Soil & Water Assessment Tool

http://swatmodel.tamu.edu/

Texas A&M AgriLife Research

Introductory Manual

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Soil & Water Assessment Tool

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Texas A&M AgriLife Research

Beginner SWAT

Training Manual

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Texas A&M University

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Section 1

SWAT Overview

Soil and Water Assessment Tool

http://swatmodel.tamu.edu

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Model Philosophy

- **Readily available input – Physically based**
- **Comprehensive – Process Interactions**
- **Simulate Management**

Model Philosophy

- **"Everything should be made as simple as possible. I have no interest in the laws of physics if they can't be made simple"**

Albert Einstein

SWAT

ARS Modeling History Time Line

USLE	CREAMS (CLEAN WATER ACT)	EPIC	SWRRB	SWAT
1960's	1970's	1980's		1990's
		GLEAMS	WEPP AGNPS	ANN AGNPS

SWAT

Environmental Models Maintained at Temple, TX

- **EPIC—Field Scale**
- **ALMANAC—Field Scale**
- **APEX—Farm Scale**
- **SWAT—Watershed Scale**

SWAT

Global Applications

Hydrologic Unit Modeling for Global Eosystem/Environment

2001 Giessen, Germany
2003 Bari, Italy
2005 Zurich, Switzerland
2006 Potsdam, Germany
2007 Delft, Netherlands
2008 Beijing, China
2009 Chiang Mai, Thailand
2009 Boulder, CO, USA
2010 New Delhi, India
2011 Toledo, Spain

International SWAT Conferences

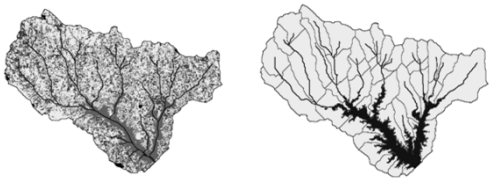
SWAT

General Description

- Continuous Time
  - Daily Time Step
  - One Day ⟶ Hundreds of Years
- Distributed Parameter
  - Unlimited Number of Subwatersheds
- Comprehensive – Process Interactions
- Simulate Management

SWAT

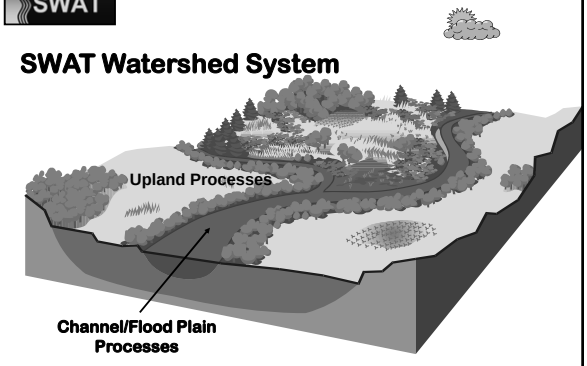
Example Configuration



- Cells/Subwatersheds
- Hydrologic Response Units
- Output from other Models
- Point Sources - Treatment Plants

