

ARC GIS-SWAT: A GEODATA MODEL AND GIS INTERFACE FOR SWAT¹

*Francisco Olivera, Milver Valenzuela, R. Srinivasan, Janghwoan Choi,
Hiudae Cho, Srikanth Koka, and Ashish Agrawal²*

ABSTRACT: This paper presents ArcGIS-SWAT, a geodata model and geographic information system (GIS) interface for the Soil and Water Assessment Tool (SWAT). The ArcGIS-SWAT data model is a system of geodatabases that store SWAT geographic, numeric, and text input data and results in an organized fashion. Thus, it is proposed that a single and comprehensive geodatabase be used as the repository of a SWAT simulation. The ArcGIS-SWAT interface uses programming objects that conform to the Component Object Model (COM) design standard, which facilitate the use of functionality of other Windows-based applications within ArcGIS-SWAT. In particular, the use of MS Excel and MATLAB functionality for data analysis and visualization of results is demonstrated. Likewise, it is proposed to conduct hydrologic model integration through the sharing of information with a not-model-specific hub data model where information common to different models can be stored and from which it can be retrieved. As an example, it is demonstrated how the Hydrologic Modeling System (HMS) – a computer application for flood analysis – can use information originally developed by ArcGIS-SWAT for SWAT. The application of ArcGIS-SWAT to the Seco Creek watershed in Texas is presented.

(KEY TERMS: watershed management; geographic information systems (GIS); water quality; hydrologic modeling; computational methods; computer interface.)

Olivera, Francisco, Milver Valenzuela, R. Srinivasan, Janghwoan Choi, Hiudae Cho, Srikanth Koka, and Ashish Agrawal, 2006. ArcGIS-SWAT: A Geodata Model and GIS Interface for SWAT. *Journal of the American Water Resources Association (JAWRA)* 42(2):295-309.

INTRODUCTION

This paper presents ArcGIS-SWAT, a geodata model and GIS interface for the Soil and Water Assessment Tool (SWAT) (Neitsch *et al.*, 2002a,b). SWAT is a physically based, continuous time, river basin scale model that quantifies the impact of land management practices on flows, sediment loads, and chemical yields. It models the entire hydrologic cycle, including the evapotranspiration, shallow infiltration, percolation to deep aquifers, and lateral flow processes (Arnold *et al.*, 1998).

Since a significant amount of SWAT's input data are of a spatial character (such as those derived from stream network, drainage divide, land use, and soil type maps), GIS tools for extracting information for SWAT from readily available digital spatial data have been developed. Srinivasan and Arnold (1994), for example, developed an interface in the GRASS platform, which was a front-end preprocessor that wrote SWAT input files. Bian *et al.* (1996), in turn, developed an interface that worked in the ARC/INFO platform (ESRI, Redlands, California) and ran in UNIX systems. Di Luzio *et al.* (1998) likewise developed a comprehensive ArcView 3.x (ESRI, Redlands, California) interface for SWAT that took advantage of its graphical user interface (GUI) and ran in Windows systems. Di Luzio *et al.* (2000, 2002) further developed Di Luzio *et al.*'s (1998) interface by adding to it capabilities for terrain analysis based on digital elevation models (DEM).

¹Paper No. 04087 of the *Journal of the American Water Resources Association (JAWRA)* (Copyright © 2006). **Discussions are open until October 1, 2006.**

²Respectively, (Olivera) Assistant Professor of Civil Engineering, (Valenzuela, Choi, Cho, Koka, Agrawal) Graduate Research Assistants, Texas A&M University, 3136 TAMU, College Station, Texas 77843; (Srinivasan) Associate Professor of Biological and Agricultural Engineering, Texas A&M University, 1500 Research Parkway, Suite 221E, College Station, Texas 77845 (E-Mail/Olivera: folivera@civil.tamu.edu).

ArcGIS-SWAT has been developed for the ArcGIS platform. The ArcGIS-SWAT data model stores SWAT geographic, numeric, and text input data and results. The geodatabase data structure, which is that of a relational database with the capability of storing geographic information in addition to numbers and text, was used for the data model. Therefore, a geodatabase is proposed as the repository of all the spatial and temporal information of a SWAT simulation, as opposed to a series of text files. Likewise, the ArcGIS-SWAT interface uses ArcObjects (Zeiler, 2001), which conform to the Component Object Model (COM) protocol and therefore facilitate the use, within ArcGIS-SWAT, of already available functionalities in other Windows-based applications. In particular, the use of Microsoft Excel and MATLAB for result visualization and statistical analysis is demonstrated. Another feature of ArcGIS-SWAT is its capability to georeference the hydrologic response units (HRUs), which allows a more accurate calculation of the model parameters than what would be obtained if they were averaged over the subbasins.

Integration with other hydrologic models is accomplished through the sharing of geographic and hydrologic data. For this purpose, hydrologic objects (e.g., watershed polygons) and their corresponding parameters (e.g., watershed times of concentration) are exported from the ArcGIS-SWAT geodatabase to a not-model-specific hub geodatabase, from which they can be imported by another interface for use in a different model. By implementing the hub geodatabase concept, model integration consists of interfacing each model to the hub rather than to each of the other models. As an example, it is presented how HMS – a computer application for flood analysis developed by the Hydrologic Engineering Center (HEC) (USACE, 2005) and not related to SWAT – uses information originally developed by the ArcGIS-SWAT interface and stored in the ArcGIS-SWAT data model.

THE GEODATABASE DATA STRUCTURE AND ARCHYDRO

The ArcGIS-SWAT data model is based on the geodatabase data structure. Geodatabases are relational databases that can also store geographic features (MacDonald, 1999). That is, a geodatabase is a collection of tables whose fields can store a geographic shape (i.e., a point, a line, or a polygon), a string, or a number and that are related to each other through key fields. Regardless of the number of tables and relationships in a geodatabase, it is stored in a single file, and its contents can be explored using database management systems (DBMS). Non-GIS DBMS (e.g.,

Microsoft Access), however, cannot access the geographic information in the geodatabases. Geodatabase tables are object classes in which each row represents an object and each column stores an attribute of the object. Feature classes are particular cases of object classes in which each object is additionally attributed with a feature (i.e., a geographic shape). Feature classes collect features of a single type, so that they are either point feature classes, line feature classes, or polygon feature classes. Furthermore, feature classes that share the same spatial extent can be collected in feature datasets. Within feature datasets, geometric networks can be built based on line feature classes, which establish topologic relationships among their elements. Finally, relationship classes can be created to associate objects of different classes through key fields and can be stored as part of the geodatabase.

Maidment (2002) pioneered the use of geodatabase data structures in water resources engineering by developing the ArcHydro data model. ArcHydro is a geospatial and temporal data model that supports hydrologic simulation models but is not a simulation model itself. In ArcHydro, the structure of a hydrologic system is defined around the stream geometric network, in which links and junctions are defined. Drainage areas are related to network junctions, and time series are related to monitoring points in the map, which in turn are related to network junctions. Thus, the stream network and the relationships among the different hydrologic elements and the network junctions constitute the backbone of the ArcHydro representation of a system (Olivera *et al.*, 2002).

The ArcHydro data model was developed with the envisioned purpose of storing in an organized fashion spatial and time series data to support most (if not all) hydrologic models. However, the SWAT data structure does not include all of the elements of ArcHydro and, more importantly, includes a number of elements not considered in it. Among the elements of ArcHydro not included in the SWAT data structure are the channel cross sections and profile lines, the stream geometric network (since the network topology in SWAT is based on attributes), and those that are redundantly stored as hydrographic elements and as drainage elements. The SWAT data structure, on the other hand, includes many land and stream parameters to model the soil water balance, plant growth, irrigation and fertilization practices, and pollutant transport that are not included in ArcHydro. Hence, using ArcHydro as the SWAT data model would have required such a level of customization that it would have left little of its original design, and it was decided to develop a new geodata model specifically for SWAT.

