allows the direct integration of APEX model into SWAT.

2.7 Integration with SWAT

Once an APEX model run has been completed in ArcAPEX, one must return to a SWAT model project to complete the linkage of the two models. A menu option has been added to the ArcSWAT interface that allows for the specification of APEX model outputs to replace the inputs from a set of selected SWAT subbasins. This is accomplished by replacing the loadings generated by subbasin and HRU processes in SWAT with a point source input in the SWAT channel network. The point source loadings come from the APEX watershed simulation results. The user must select the subbasins modeled with APEX and then identify the APEX output folder that contains the results of the APEX simulations. The communication between the ArcAPEX and ArcSWAT interfaces ensures that the watershed "site" IDs in the ArcAPEX project correspond with the "subbasin" IDs in the ArcSWAT project, relieving the user from needing to keep track of file names and lookups between SWAT and APEX. To complete the connection between the APEX and SWAT models, the ArcSWAT interface re-writes the SWAT 'watershed configuration file' (fig.fig) to insert APEX inputs as point sources in place of SWAT subbasin inputs. The fig.fig file contains information used by SWAT to simulate processes occurring within the HRU/subbasin and route the loadings through the watershed channel network. The user will always have the option of resetting the SWAT fig.fig file to its original structure which uses the SWAT subbasin simulations instead of the APEX inputs. This functionality provides a method to quickly evaluate the differences in simulations between APEX and SWAT simulated subbasins.

Table 1: APEX input files and associated database tables

APEX0604 Input File	APEX Geodatabase	Geodatabase Table(s)
APEX Control	Project	APEXCONT
APEX Site	Project	APEXSITE
APEX Subarea	Project	SUBAREA
APEX Soils	Project	APEXSOIL_COMP, APEXSOIL_LAYER
APEX Operation Schedules	Parameters	tblOPSCCOM, tblAPEXOPSC
APEX Monthly Weather	Parameters	tblWPM1MO
APEX Monthly Wind	Parameters	tblWINDMO
APEX Tillage	Parameters	tblTILLCOM
APEX Crop	Parameters	tblCROPCOM
APEX Fertilizer	Parameters	tblFERTCOM
APEX Pesticide	Parameters	tblPESTCOM
APEX PARAM	Project	APEXPARM
APEX Herd	Project	APEXHERD
APEX Print	Project	tblAPEXPRNT

3. APPLICATION

The following sections describe a study wherein ArcAPEX is applied to evaluate the water quality impacts of various agricultural conservation practices (also referred to as best management practices (BMPs)) over a watershed in central Texas. The BMPs are on-farm or in-stream activities that are designed to conserve water by reducing runoff and increasing infiltration into the soil profile, and to reduce sediment, nutrients and pesticides loss in drainage waters. The agricultural BMPs are encouraged for wider adoption in the US to preserve and/or enhance the quality of receiving waterbodies. Simulating these BMPs and assessing their impacts using watershed models is gaining wider scope due to the fact that models are efficient scientific tools to simulate the impact of potential changes in landscape and land management on downstream water quality. Moreover, due to the general complex nature of the landscape, effect of a BMP might vary from one location to another as function of soil type, land management, and climatic conditions. Also, conducting long-term experiments to monitor the effectiveness of BMPs in large watershed becomes overly expensive.

3.1 Watershed Description and Input Data

The selected area for ArcAPEX application is a subwatershed of Bosque River watershed in central Texas (Fig. 3). This subwatershed drains Tonk Creek (TC) and Wasp Creek (WC) and has a combined drainage area of 104 km^2. A DEM of 10m horizontal resolution was used as an input to establish the topographic characteristics of the watershed. A threshold drainage area of 0.55 km^2 (i.e., 6071 DEM cells), as determined by the ArcAPEX interface, was used to derive the stream network. Several additional outlets were manually added through the interface. Accordingly, a total of 102 outlets were defined that resulted in subdividing the study watershed into 102 subareas (fig. 3).