SWAT

SWAT Watershed System

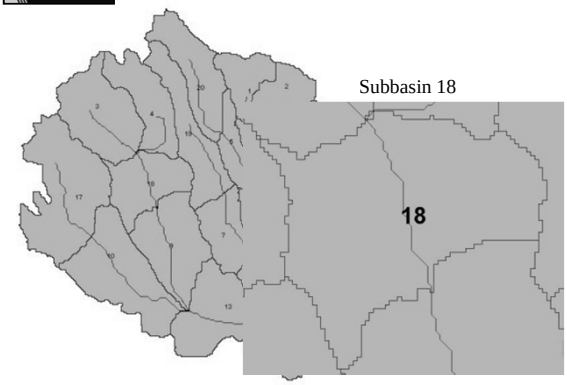


SWAT

Subbasins and Streams

SWAT

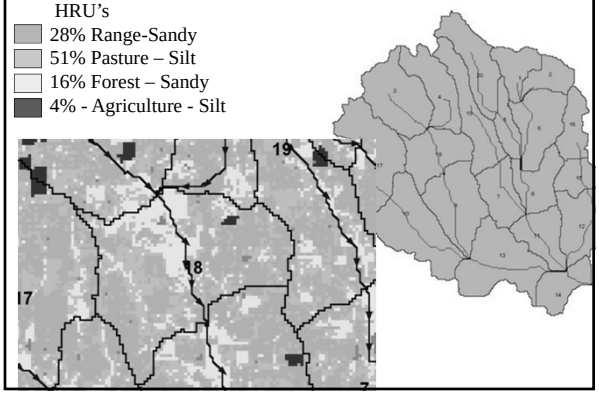
Subbasins and Streams



SWAT

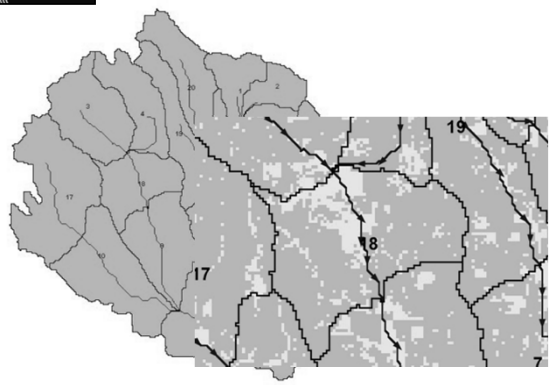
Subbasins and Streams

HRU's
28% Range-Sandy
51% Pasture – Silt
16% Forest – Sandy
4% - Agriculture - Silt



SWAT

Subbasins and Streams



SWAT

Upland Processes

- **Weather**
- **Hydrology**
- **Sedimentation**
- **Plant Growth**
- **Nutrient Cycling**
- **Pesticide Dynamics**
- **Management**
- **Bacteria**

SWAT

Climate

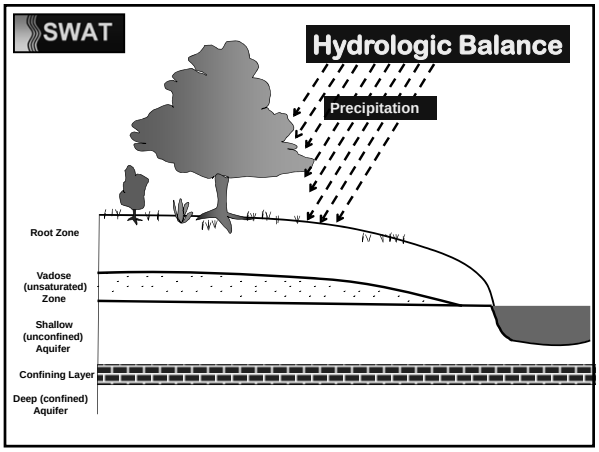
- **Weather**
  - Precipitation
  - Air Temperature and Solar Radiation
  - Wind Speed
  - Relative Humidity
- **Snow**
  - Snow Cover
  - Snow Melt
  - Elevation Bands
- **Soil Temperature**