The SWAT data model presented in this paper is a system of geodatabases with object classes, feature classes, and feature datasets from which all input data needed by SWAT can be retrieved and in which all output generated by SWAT can be stored. With respect to the SWAT input and output text files, geodatabases have the advantage that they can store geographic data to describe subbasins, reaches, outlets, reservoirs, and inlets and benefit from existing database technology. (Geodatabases are a particular case of databases.) Database technology would be needed, for example, to query the information to describe the changes of a hydrologic variable over time at a given location or to describe the status of the system at different locations at a given time. Among other capabilities, database technology includes cross-referencing of records in different tables by means of common attributes, speeding up the query of records that match a given criteria and extending that query to cross-referenced records in other tables, updating records in bulk, and performing complex aggregate calculations. Most importantly, database technology has been developed to work with large amounts of information otherwise impossible to handle with text files. In the specific case of SWAT, the amount of information is significant because the geodatabase stores geographic information, hydrologic parameters, and time series of each hydrologic feature of the system.

METHODOLOGY

The ArcGIS-SWAT data model consists of a dynamic geodatabase that stores information of the study area and a static geodatabase that stores non-project-specific information such as lookup tables and databases of default parameter values. The ArcGIS-SWAT interface includes modules for watershed delineation, HRU definition, synthetic weather generation, exporting data from the geodatabases to prepare SWAT input files, importing SWAT results from the output files to the dynamic geodatabase, analysis of propagation of uncertainty, data visualization and statistical analysis, and model integration. The first three modules include spatial analysis using topographic, land use, soil type, and weather data. The other modules connect the SWAT data model to SWAT and support hydrologic analysis and model integration. For clarity purposes, in the following, object classes and feature classes are referred to as *<(Object class name)>* and *[(Feature class name)]* respectively, in which italic font in parenthesis indicates the text has to be replaced with the corresponding name.

Watershed Delineation

The watershed delineation module identifies streams and drainage divides from DEMs using the eight-direction pour point algorithm (Jensen and Domingue, 1988). It follows the procedure presented by Olivera (2001) for DEM-based stream and watershed delineation but adapted to the SWAT data structure. Reaches are defined wherever drainage areas are greater than a user defined threshold value; subbasin outlets are automatically defined on each of the reaches right upstream of the confluences and at user defined points; and subbasins are defined as the incremental drainage area of each outlet. Thus, as required by SWAT, one-to-one relationships are established between reaches, outlets, and subbasins (i.e., no subbasin has more than one reach, and no reach lies in more than one subbasin). Additionally, other elements can be interactively defined on the map such as inlet points to the system (which allow one to exclude upstream drainage areas and isolate the portion of the watershed to be modeled), reservoirs (which are also subbasin outlets), and point source discharges. Likewise, the subbasin longest path is used by SWAT as a surrogate of the residence time in the subbasin. Figure 1 shows the hydrologic elements of the Seco Creek watershed in Texas. The watershed delineation module creates six feature classes in a feature dataset: [Watershed], [SubBasin], [Reach], [LongestPath], [Outlet], and [MonitoringPoint] (see Figure 2). [PolyHRU] is created by the HRU Definition module that will be discussed below. [Watershed] stores the polygon that represents the entire study area; [SubBasin] stores the subbasin polygons; [Reach] stores the segments of the channel network; [LongestPath] stores the longest flow path within each subbasin; [Outlet] stores the subbasin outlet points; and [MonitoringPoint] stores inlet points to the watershed, reservoir points, point source discharges, and a copy of the subbasin outlet points, among others points that are appended by other interface modules. In Figure 1, note that white circles are used to represent those monitoring points that coincide with outlets, while black circles to represent those that do not coincide with outlets, such as rain gauges. [MonitoringPoint] is also related to object class *<TimeSeries>*, which stores all observed and calculated hydrologic time series for all the features of the system. By storing a copy of the outlet points in [MonitoringPoint], time series of any feature of the system can be related to its corresponding location in the map.

Additionally, all features have a unique identification number stored in the field HYDROID, which is used to establish relationships between the different

classes. These relationships are represented by arrows in Figure 2. For example, the relationship between [Outlet] and [Subbasin] is established by storing the HYDROID value of the subbasin outlet point in the OUTLET field of the subbasin polygon. Note that in <TimeSeries>, the field FEATUREID stores the HYDROID value of the corresponding feature. The feature classes also have fields related to their geometry (i.e., AREA for polygons and LENGTH for lines), and [Reach], in particular, has FNODE and TNODE that store the upstream and downstream points of each reach segment, which are used to establish the stream network topology. Other attributes such as elevation, slope, and location (i.e., longitude and latitude) are also included.

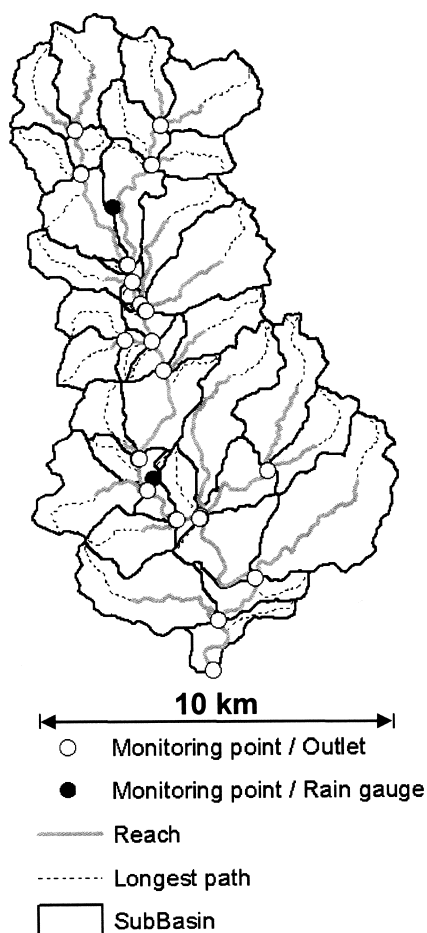


Figure 1. Feature Classes Generated by the Watershed Delineator.

HRU Definition

The HRU definition module identifies unique combinations of soil and land use within each subbasin.

Soil and land use data can be provided by the user; however, tools have been included for easy use of soil data from the State Soil Geographic (STATSGO) database (USDA-NRCS, 1995) and lookup tables for converting different land use classifications to the SWAT classification.

The STATSGO database defines map units, each of which consists of one or more polygonal areas of the same soil type. This database, whose format is different from the one defined in USDA-NRCS (1995), includes one feature class of map-unit polygons per state, called [(State Name)], and one object class per map unit, called <(Map unit)>. Texas, for example, has 633 map units represented by 4,031 polygons, and consequently if the study area were in Texas, a feature class [Texas] with 4,031 map unit polygons and 633 map unit object classes <TX001>, <TX002>, ... <TX633> would be included in the static geodatabase. In these object classes, the records refer to the different soil components of the map unit, and the fields store soil properties of the component and of up to 10 layers of the component, as well as the percentage of the component in the map unit. To speed up the database operations, only the feature and object classes of the states needed are added to the static geodatabase from a source set of 48 geodatabases of STATSGO data (i.e., one geodatabase per state of the conterminous United States). The reader is referred to USDA-NRCS (1995) for detailed STATSGO documentation on soil map units, components, and layers. Similarly, land use data consist of polygonal areas within which a single land use is found. Land uses can be classified with any land use classification system but should be converted to the SWAT classification system for implementation with SWAT. Thus, a lookup table, that the user can modify if needed, has been included to define the equivalence of the Anderson *et al.* (1976), National Land Cover Dataset (NLCD) (USGS, 2004a), and SWAT land use classification systems.

Regardless of the sources of the input data, one soil type grid and one land use grid are created. After identifying the grid cells that have the same soil type and land use within each subbasin, they are grouped together and converted into polygons that represent HRUs. Thus, in the resulting polygon feature class, called [PolyHRU], the features have a unique combination of input data. As can be seen in Figure 2, [PolyHRU] polygons have a unique identification number stored in field HYDROID, which is used to establish relationships with [SubBasin] and <TimeSeries>.