USDA-Natural Resources Conservation Service (NRCS, 2008) 2007 land use/land cover data (fig. 4(a)) and SSURGO soils data (fig. 4(b)) were used to define the subarea landuse and soil characteristics. Daily rainfall records from a rain gage station maintained by the Texas Institute of Applied Environmental Research (TIAER) at the TC monitoring site was used in this study (fig. 3). Daily

minimum and maximum temperature data was obtained from the nearby cooperative weather station. Solar radiation, relative humidity, and wind data were generated based from the weather statistics from the closest weather station in the ArcAPEX Parameters geodatabase. Most of the initial parameter values were default values from the database. Corn and wheat are the major crops grown in the watershed. A three year conventionally tilled 'corn-corn-winter wheat' rotation was simulated on all croplands. Both rangelands and pasture lands were simulated as grazed. Rangeland was not fertilized while pasture was fertilized. Management scheduling for cropland, rangeland, and pastureland was obtained from local 'soil and water conservation district' personnel (A. Spencer. Personal Communication. Conservation Agronomist, USDA-NRCS, Weatherford, Texas).

The model options considered to simulate various hydrological processes were NRCS curve number (CN) method for runoff estimation, variable daily CN soil moisture index method (Wang et al., 2009) to estimate daily CN, modified rational equation to calculate peak flow, Hargreaves method to calculate potential evapotranspiration, and modified Universal Soil Loss Equation (USLE) to calculate erosion. A detailed description of the model concepts and mathematical relationships used to simulate these processes is given in Williams et al. (2008b).

The period of simulation run was January 1994 through March 2003 including January 1994 through September 1995 as model warm-up period. Calibration was performed for October 1995 through December 1999 and validation for January 2000 through March 2003. The parameters adjusted during calibration include curve number (reduced by -8% from the baseline values), parm8 (25), parm14 (0.2), parm18 (1.0), parm19 (0.01), parm29 (0.3), parm31 (0.3), parm35 (0.9), parm42 (1.2), parm46 (1.0), parm59 (3), and parm72 (0.4). The values within the parenthesis denote the actual value used for model calibration. See Williams et al. (2008a) for description of these parameters. The model simulated stream flow and water quality values were compared against the corresponding observed values at the WC monitoring station maintained by TIAER. Coefficient of determination (r^2) and Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) were used to evaluate model predicted monthly streamflow, sediment, total nitrogen, and total phosphorus loads with observed values.
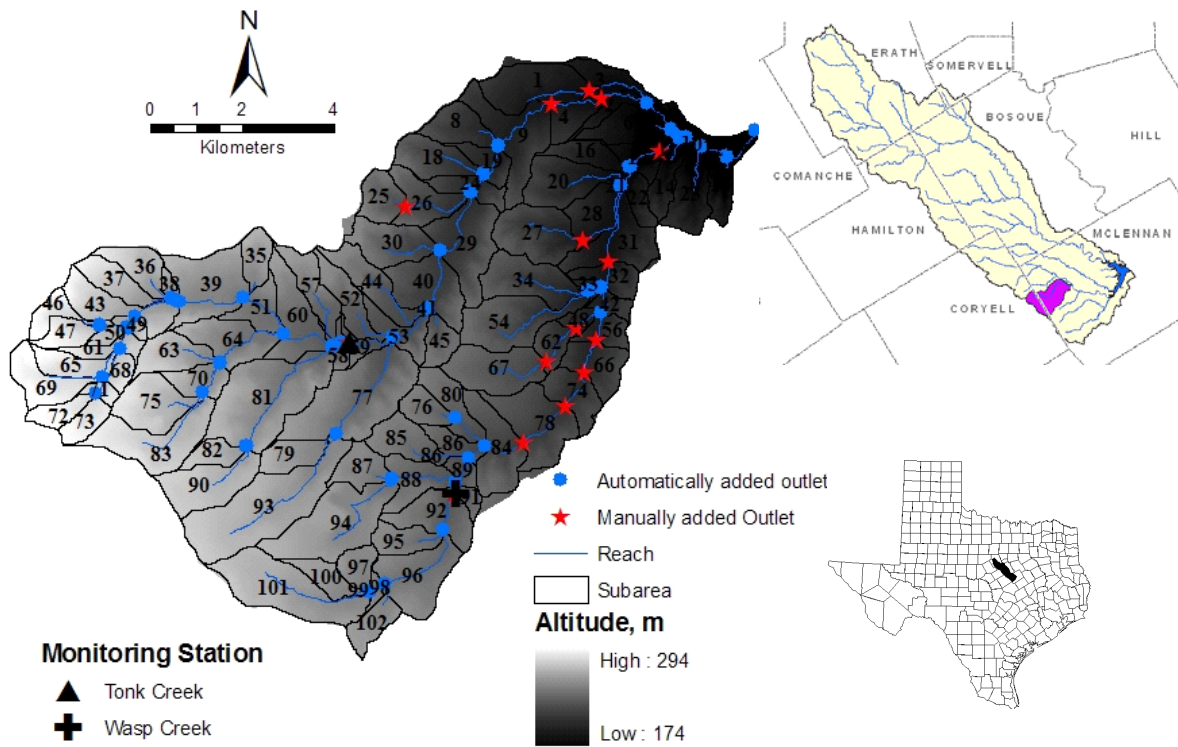
Fig. 3: Subarea delineation, stream network, and automatically and manually added outlets in Tonk Creek and Wasp Creek Watersheds (104 km^2) draining to Middle Bosque River eventually draining to Lake Waco in McLennan County in central Texas