SWAT

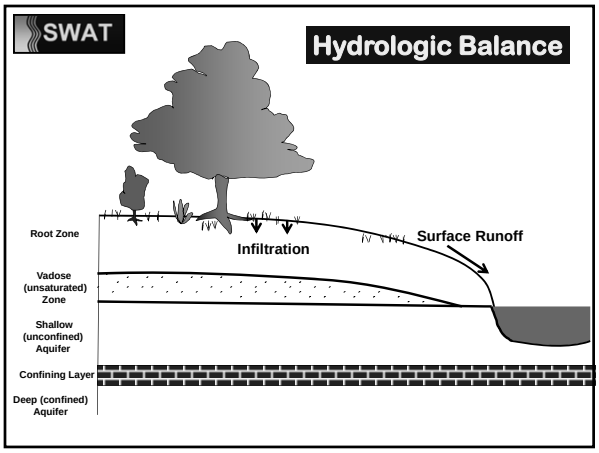
Hydrology

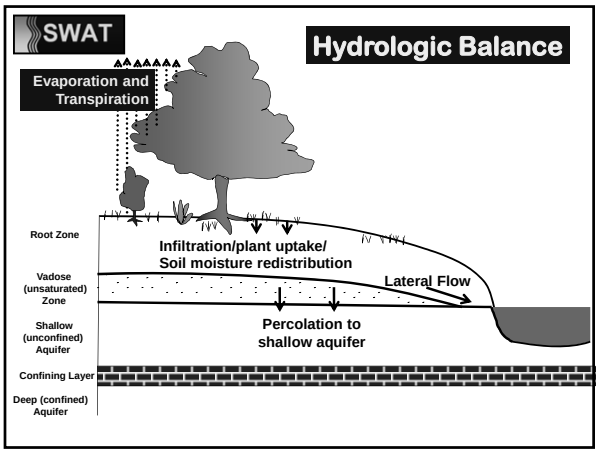
- **Canopy Storage**
- **Infiltration**
- **Redistribution**
- **Evapotranspiration**
- **Lateral Subsurface Flow**
- **Surface Runoff**
  - Surface runoff volume
  - Peak runoff
- **Ponds**
- **Tributary Channels**
  - Transmission Losses