Additionally, ArcGIS-SWAT calculates runoff curve numbers (USDA-SCS, 1972) and terrain slopes per HRU. Runoff curve numbers are calculated based on

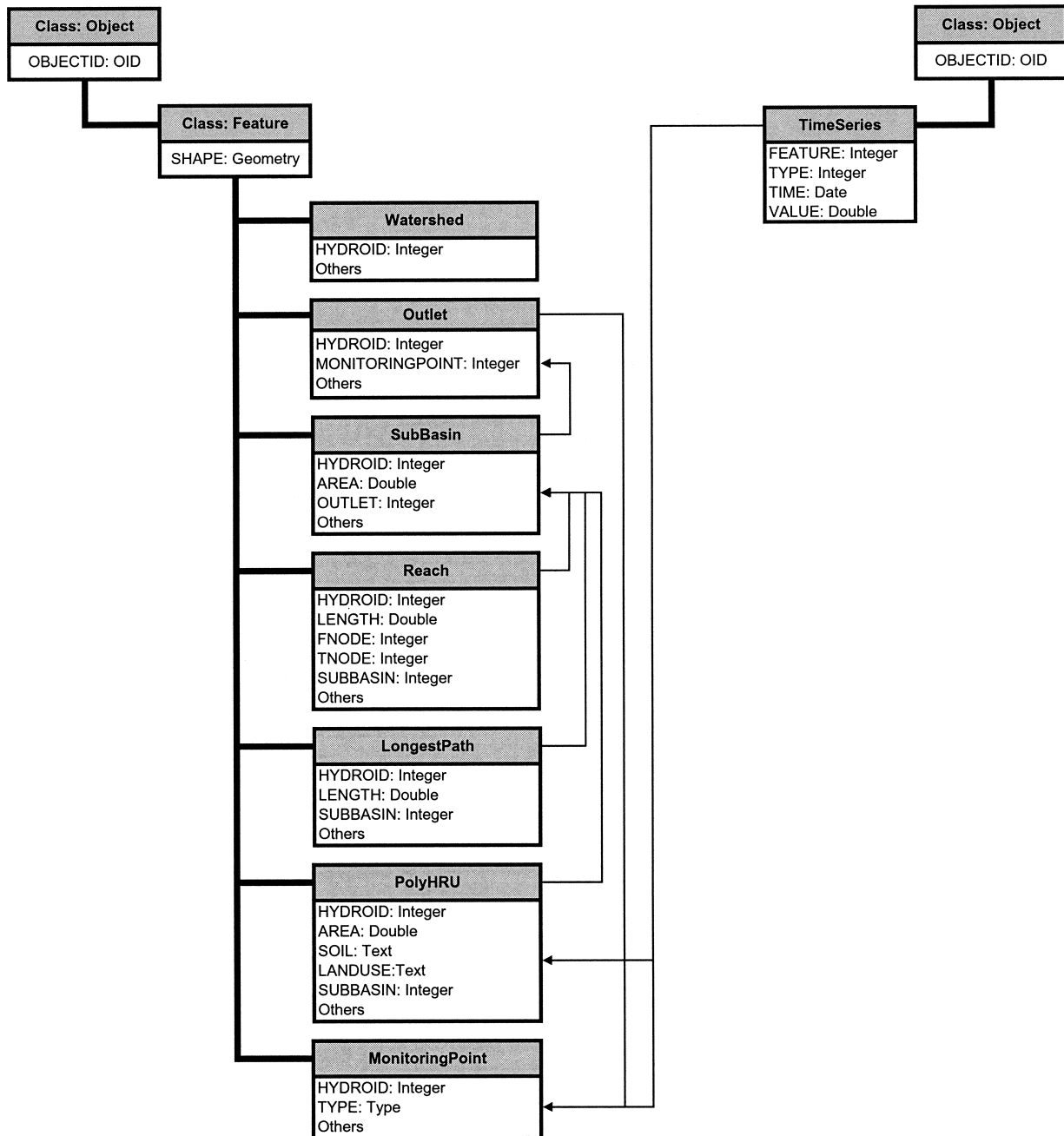


Figure 2. Attributes of and Relationships Among the Feature Classes and the Time Series Object Class. Rectangular boxes represent feature and object classes. Text on gray background indicates the class name, and text on white background indicates the class attributes. Arrows indicate relationships.

the hydrologic soil group (i.e., A, B, C, or D) of the STATSGO map unit and on the land use in the HRU. A user defined lookup table provides information of curve number values for each combination of hydrologic soil group and land use code. Terrain slopes are calculated as the average slope in the HRU polygon.

Weather Generation

SWAT has the capability of generating synthetic time series of precipitation, temperature, solar radiation, wind speed, and relative humidity for each sub-basin based on station weather statistics. The weather stations and statistics can be provided by the user, but ArcGIS-SWAT includes a point feature class

of weather stations in the static geodatabase, called [USWeather]. [USWeather] includes the location as well as multiannual statistics of temperature, precipitation, solar radiation, and wind speed for each of the 12 months of the year for 1,041 National Climatic Data Center (NCDC) stations (USEPA, 2004). The ArcGIS-SWAT weather generation module assigns one station in [USWeather] to each subbasin in [Sub-Basin] based on proximity to its centroid and stores the matches in object class <SubWGN> and the weather statistics of the assigned stations in object class <WGN>.

Alternatively, observed weather time series at user-provided stations can be used. As in the previous case, the weather generation module assigns a station to each subbasin based on proximity to its centroid, but now it stores the matches in object classes <SubPcp>, <SubTmp>, <SubSlr>, <SubWnd>, and <SubHmd> and the time series in object classes <Pcp>, <Tmp>, <Slr>, <Wnd>, and <Hmd> for precipitation, temperature, solar radiation, wind speed, and relative humidity, respectively. Finally, the weather time series are redundantly stored in <TimeSeries> (where all input and output temporal information is consolidated), and all matched weather stations are appended to [MonitoringPoints] and related to <TimeSeries>.

Preparing SWAT Input Files

After the data are developed and stored in the dynamic geodatabase, the input files can be prepared. The preparation of the input files consists of automatically retrieving information from the dynamic and static geodatabases, entering information on-screen, and formatting it for SWAT use.

The SWAT input files can be subdivided into five groups: watershed files, subbasin files, HRU files, reservoir files, and point source files. Detailed descriptions of the SWAT input files can be found in Neitsch *et al.* (2002b). For each group of input files, Tables 1 to 5 contain the file name in the first column; a short description of it in the second column; the source of the data used to create the file in the third, fourth, and fifth columns; and the name of the object class or classes generated when creating it in the last column. The asterisk in parenthesis next to the file name indicates that its use is optional. Object classes under the header Input/Static are not project-specific and are default SWAT values stored in the static geodatabase. Object and feature classes under the header Input/Dynamic are project specific. Note that all object and feature classes listed under Input/Dynamic are developed by the watershed delineation, HRU definition, or synthetic weather generation modules and

stored in the dynamic geodatabase. The term “On-screen” under the header “Input/Other” refers to input entered by the modeler interactively; and “Time series” under the same header refers to a pointer to a time series file. The object classes under the header “Output/Dynamic” are created to organize the input entered interactively by the user. It should be noted that user input is unavoidable in an application that assesses the effect of human actions and land management practices on water quantity and quality.

In the process of preparing the input files, soil type and land use data are used to populate the HRU files. Soils information of the predominant STATSGO component in the HRU is transferred to the HRU soil files (*HRU name*).sol. Likewise, land use information is used to select, from a database of default values, HRU management parameters such as the support practice factor of the modified universal soil loss equation (Williams, 1995) or the percentage of the area where specific land management practices apply, such as planting, irrigating, fertilizing, harvesting, or street sweeping, and transfer them to the HRU management files (*HRU name*).mgt.

ArcGIS-SWAT also allows the user to modify the dynamic and static geodatabases and, after changes are made, create a new set of input files that reflect these changes. Thus, the information in the geodatabases is always updated and consistent with the input files.

Processing SWAT Output Files

After running SWAT, five output files in text format are created: *basins.sbs*, *basins.bsb*, *basins.rch*, *basins.wtr*, and *basins.rsv*. As indicated in Table 6, each of these files contains summary information of a specific type of hydrologic element, which is stored as an object class in the dynamic geodatabase. Additionally, time series data included in the five output files are also stored in <TimeSeries>, which has four fields: FEATURE, TYPE, TIME, and VALUE. These fields store where each time series record was observed/calculated (e.g., HRU, reach), what was observed/calculated (e.g., flow, sediment load), when it was observed/calculated (e.g., day and time), and how much was observed/calculated (e.g., value). Thus, all of SWAT's output is stored in the dynamic geodatabase in <sbs>, <bsb>, <rch>, <wtr> and <rsv> and in <TimeSeries>.

TABLE 1. Watershed Input Files.