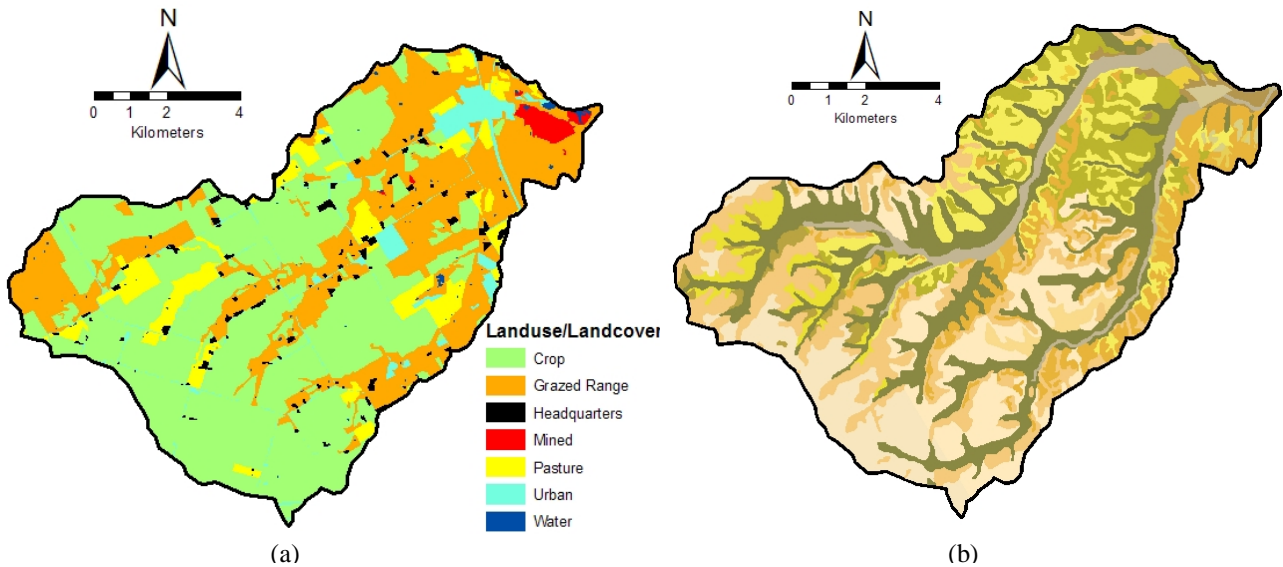(a)   (b)

Fig. 4: Landuse/landcover (a) and SSURGO soils map (b) of the study watershed
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The calibrated model was then run for a longer period (30 years, using 1977 to 2006 climate data) to establish the baseline condition against which the BMP effects were evaluated. The interface was further used to represent three BMPs: contour farming, no-till cropping, and furrow diking. Details of these practices can be found in USDA-NRCS (2007). The BMPs were simulated individually, and all inputs except the parameters used to represent a BMP were held constant.