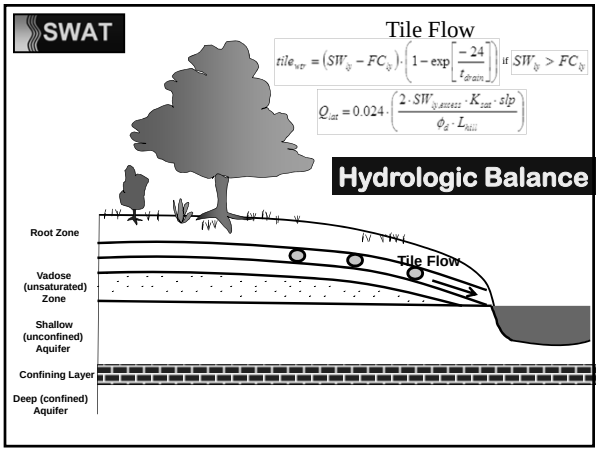
SWAT

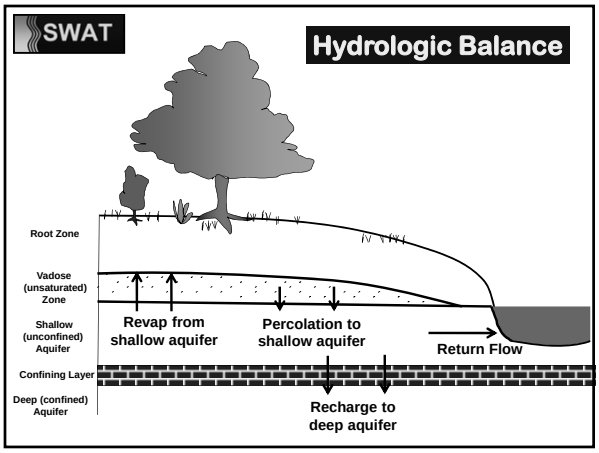


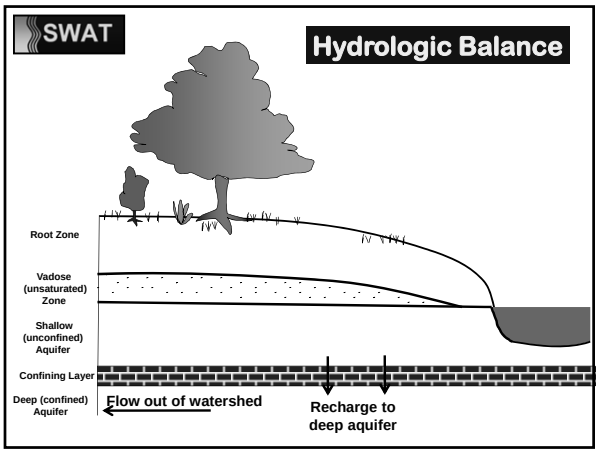
SWAT

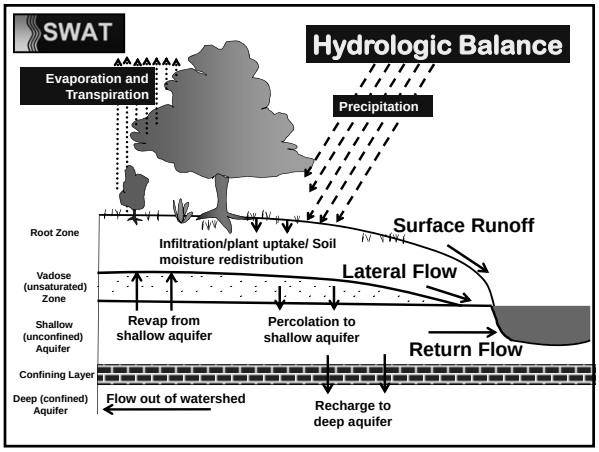


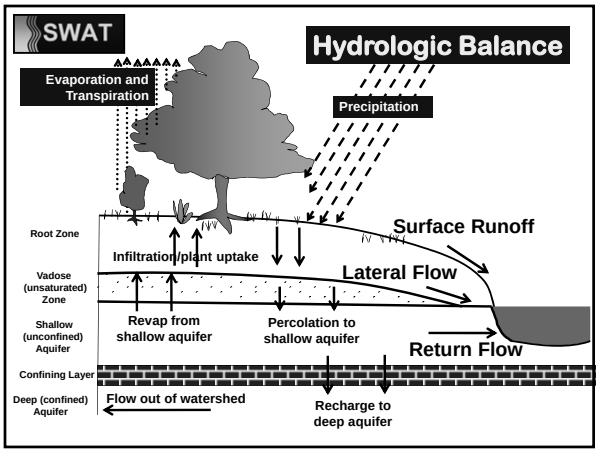

SWAT
Hydrologic Balance
Evaporation and Transpiration
Root Zone
Infiltration/plant uptake/
Soil moisture redistribution
Vadose (unsaturated) Zone
Lateral Flow
Shallow (unconfined) Aquifer
Percolation to shallow aquifer
Confining Layer
Deep (confined) Aquifer


SWAT
Tile Flow
$tile_{wp} = (SW_{ly} - FC_{ly}) \cdot \left(1 - \exp\left[\frac{-24}{t_{drain}}\right]\right)$ if $SW_{ly} > FC_{ly}$
$Q_{lat} = 0.024 \cdot \left(\frac{2 \cdot SW_{ly,excess} \cdot K_{sat} \cdot slp}{\phi_d \cdot L_{hill}}\right)$
Hydrologic Balance
Root Zone
Tile Flow
Vadose (unsaturated) Zone
Shallow (unconfined) Aquifer
Confining Layer
Deep (confined) Aquifer


SWAT
Hydrologic Balance
Root Zone
Vadose (unsaturated) Zone
Revap from shallow aquifer
Percolation to shallow aquifer
Return Flow
Shallow (unconfined) Aquifer
Confining Layer
Deep (confined) Aquifer
Recharge to deep aquifer

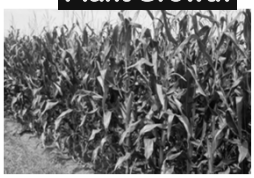

SWAT
Hydrologic Balance
Root Zone
Vadose (unsaturated) Zone
Shallow (unconfined) Aquifer
Confining Layer
Deep (confined) Aquifer
Flow out of watershed
Recharge to deep aquifer