	Watershed Files	Input Static	Input Dynamic	Input Other	Output Dynamic
file.cio	Control input/output file: Contains names of input files for all watershed and subbasin level variables.		[Watershed], <SubWGn>, <SubPcp> (*), <SubTmp> (*), <SubSIR> (*), <SubWnd> (*), <SubHmd> (*)	On screen	
basins.fig	Watershed configuration file: Defines the routing network in the watershed.		[Reach], [MonitoringPoint]		
basins.cod	Input control code file: Specifies the length of the simulation, the printing frequency and selected options for various processes.			On screen	<cod>
basins.bsn	Basin input file: Stores watershed parameters		[Watershed]	On screen	<bsn>
pcp.pcp (*)	Precipitation file: Stores daily measured precipitation for a number of gauges.		<Pcp> (*)		
tmp.tmp (*)	Temperature file: Stores daily measured maximum and minimum temperature for a number of gauges.		<Tmp> (*)		
slr.slr (*)	Solar radiation file: Stores daily solar radiation for a number of gauges.		<SIR> (*)		
wnd.wnd (*)	Wind file: Stores daily average wind speed for a number of gauges.		<Wnd> (*)		
hmd.hmd (*)	Humidity file: Stores daily relative humidity for a number of gauges.		<Hmd> (*)		
pet.pet (*)	Potential evapotranspiration file: Stores daily potential evapotranspiration for the watershed.			Time series (*)	
crop.dat	Land cover and plant growth file: Contains plant growth parameters for all land covers in the watershed.	<Crop>			
fert.dat	Fertilizer file: Contains information on the nutrient content for all fertilizers and manures in the watershed.	<Fert>			
pest.dat	Pesticide file: Contains information on mobility and degradation for all pesticides in the watershed.	<Pest>			
till.dat	Tillage file: Contains information on the amount and depth of mixing caused by tillage operations in the watershed.	<Till>			
urban.dat	Urban file: Contains information on the build-up/wash-off of solids in urban areas in the watershed.	<Urban>			
basins.wwq (*)	Water quality file: Contains QUAL2E parameters to model transformations in the main channels.			On screen	

(*) Optional file.

Propagation of Uncertainty

Uncertainty in a model's output can be caused, among other sources, by uncertainty in the value of the model parameters. SWAT is a model that includes a large number of parameters. Each of the param-

eters is known with a different level of accuracy and takes part in a different hydrologic process. Assessing this uncertainty in an analytical way is not always possible. The authors have developed a method based on Monte Carlo simulations that generates frequency distributions of the SWAT output variables (as opposed to a single value).

TABLE 2. Subbasin Input Files.

	Subbasin Files	Input Static	Input Dynamic	Input Other	Output Dynamic
(Subbasin name).sub	Subbasin file: Stores subbasin parameters	–	[SubBasin], [LongestPath], [PolyHRU]		<sub>
(Subbasin name).pnd (*)	Pond/wetland file: Contains information for impoundments within the subbasin.	–	[SubBasin]	On screen	<Pnd>
(Subbasin name).wus (*)	Water use file: Contains information for consumptive water use in the subbasin.	–	[SubBasin]	On screen	<WUs>
(Subbasin name).rte	Main channel file: Contains parameters governing water and sediment movement in the main channel of the subbasin.	–	[SubBasin]	On screen	<RTE>
(Subbasin name).swq (*)	Stream water quality file: Contains parameters to model pesticide and QUAL2E nutrient transformations in the main channel of the subbasin.	–	[SubBasin]	On screen	<SQW>
(Subbasin name).wgn	Weather generator file: Contains statistical data needed to generate synthetic daily climatic data for the subbasins.	–	[SubBasin] <WGn> [MonitoringPoint]		

(*) Optional file.

TABLE 3. HRU Input Files.

	HRU Files	Input Static	Input Dynamic	Input Other	Output Dynamic
(HRU name).hru	HRU file: HRU parameters	–	[PolyHRU]	On screen	<HRU>
(HRU name).sol	Soil file: Contains information about the physical properties of the soils in the HRU.	–	[PolyHRU], <(Map Unit)>	On screen	<Sol>
(HRU name).chm (*)	Soil chemical file: Contains information about the initial nutrient and pesticide levels of the soil in the HRU.	–	[PolyHRU]	On screen	<Chm>
(HRU name).gw	Ground water file: Contains information about the shallow and deep aquifer in the subbasin.	–	[PolyHRU]	On screen	<GW>
(HRU name).mgt	Land management file: Contains management scenarios and specifies the land cover in the HRU.	<Irr> <MgtType>, <MgtDate>, <MgtSCS>	[PolyHRU]	On screen	<Mgt1>, <Mgt2>

(*) Optional file.

TABLE 4. Reservoir Input Files.

	Reservoir Files	Input Static	Input Dynamic	Input Other	Output Dynamic
basins.res (*)	Reservoir file: Contains parameters to model the movement of water and sediment through a reservoir.	–	[SubBasin]	On screen	<Res>
basins.lwq (*)	Lake water quality file: Contains parameters to model the movement of nutrients and pesticides through a reservoir.	–	[SubBasin]	On screen	<Res>

(*) Optional file.

TABLE 5. Point Source Input Files.

Point Source Files		Input Static	Input Dynamic	Input Other	Output Dynamic
recday.dat (*), recmon.dat (*), recyear.dat (*), reccnst.dat (*)	Point source discharge files: Contain information about loadings to the channel network from point sources.		[MonitoringPoint]	On-screen	

(*) Optional file.

TABLE 6. Output Files.

Output Files	Summary Information of	Object Class in Dynamic Database
basins.sbs	HRUs	<sbs>
basins.bsb	Subbasins	<bsb>
basins.rch	Reaches	<rch>
basins.wtr	Pond, wetland and depressional/ impoundment area in the HRUs	<wtr>
basins.rsv	Reservoirs	<rsv>

The method assumes the model parameters as random variables for which probability density functions (pdfs) are defined. Although all parameters can be assumed as random variables, the pdf definition is implemented only for a user-selected set of input parameters out of the 27 that Neitsch *et al.* (2002b) identify as those that most affect the model output. The pdfs are defined based on maximum, minimum, and best-estimate values documented in the literature for the selected parameters (Neitsch *et al.*, 2002b). Even though any probability distribution that captures these recommended values can be used, only normal and triangular distributions have been implemented. Once the pdfs are defined, values of the selected parameters are sampled randomly from their corresponding pdfs and used to prepare SWAT input files. These SWAT input files are then used to run a SWAT simulation. After repeating the sampling, input file preparation, and SWAT simulation processes a number of times, the frequency of the values obtained for a given variable is plotted to give the variable distribution. The more simulations, the more representative the resulting distribution is of the uncertainty of the given variable. The effects of the pdf definition and of the number of simulations on the resulting variable distributions are matters currently being studied by the authors and are beyond the scope of this paper.

COM-Based Application Integration

The use of programming objects that conform to the Component Object Model (COM) design standard allows the use of functionality of different Windows-based applications within ArcGIS. In this paper, the use of MS Excel and MATLAB for statistical analysis and two-dimensional and three-dimensional visualization of SWAT results is presented.

For visualizing time series with MS Excel, <TimeSeries> is queried so that only information of a given variable (e.g., flow, sediment load) and at a given location (e.g., reach, subbasin, HRU) is plotted. Similarly, for visualizing and analyzing the dependency of one variable with respect to another, <TimeSeries> is queried so that only information of the two given variables at a given location is used. After this selection is made, the table is further processed so that the records that correspond to the same time are matched, plotted, and analyzed. For visualizing simultaneously how a variable changes over space and time with MATLAB, <TimeSeries> is queried for information of the given variable along a sequence of reaches. This information can then be plotted against the distance along the reaches and time, as will be seen in the application case presented below.

It is important to stress that these tools for results visualization and statistical analysis are entirely based on capabilities already existing in MS Excel and MATLAB have been called and not developed. This calling of existing capabilities can be easily extended to other COM-compliant applications.