Contouring was represented by the USLE conservation support practice factor (PEC) in *.SUB file and curve number (CN) in *.OPC file. A PEC value of 1.0 in the baseline condition was altered to 0.6 or 0.5 depending on the average upland slope of the subarea (Schwab et al., 1995; Arabi et al., 2008). The CN was reduced by 3 from the baseline condition (Arabi et al., 2008). No-till was represented in APEX by excluding all tillage operations, replacing row crop planters for corn and drills for winterwheat with no-till planters and no-till drills, and fertilizer was injected to a depth of 75 mm below the soil surface. Furrow diking was simulated by building furrow dikes during planting corn and removing them after harvest. The simulated furrow dikes were spaced 1 m apart and offset at 150 mm in height. These BMPs were simulated for all cropland subareas. There were 52 cropland subareas with a total area of 63.4 km^2 (61% of the total watershed area). For each BMP, the model was run for the same 30-year period as simulated in the baseline scenario. Model output results were then compared between the baseline and BMP scenarios. This comparison provides an assessment of the effectiveness of the BMPs in terms of reducing pollutant loadings over a multi-year period. The effectiveness of BMPs was evaluated in terms of percent reductions in average annual surface runoff, sediment, TN, and TP loadings at the subarea levels and at the watershed outlet. Load reductions at the watershed outlet include cumulative load reductions considering overland transport and routing through the stream network. The percent reduction was calculated as:

$$reduction,\% = \frac{100(baseline - postBMP)}{baseline} \quad (1)$$

where,
baseline = long-term calibrated model run without BMP
postBMP = long-term calibrated model run with BMP

4. RESULTS

Time series of measured and simulated monthly flows at the WC monitoring site matched well during both calibration and validation periods (fig. 5), with the exception of September 1996. The r^2 and NSE statistics at WC monitoring station are summarized in table 2. Although, the model generally performed well in predicting sediment and nutrients during calibration, the model performance during the validation period was poor. This could partly be attributed to the fact that the calibration period contained higher rainfall events compared to validation period. Moreover, the drainage area at the WC station is only about 10 km^2 with an average flow of 0.03 m^3/s over the simulation period. The discrepancy between the measured and predicted values could be due to rainfall variability and the fact that rainfall records from only one rainfall station was used for the entire watershed of 104 km^2, as well as the uncertainty in model input data and measured flow and water quality data. The validation results are generally weaker than those reported by Gassman et al. (2009) for previous APEX studies and point to the need for further investigation to improve the results obtained in this study.

Table 2: Summary statistics of monthly calibration and validation results

	Calibration		Validation	
	r^2	NSE	r^2	NSE
Flow	0.71	0.55	0.66	0.63
Sediment	0.68	0.68	0.17	0.02
Total Nitrogen	0.75	0.57	0.38	0.30
Total Phosphorus	0.65	0.60	0.27	0.16

Percentage reduction in surface runoff, sediment, TN, and TP due to no-till, furrow dike, and contour farming practices at the subarea level is illustrated in figure 6. On an average annual basis, no-till, furrow dikes, and contour farming reduced runoff by 11%, 21%, and 29% respectively. Contour farming was highly effective in reducing all constituents considered compared to no-till and furrow diking. Soils in this watershed are of hydrologic group D, which are mainly clayey with very slow infiltration rates and therefore have high runoff potential. As runoff CN is a very sensitive model parameter in controlling estimated surface runoff, reducing its value by 3 to represent contour farming practice on soils of high runoff potential contributed to higher