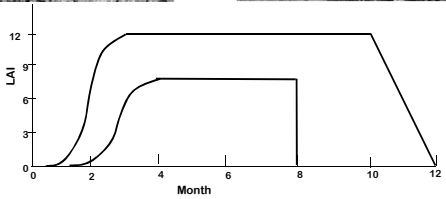

SWAT
Hydrologic Balance
Evaporation and Transpiration
Precipitation
Surface Runoff
Infiltration/plant uptake/ Soil moisture redistribution
Lateral Flow
Root Zone
Vadose (unsaturated) Zone
Shallow (unconfined) Aquifer
Revap from shallow aquifer
Percolation to shallow aquifer
Return Flow
Confining Layer
Deep (confined) Aquifer
Flow out of watershed
Recharge to deep aquifer


SWAT
Hydrologic Balance
Evaporation and Transpiration
Precipitation
Surface Runoff
Root Zone
Infiltration/plant uptake
Lateral Flow
Vadose (unsaturated) Zone
Shallow (unconfined) Aquifer
Revap from shallow aquifer
Percolation to shallow aquifer
Return Flow
Confining Layer
Deep (confined) Aquifer
Flow out of watershed
Recharge to deep aquifer

SWAT

Plant Growth





SWAT

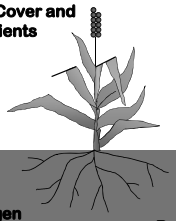
Plant Growth

Yield Prediction
- Harvest Index – Water Stress
- Residue – Cover and Nutrients

Optimum Growth
- Radiation Interception LAI
- Radiation Use Efficiency

Constraints
- Water, Temperature, Nitrogen, Phosphorus

Residue – Cover and Nutrients



Water, Nitrogen and Phosphorus Uptake

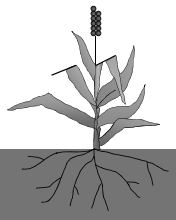
Root Growth

SWAT

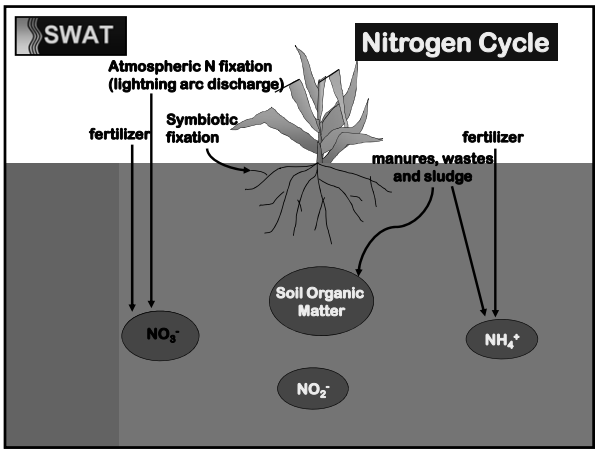
Climate Change

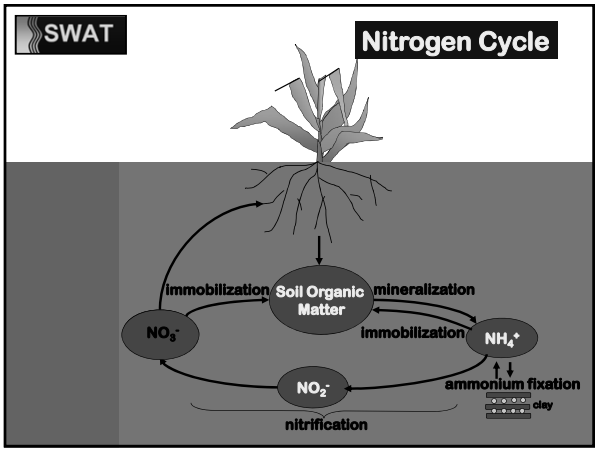
Radiation Use Efficiency
- Adjusted for CO_2