Hydrologic Model Integration

It is envisioned that GIS interfaces to other hydrologic models will also require the design of model specific geodatabases, analogous to the one presented in this paper for SWAT. Likewise, it is proposed here to conduct model integration through a nonmodel specific hub geodatabase to which data are transferred from the model geodatabases, and vice versa. Thus, protocols are to be developed to transfer data between each

model geodatabase and the hub geodatabase, independently of other models. According to this approach, the number of required protocols would increase linearly with the number of models, because one protocol would be needed per model. On the contrary, if no hub geodatabase were used and data were transferred between each match of two model geodatabases, the number of protocols would be equal to the combination of the number of models taken two at a time, which is equal to $\frac{n(n-1)}{2}$ where n is the number of models. The hub geodatabase can be as simple or complex as needed, depending on the models that will be integrated and on the data that will be shared. The hub-geodatabase concept stems from Olivera et al. (2003), in which ArcHydro (Maidment, 2002) was proposed as the hub geodatabase. However, the point conveyed here is that any geodatabase that can store the hydrologic elements common to the models that are being integrated (including ArcHydro) can be used as the hub geodatabase.

The hub geodatabase presented here addresses the hydrologic elements and their topologic relationships and is suitable for integrating models that share the same watershed structure and stream network. It includes five feature classes: [Stream], [ExitPoint], [DrainageArea], [Lake], and [Station]. [Stream] stores the segments of the channel network; [ExitPoint] stores the points on the channel network from which drainage areas are delineated; [DrainageArea] stores the incremental drainage area of each point in [ExitPoint]; [Lake] stores outlet points of water bodies on the channel network from which drainage areas are delineated; and [Station] stores the points where precipitation, flow gauging, and/or water quality monitoring stations are located. All features in the five feature classes have a unique identification number stored in a field called ID. Additionally, the features are cross referenced through the ID field so that drainage areas are related to their exit points, streams are related to the drainage area where they are located, and lakes are related to the exit point that represents them. Likewise, [Stream] includes fields FNODE and TNODE that store identification codes of the upstream and downstream nodes of the segments, which are used for establishing the network topology.

Once the hub geodatabase is populated – for example, by copying features and attributes from the SWAT geodatabases – its contents can be used by another model interface. As an application example, the use of data developed by ArcGIS-SWAT and stored in the hub geodatabase for creating an HEC-HMS model is demonstrated. The tool to retrieve the data from the hub geodatabase and format it for HEC-HMS is a separate application and is not part of

ArcGIS-SWAT. It has been presented here only to stress the advantages of the use of the geodatabase and hub geodatabase approach.

APPLICATION

ArcGIS-SWAT was applied to the Upper Seco Creek in Central Texas for which studies have been conducted in the past (Srinivasan and Arnold, 1994; Baird *et al.*, 1996; Brown and Raines, 2002) and data are available. The Upper Seco Creek is part of the Nueces basin (Figure 3). The study area was the catchment of U.S. Geological Survey (USGS) gauging station 08201500 (Seco Creek at Miller Ranch near Utopia), which has a drainage area of 116 km².

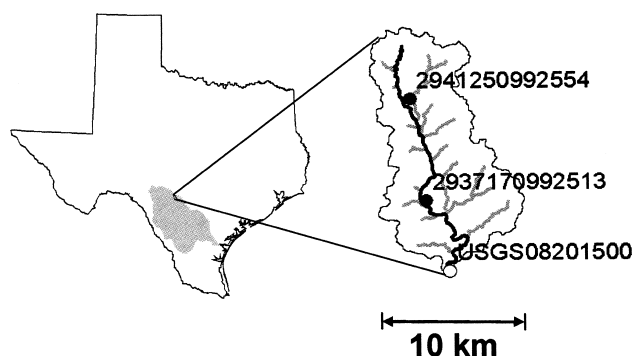


Figure 3. The Seco Creek Watershed is Part of the Nueces River Basin (in gray) in Texas. Points 2941250992554 and 2937170992513 are the rain gauges located at 99°25'54"W, 29°41'25"N and 99°25'13"W, 29°37'17"N; and point USGS08201500 is the flow gauging station located at 99°24'10"W, 29°34'23"N. The stream highlighted in black is the longest flow path in the watershed.

Daily precipitation data were obtained from two stations set as part of the Seco Creek Water Quality Demonstration Project (Brown *et al.*, 1998; Brown and Raines, 2002) (Figure 3). Likewise, daily flow data were obtained for USGS flow gauging station 08201500 (USGS, 2006) (Figure 3). Temperature, solar radiation, wind, and humidity data were generated from the weather statistics stored in [USWeather]. Topographic data in DEM format, with a horizontal resolution of 10 m, were obtained from USGS (2004b). Streams were delineated for drainage areas greater than 2 km² (i.e., 20,000 DEM cells), and a total of 39 stream-subbasin-outlet sets were identified (Figure 1). Land use data in grid format, with a horizontal resolution of 30 m, were taken from NLCD

(USGS, 2004a) (Figure 4a). Soil data were retrieved from the STATSGO database (USDA-NRCS, 1995) included in the static geodatabase. The STATSGO map units in the watershed were TX155 and TX525, which covered 81 percent and 19 percent of its area, respectively (Figure 4b). In both map units, the hydrologic soil group of the dominant soil component was D. A curve number grid, with the same resolution as the DEM, was generated based on the land use and soils data. Unique combinations of subbasins, land use, and soil type led to a total of 323 HRUs in the watershed (Figure 5).

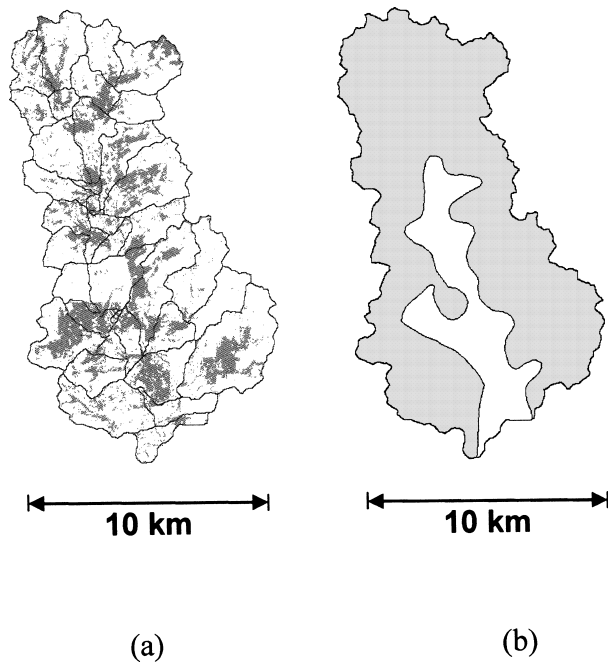


Figure 4. Seco Creek Watershed: (a) Land Use/cover According to NLCD: Forest (white), Urban (black), and Agriculture, Pasture and Others (gray); (b) Soils According to the STATSGO Database: TX155 (gray) and TX525 (white).

SWAT input files were prepared based on the hydrologic features and parameters developed and stored in the dynamic geodatabase. The model configuration considered: curve number method for runoff depth calculation; daily time step (which follows from the use of the curve number method); Priestley-Taylor method for potential evapotranspiration calculation; and Muskingum method for stream routing. The reader is referred to the SWAT theoretical documentation (Neitsch *et al.*, 2002a) for further discussion on these options.

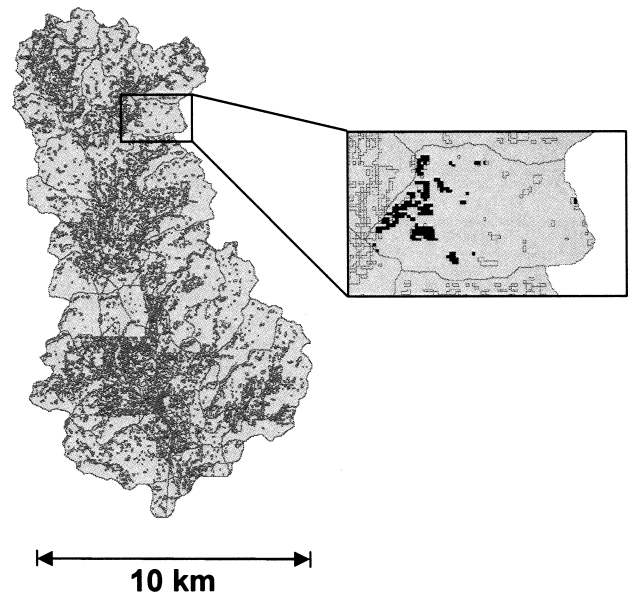


Figure 5. Hydrologic Response Units of the Seco Creek Watershed. Note that an HRU can be a complex polygon, that is, an object consisting of a series of disconnected polygons, like those shown in black in the insert.