effectiveness of the practice. Further, slower infiltration capacity of the soils render no-till and furrow dikes less effective. However, no-till effectively reduced sediment by 40% (fig. 6) and TN by 29%. At the watershed outlet, no-till reduced sediment, TN, and TP by 27%, 7%, and 30%; furrow dikes by 19%, 3%, and 26%; and contour farming by 38%, 4%, and 30%, respectively. Although only the above mentioned BMPs were evaluated in the present study for demonstration purposes, various other BMPs could be simulated and assessed for their effectiveness at different spatial scales (Gassman et al., 2009).
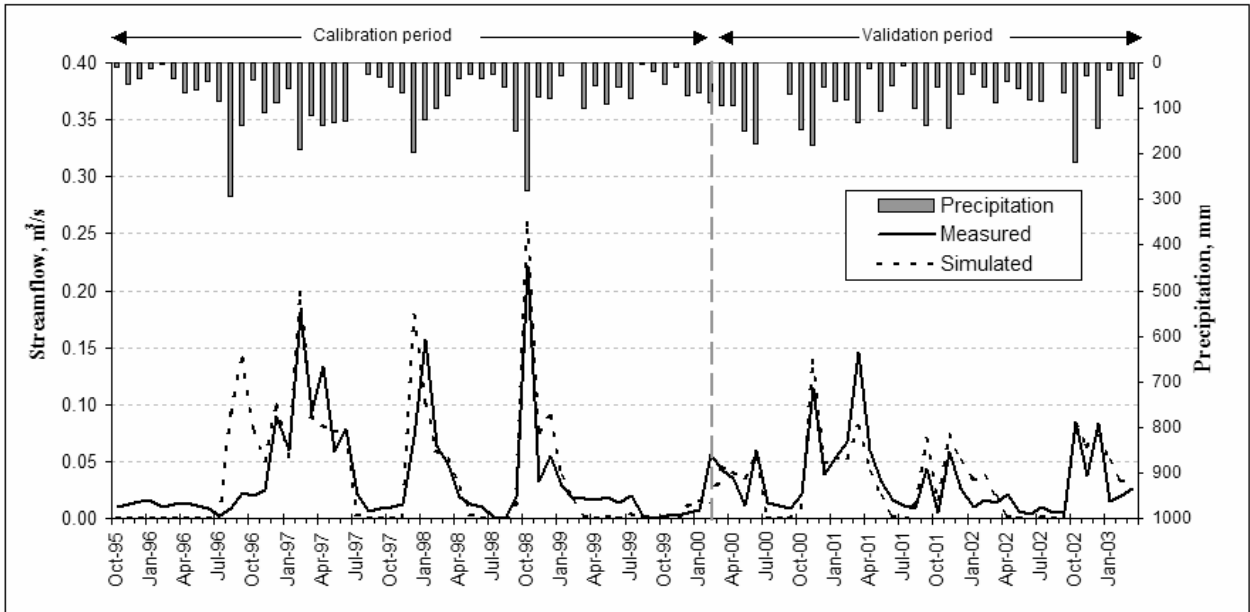

Fig. 5: Measured and simulated flows at Wasp Creek monitoring station calibration and validation periods
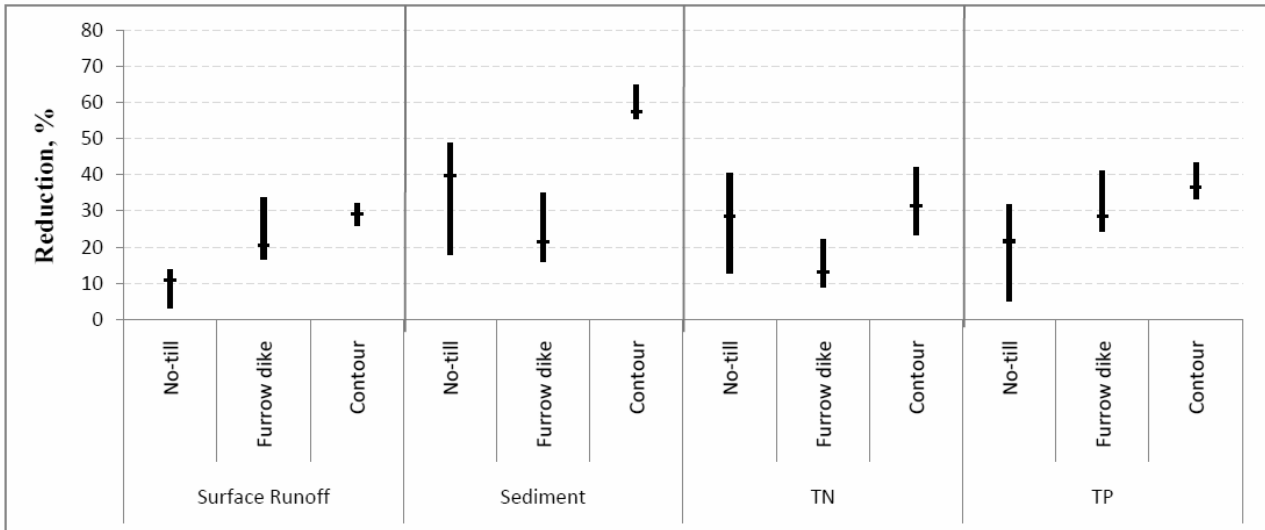