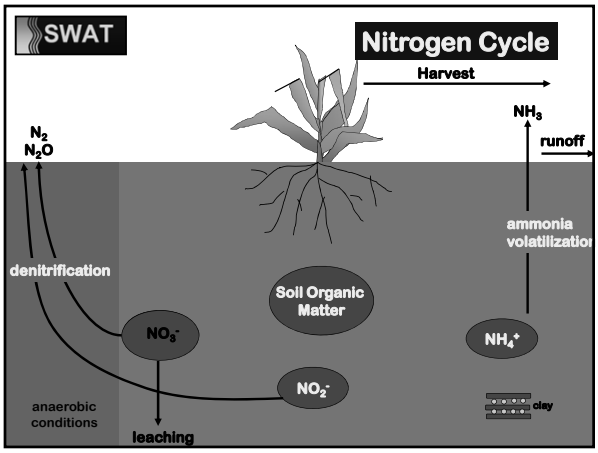
ET – Penman-Monteith
- Canopy Resistance Adjusted for CO_2 Impact on Leaf Conductance

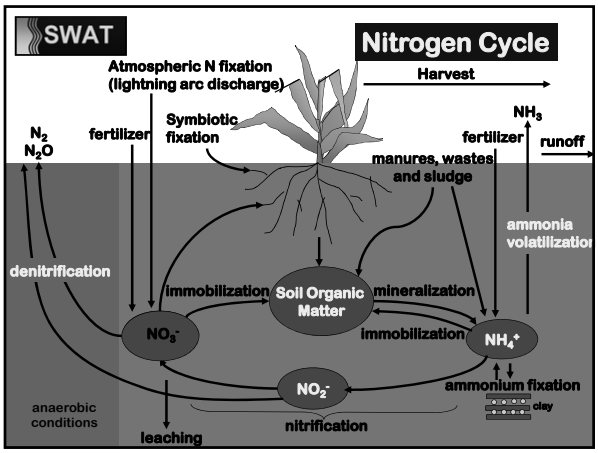


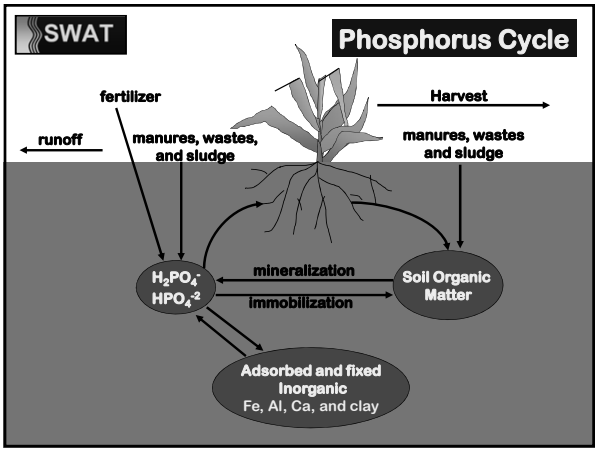
CGM Estimates of Precip, Temperature, Humidity, Solar Radiation, Wind Speed

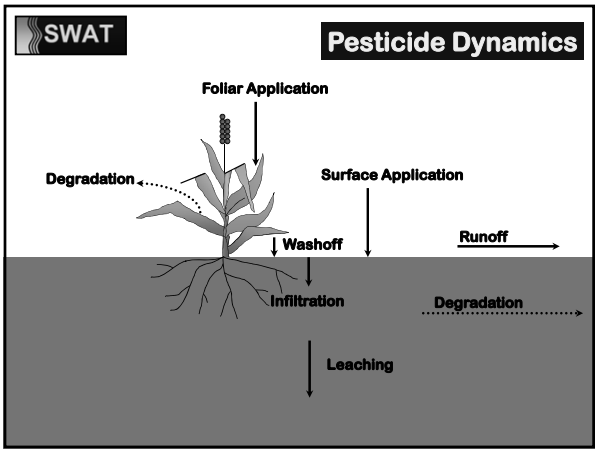

SWAT
Nitrogen Cycle
Atmospheric N fixation
(lightning arc discharge)
fertilizer
Symbiotic
fixation
fertilizer
manures, wastes
and sludge
Soil Organic
Matter
NO_3^-
NH_4^+
NO_2^-