The simulation period ran from January 1991 to June 1994. January 1991 to December 1992 was used for calibrating the model, and January 1993 to June 1994 was used for validating it. Given that SWAT requires an initial stabilization period, the model was run for three years before the actual simulation period started. The stabilization period is necessary because during the first years of simulation, the model output is affected by the estimated (and not calculated) initial conditions, such as soil water content and surface residue. Although there is no rule to determine the duration of the stabilization period, three years was used in accordance to Santhi *et al.*'s (2001) work in the North Bosque River watershed in Texas. The model was calibrated for daily flows following the steps recommended by Neitsch *et al.* (2002b). Observed and simulated monthly flows are presented in Figure 6. After running the model, all input data and simulation results, including geographic information, hydrologic parameters, and time series, were stored in the dynamic geodatabase. The goodness of fit of the hydrographs was quantified with the deviation of runoff volumes D_v (Martinec and Rango, 1989) and the Nash-Sutcliffe efficiency coefficient ENS (Nash and Sutcliffe, 1970). Note that a perfect model produces a value of D_v of zero, and of ENS of one. The reader is referred to the American Society of Civil Engineers (1993) for a detailed discussion on criteria for evaluation of watershed models.

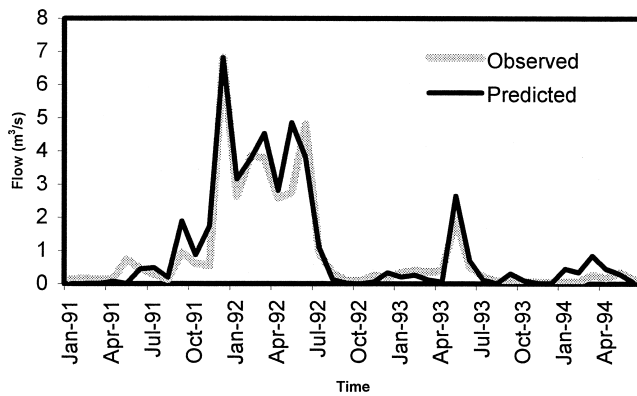


Figure 6. Observed and Simulated Monthly Flows at USGS Flow Gauging Station 08201500 (USGS, 2006).

For the calibration period, it was found that D_v was equal to 0.01 for 1991 and 0.11 for 1992; for the validation period, D_v was equal to -0.04 for 1993. Based on daily flows, it was found that ENS was equal to 0.67 for the calibration period and 0.33 for the validation period. Similarly, based on monthly flows, it was found that ENS was equal to 0.88 and 0.90 for the calibration and validation periods, respectively. Comparable values of D_v and ENS for daily and monthly flows simulated with SWAT are found in the literature (Hanratty and Stefan, 1998; King *et al.*, 1999; Rosenthal and Hoffman 1999; Spruill *et al.*, 2000; Eckhardt and Arnold, 2001; Weber *et al.*, 2001; Fontaine *et al.*, 2002; Neitsch *et al.*, 2002c; Eckhardt *et al.*, 2003; Tripathi *et al.*, 2003). The value of ENS of 0.33 for the validation period with daily flows, though, is lower than what was found in the literature. Possible causes of this discrepancy include the fact that the model was calibrated for a period in which flows were significantly higher than those in the validation period and that the values of some of the weather variables were generated and not measured. Likewise, undistinguishable simulated flows were observed when the terrain parameters were calculated per HRU or averaged per subbasin. It is likely that this is caused by the fact that the analysis time step is much larger than the subbasins' time of concentration. It would be expected that the effect of estimating the hydrologic parameters per HRU would make a difference in simulations with longer times of concentration and/or shorter time steps.

Additionally, the lack of observed constituent load time series did not allow for proper calibration of the model for water quality. Still, model parameters were estimated using Baird *et al.*'s (1996) median sediment concentration of 245 mg/l, which was calculated from 81 discrete samples collected from 1970 to 1995 at station 08201500. Two of these calculated parameters

were α and β in the channel sediment transport equation (Neitsch *et al.*, 2002b)

$$c = \alpha v_{\text{peak}}^{\beta} \quad (1)$$

where c (kg/l) is the maximum concentration of sediment that can be transported by the flow and v (m/s) is the peak channel velocity. It was found that $\alpha = 0.001$ and $\beta = 1.5$. Since the calculation of these parameters considered only Bairds *et al.*'s (1996) estimated median concentration, to account for the uncertainty in the sediment loads caused by the uncertainty in these two parameters, 1,000 SWAT simulations were run for different combinations of values of α and β . The values of α were drawn randomly from a triangular pdf of $\log \alpha$, in which the minimum and maximum values of α were 0.0001 and 0.01, as recommended by Neitsch *et al.* (2002b), and the mode 0.001 (i.e., the value of α obtained previously). Similarly, the value of β was drawn randomly from a triangular pdf, in which the minimum and maximum values were 1 and 2, as recommended by Neitsch *et al.* (2002b), and the mode 1.5 (i.e., the value of β obtained previously). The resulting cumulative frequency distribution of the 3.5-year median sediment concentration at Station 08201500 is shown in Figure 7. From the figure, it can be concluded, for example, that there is a 33 percent chance of obtaining a median concentration greater than 400 mg/l, or a 10 percent chance of obtaining a median concentration greater than 900 mg/l. The minimum number of simulations necessary to realistically capture the distribution of a variable is currently a matter of research by the authors. The number of 1,000 was chosen because it was observed that the mean and standard deviation of the distribution were not affected by additional simulations.

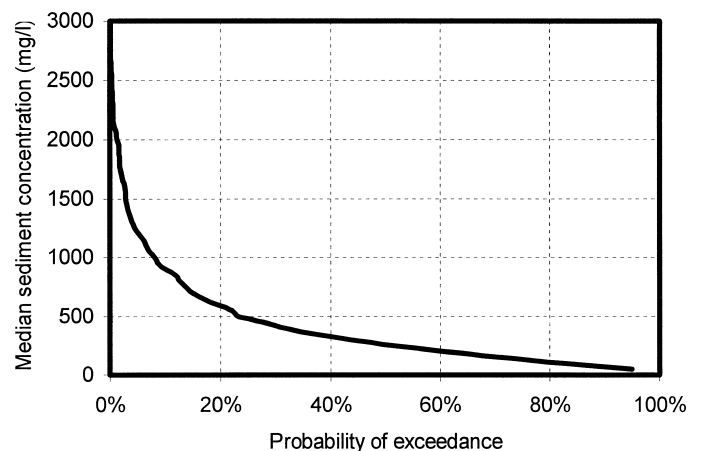


Figure 7. Probability That the Median Sediment Concentration Will Exceed a Given Value.

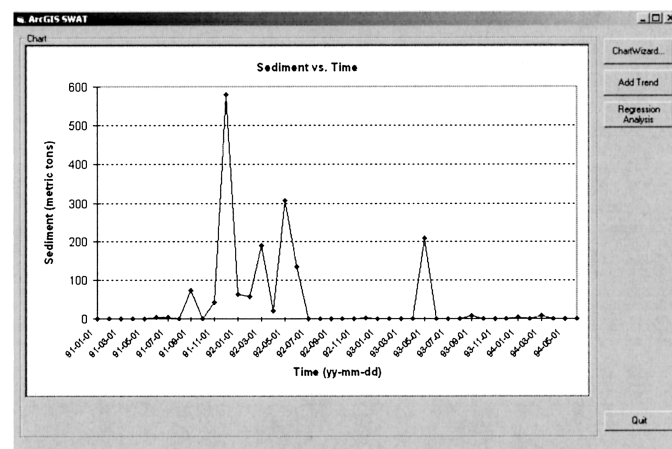
Likewise, the tools for visualization and statistical analysis of the SWAT output called MS Excel COM objects and used their functionality within ArcGIS for plotting the time series of monthly sediment load (Figure 8a) and monthly sediment load as a function of the monthly flow (Figure 8b) and performing statistical analysis (i.e., trend line). Correlation and regression analysis, as well as analysis of variance (ANOVA) can also be performed by MS Excel but are not discussed here. In these plots, it was observed that the sediment load was concentrated in a few number of months and that it was correlated to the monthly flow with an r^2 of 0.92. Similarly, the tools called MATLAB COM objects and used their functionality for developing a three-dimensional plot of the flow profile of the longest flow path in the watershed (Figure 8c) (the longest flow path has been highlighted in black in Figure 3). This three-dimensional plot allows one to observe the flow at a given point over time and the flow at a given time over the entire stream. Variables other than flow and sediment load can also be plotted and analyzed.