Fig. 6: Percentage reduction in surface runoff, sediment, total nitrogen (TN), and total phosphorus (TP) (mean, minimum, and maximum) due to no-till, furrow dike, and contour farming practices at the subarea level

5. CONCLUSIONS

The ArcAPEX is an ArcGIS-based user interface designed to automate the parameterization of APEX model integrating readily available topographic, hydrographic, land use, and soils spatial datasets. The interface includes an APEX-Parameters database that contains model parameterizations for a wide range of plant growth, tillage, fertilizer, and pesticide applications, as well as U.S. weather and soil data. The ArcAPEX interface and companion database allow users to very efficiently build complex models ranging in scale from the farm to watershed. Users can build and save alternative crop management operation schedules through the interface's editing dialogs, enabling the evaluation of best management practices on water quality and the environment. A key feature of the interface is the functionality it provides to directly integrate APEX simulations with watersheds modeled with SWAT. Using this modeling framework, APEX can be implemented for more detailed simulation of farms or small subwatersheds with complex agronomic systems, while SWAT can be used for larger subwatersheds with more homogeneous and less complex agricultural systems and non-agricultural landscapes, as well as for integrating constituent (runoff, sediment, nutrient, and pesticide) contributions from all subwatersheds and simulating in-stream channel processes. Together the ArcAPEX and ArcSWAT interfaces seamlessly link the APEX and SWAT modeled components.

The ArcAPEX interface was used to setup the APEX model for a 104 km^2 subwatershed of Bosque River Watershed in central Texas. Calibration and validation of the model were performed using data collected for the study watershed; those results indicate the need for further refinement of this APEX application to improve the validation accuracy. The interface was then used to represent contour farming, no-till cropping, and furrow diking BMPs and evaluate their effectiveness in reducing runoff, sediment, and nutrient loads. Other BMPs, climatic, and land use scenarios can be simulated in APEX within the ArcAPEX framework, such as those documented by Gassman et al. (2009) across a range of studies.

Improvement of ArcAPEX to support the efficient evaluation of best management practices will continue. Current plans are focused on the development of pre-built management operations schedules and best management practice scenarios for a wide range of cropping systems. These operations schedules and scenarios would be distributed as part of the APEX Parameters database and available for incorporation into APEX models developed through ArcAPEX. The vision is to streamline the scenario evaluation process to enable less sophisticated users to apply the APEX model in an intelligent way to obtain scientifically accurate and defensible results used to assist in environmental management and decision making.

Finally, the potential exists to apply APEX within ArcAPEX and/or ArcSWAT for simulation of complex agroforestry systems in southeast Asia including intercropping of tree crops and vegetables, such as the systems described by Reyes (2008). Plant competition algorithms based on the approach used in the ALMANAC model (Kiniry et al., 1992) have already been incorporated in APEX, which account for competition between multiple crops, weeds, and/or other vegetation for light, water, and nutrients. However, expanded plant parameter datasets and other improvements are needed before APEX can be applied for agroforestry systems, as discussed in detail by Johnson et al. (2009) in the context of incorporating ALMANAC multi-cropping algorithms into SWAT for simulating agroforestry systems in southeast Asia and other regions.

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