Finally, the streams and watersheds delineated by ArcGIS-SWAT and stored in the dynamic geodatabase were copied to the hub geodatabase, from which another application (unrelated to ArcGIS-SWAT) retrieved them and created a topologically correct schematic of the watershed for hydrologic analysis with HEC-HMS (Figure 9). Thus, it is demonstrated that a hub geodatabase can be used to share geographic data between different applications and that the use of data developed by ArcGIS-SWAT is not limited to SWAT.

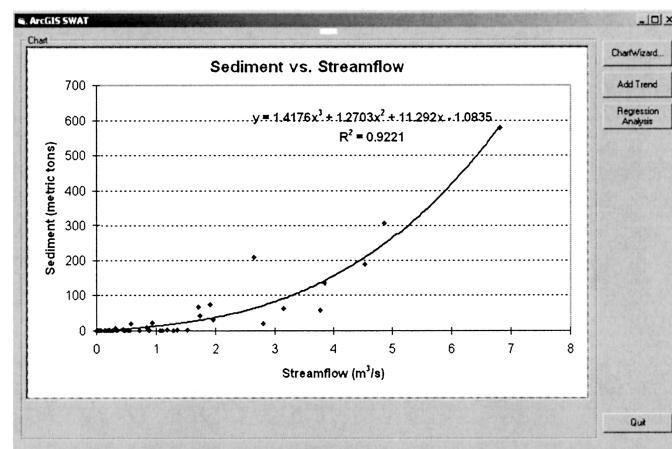
CONCLUSIONS

ArcGIS-SWAT consists of a data model and a GIS interface (i.e., pre-processor and post-processor) for SWAT. With respect to previous data models and GIS interfaces for SWAT, the ArcGIS-SWAT data model uses the geodatabase structure, which can store geographic as well as numeric and text information, and the interface uses programming objects that conform to the COM protocol, thus allowing the use of functionality of other COM compliant applications (i.e., Windows-based applications). ArcGIS-SWAT extracts hydrologic information from spatial data (delineates streams and watersheds, defines HRUs and assigns parameter values based on their soil type and land use, and matches subbasins and weather stations based on location), stores it in the data model, uses it for preparing SWAT input files, runs SWAT, and writes the SWAT output on the data model. Because

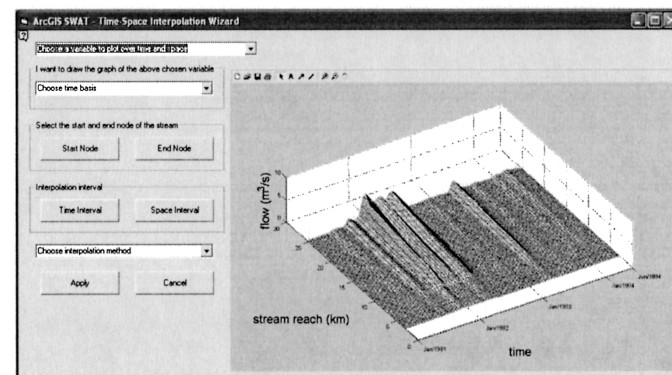
of the geodatabase capability to store geographic information, it constitutes a complete repository of a simulation's data and results, something not possible with the SWAT text input and output files.



(a)



(b)



(c)

Figure 8. Output Visualization Tools: (a) Time Series of Sediment Load at the Watershed Outlet, (b) Sediment Load Versus Flow at the Watershed Outlet, and (c) Flow Versus Time and Distance for the Watershed's Longest Flow Path.

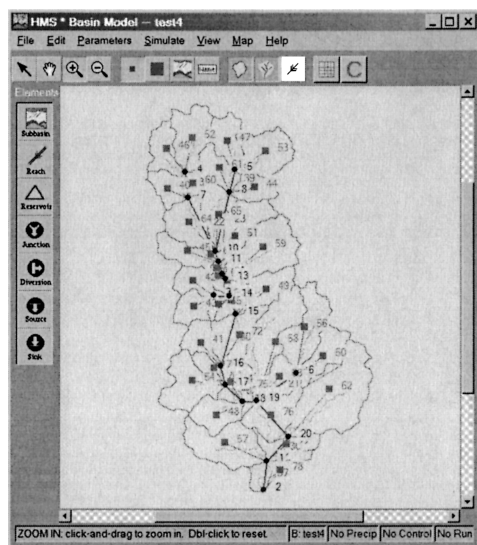


Figure 9. HMS Model of the Seco Creek Watershed.

A feature of ArcGIS-SWAT is its capability to georeference the HRUs, which allows accounting for the HRU's location within the subbasin and the estimation of individual parameter values, without lumping them over their subbasin. However, the quantification of the effect of accounting for the HRU's location on flows and loads was beyond the scope of this paper. The use of Monte Carlo simulations in combination with the ArcGIS-SWAT data model allows the estimation of the uncertainty of the SWAT results by producing frequency distributions of the variables rather than a single value. By generating results such as "there is a 10 percent chance that the median sediment concentration will be greater than 900 mg/l," the modeler is provided valuable information for interpreting the SWAT output. Likewise, the use of programming objects that conform the COM protocol allowed the implementation of functionality of other Windows-based applications within ArcGIS. In particular, the use of MS Excel functionality for plotting and regression analysis as well as of MATLAB functionality for three-dimensional plotting was demonstrated. For model integration, the use of a hub geodatabase that stores geographic and hydrologic data relevant to different models is proposed and demonstrated. In particular, it was presented how information developed by ArcGIS-SWAT for use by SWAT was transferred to the hub geodatabase, from which it was retrieved by another application and used to create an HMS model for flood analysis. It is envisioned that the use of the hub geodatabase concept will ease model integration.

With respect to previous SWAT GIS interfaces, ArcGIS-SWAT takes advantage of programming technology – such as the geodatabase data structure and

COM objects – for exchange of computer application functionality and hydrologic model integration. However, it is considered that hydrologic model integration is more a long term goal than a short term task and that the geodatabase and hub geodatabase approach presented in this paper is a step in this direction but at the same time, that further work along these lines, including the implementation with a wide variety of models, is necessary to assess the advantages of this new concept and the needs for the geodatabase structures.

ACKNOWLEDGMENTS

The authors would like to thank three anonymous manuscript reviewers whose input has been fundamental for improving the text. This work has been conducted with support of the U.S. Army Corps of Engineers-Fort Worth District in Texas.

LITERATURE CITED

- American Society of Civil Engineers, 1993. Criteria for Evaluation of Watershed Models. ASCE Task Committee on the Definition of Criteria for Evaluation of Watershed Models of the Watershed Management Committee, Irrigation and Drainage Committee. *Journal of Irrigation and Drainage Engineering* 119(3):429-442.
- Anderson, J.R., E.E. Hardy, J.T. Roach, and R.E. Witmer, 1976. A Land Use and Land Cover Classification System for Use With Remote Sensor Data. Geological Survey Professional Paper 964, U.S. Government Printing Office, Washington D.C. Available at <http://landcover.usgs.gov/pdf/anderson.pdf>. Accessed on April 21, 2004.
- Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams, 1998. Large Area Hydrologic Modeling and Assessment – Part I: Model Development. *Journal of the American Water Resources Association (JAWRA)* 34(1):73-89.
- Baird, C., M. Jennings, D. Ockerman, and T. Dybala, 1996. Characterization of Nonpoint Sources and Loadings to the Corpus Christi Bay National Estuary Program Study Area. Corpus Christi Bay National Estuary Program CCBNEP-05, 226 pp., Texas Natural Resources Conservation Commission (TNRCC), Austin, Texas.
- Bian, L., H. Sun, C. Blodgett, S. Egbert, L. WeiPing, R. LiMei, and A. Koussis, 1996. An Integrated Interface System to Couple the SWAT Model and ARC/INFO. In: *Proceedings of the 3rd International Conference on Integrating GIS and Environmental Modeling*. U.S. National Center for Geographic Information and Analysis, Santa Fe, New Mexico, CD-ROM.
- Brown, D. and T. Raines, 2002. Simulation of Flow and Effects of Best Management Practices in the Upper Seco Creek Basin, South-Central Texas, 1991-98. U.S. Geological Survey Water Resources Investigations Report 02-4249, Austin, Texas.
- Brown, D., R. Slattery, and J. Gilhousen, 1998. Summary Statistics and Graphical Comparisons of Historical Hydrologic and Water-Quality Data, Seco Creek Watershed, South-Central Texas. U.S. Geological Survey Open-File Report 98-627, 37 pp.
- Di Luzio, M., R. Srinivasan, and J.G. Arnold, 1998. Watershed Oriented Non-point Pollution Assessment Tool. In: *Proceedings of the 7th International Conference on Computers in Agriculture*. American Society of Agricultural Engineers, St. Joseph, Michigan, pp. 233-241.

- Di Luzio, M., R. Srinivasan, and J.G. Arnold, 2002. Integration of Watershed Tools and SWAT Model Into BASINS. *Journal of the American Water Resources Association (JAWRA)* 38(4):1127-1141.
- Di Luzio, M., R. Srinivasan, J.G. Arnold, and S.L. Neitsch, 2000. Soil and Water Assessment Tool – ArcView GIS Interface Manual – Version 2000. Grassland, Soil and Water Research Laboratory, Agricultural Research Service and Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas.
- Eckhardt, K. and J.G. Arnold, 2001. Automatic Calibration of a Distributed Catchment Model. *Journal of Hydrology* 251(2001):103-109.
- Eckhardt, K., L. Breuer, and H.G. Frede, 2003. Parameter Uncertainty and the Significance of Simulated Land Use Change Effects. *Journal of Hydrology* 273(2003):164-176.
- Fontaine, T.A., T.S. Cruickshank, J.G. Arnold, and R.H. Hotchkiss, 2002. Development of a Snowfall-Snowmelt Routine for Mountainous Terrain for SWAT. *Journal of Hydrology* 262(2002):209-223.
- Hanratty, M.P. and H.G. Stefan, 1998. Simulating Climate Change Effects in a Minnesota Agricultural Watershed. *Journal of Environmental Quality* 27:1524-1532.
- Jensen, S.K. and J.O. Domingue, 1988. Extracting Topographic Structure From Digital Elevation Data for Geographic Information System Analysis. *Photogrammetric Engineering and Remote Sensing* 54(11).
- King, K.W., J.G. Arnold, and R.L. Bingner, 1999. Comparison of Green-Ampt and Curve Number Methods on Goodwin Creek Watershed Using SWAT. *Transactions ASAE* 42(4):919-925.
- MacDonald, A., 1999. Building a Geodatabase. ESRI Press, Redlands, California.
- Maidment, D.R. (Editor), 2002. *ArcHydro: GIS for Water Resources*. ESRI Press, Redlands, California.
- Martinez, J. and A. Rango, 1989. Merits of Statistical Criteria for the Performance of Hydrological Models. *Water Resources Bulletin* 25(2):421-432.
- Nash, J.E. and J.E. Sutcliffe, 1970. River Flow Forecasting Through Conceptual Models – Part 1-A: Discussion of Principles. *Journal of Hydrology* 10(82):282-290.
- Neitsch, S.L., J.G. Arnold, J.R. Kiniry, J.R. Williams, and K.W. King, 2002a. Soil and Water Assessment Tool – Theoretical Documentation – Version 2000. Grassland, Soil and Water Research Laboratory, Agricultural Research Service and Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas.
- Neitsch, S.L., J.G. Arnold, J.R. Kiniry, R. Srinivasan, and J.R. Williams, 2002b. Soil and Water Assessment Tool – User's Manual – Version 2000. Grassland, Soil and Water Research Laboratory, Agricultural Research Service and Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas.
- Neitsch, S.L., J.G. Arnold, and R. Srinivasan, 2002c. Pesticides Fate and Transport Predicted by the Soil and Water Assessment Tool (SWAT) – Atrazine, Metolachlor and Trifluralin in the Sugar Creek Watershed. Grassland, Soil and Water Research Laboratory, Agricultural Research Service and Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas.
- Olivera, F., 2001. Extracting Hydrologic Information From Spatial Data for HMS Modeling. *Journal of Hydrologic Engineering* 6 (6):524-530.
- Olivera, F., R. Dodson, and D. Djokic, 2003. Use of Arc Hydro for Integration of Hydrologic Applications. *In: Proceedings of the American Society of Civil Engineers (ASCE) World Water and Environmental Resources Congress 2003*, Philadelphia, Pennsylvania. American Society of Civil Engineers (ASCE), Reston, Virginia, doi 10.1061/40685(2003)249.
- Olivera, F., D.R. Maidment, and D. Honeycutt, 2002. HydroNetworks. *In: ArcHydro: GIS for Water Resources*, D.R. Maidment (Editor). ESRI Press, Redlands, California, pp. 33-53.
- Rosenthal, W.D. and D.W. Hoffman, 1999. Hydrologic Modeling/GIS as an Aid in Locating Monitoring Sites. *Transactions ASAE* 42 (6):1591-1598.
- Santhi, C., J.G. Arnold, J.R. Williams, W.A. Dugas, R. Srinivasan, and L.M. Hauck, 2001. Validation of the SWAT Model on a Large River Basin With Point and Nonpoint Sources. *Journal of American Water Resources Association (JAWRA)* 37(5):1169-1188.
- Spruill, C.A., S.R. Workman, and J.L. Taraba, 2000. Simulation of Daily and Monthly Stream Discharge From Small Watersheds Using the SWAT Model. *Transactions ASAE* 43(6):1431-1439.
- Srinivasan, R. and J.G. Arnold, 1994. Integration of a Basin-Scale Water Quality Model With GIS. *Journal of the American Water Resources Association (JAWRA)* 30(3):453-462.
- Tripathi, M.P., R.K. Panda, and N.S. Raghuwanshi, 2003. Identification and Prioritization of Critical Sub-Watersheds for Soil Conservation Management Using the SWAT Model. *Biosystems Engineering* 85 (3):365-379.
- USACE (U.S. Army Corps of Engineers), 2005. *Hydrologic Modeling System – HEC-HMS – User's Manual*, Vol. 3.0.0. U.S. Army Corps of Engineers-Hydrologic Engineering Center, CPD-74A, Davis, California.
- USDA-NRCS (U.S. Department of Agriculture-Natural Resources Conservation Service), 1995. *State Soil Geographic (STATSGO) Database – Data User Guide*. U.S. Department of Agriculture, Natural Resources Conservation Service, Miscellaneous Publication Number 1492, Washington D.C.
- USDA-SCS (U.S. Department of Agriculture-Soil Conservation Service), 1972. *National Engineering Handbook – Section 4: Hydrology*. U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C.
- USEPA (U.S. Environmental Protection Agency), 2004. *BASINS: Better Assessment Science Integrating Point and Nonpoint Sources – NOAA's National Climatic Data Centers (NCDC) Weather Data Management (WDM) Stations Point Locations in the United States, Puerto Rico, and the U.S. Virgin Islands*. Available at <http://www.epa.gov/waterscience/basins/metadata/wdm.htm>. Accessed on September 30, 2004.
- USGS (U.S. Geological Survey), 2004a. *National Land Cover Dataset 1992 (NLCD 1992)*. Available at <http://landcover.usgs.gov/natl/landcover.asp>. Accessed on April 2004.
- USGS (U.S. Geological Survey), 2004b. *Seamless Data Distribution System, Earth Resources Observation and Science (EROS)*. Available at <http://seamless.usgs.gov/>. Accessed on April 2004.
- USGS (U.S. Geological Survey), 2006. *Daily Streamflow for the Nation*. Available at <http://nwis.waterdata.usgs.gov/usa/nwis/discharge>. Accessed in January 2006.
- Weber, A., N. Fohrer, and D. Moller, 2001. Long-Term Land Use Changes in a Mesoscale Watershed Due to Socio-Economics Factors – Effects on Landscape Structures and Functions. *Ecological Modeling* 140:125-140.
- Williams, J.R., 1995. The EPIC Model. *In: Computer Models of Watershed Hydrology*, V.P. Singh (Editor). Water Resources Publications, Highlands Ranch, Colorado, pp. 909-1000.
- Zeiler, M., 2001. *Exploring ArcObjects*. ESRI Press, Redlands, California.