SWAT
Nitrogen Cycle
immobilization
Soil Organic
Matter
mineralization
immobilization
NO_3^-
NH_4^+
NO_2^-
ammonium fixation
clay
nitrification


SWAT
Nitrogen Cycle
Harvest
NH_3
runoff
N_2
N_2O
ammonia
volatilizatio
denitrification
Soil Organic
Matter
NO_3^-
NH_4^+
NO_2^-
clay
anaerobic
conditions
leaching


SWAT
Nitrogen Cycle
Atmospheric N fixation
(lightning arc discharge)
Harvest
NH_3
N_2
N_2O
fertilizer
Symbiotic
fixation
fertilizer
runoff
manures, wastes
and sludge
ammonia
volatilizatio
denitrification
immobilization
Soil Organic
Matter
mineralization
NO_3^-
immobilization
NH_4^+
NO_2^-
ammonium fixation
clay
anaerobic
conditions
leaching
nitrification


SWAT
Phosphorus Cycle
fertilizer
Harvest
runoff
manures, wastes,
and sludge
manures, wastes
and sludge
$H_2PO_4^-$
HPO_4^{-2}
mineralization
immobilization
Soil Organic
Matter
Adsorbed and fixed
Inorganic
Fe, Al, Ca, and clay


SWAT
Pesticide Dynamics
Foliar Application
Degradation
Surface Application
Washoff
Runoff
Infiltration
Degradation
Leaching

SWAT

Management

- Crop Rotations
- Removal of Biomass as Harvest/
  Conversion of Biomass to Residue
- Tillage / Biomixing of Soil
- Fertilizer Applications
- Grazing
- Pesticide Applications

SWAT

Management

- Irrigation
- Subsurface (Tile) Drainage
- Water Impoundment (e.g. Rice)

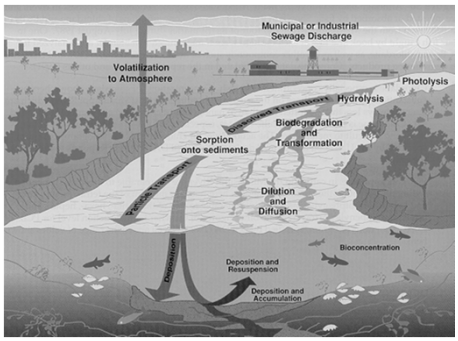
SWAT

Management

- Urban Areas
  - Pervious/Impervious Areas
  - Street Sweeping
  - Lawn Chemicals
- Edge of Field Buffers

SWAT

Channel Processes



SWAT

Channel Processes

- **Flood Routing**
  - **Variable Storage**
  - **Muskingum**
- **Transmission Losses, Evaporation**
- **Sediment Routing**
  - **Degradation and deposition computed simultaneously**

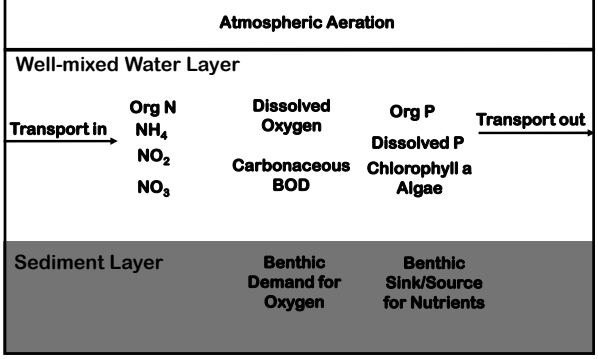
SWAT

Channel Processes

- **Nutrients**
  - **modified QUAL2E/WASP**
- **Pesticide**
  - **Toxic balance developed at University of Colorado**

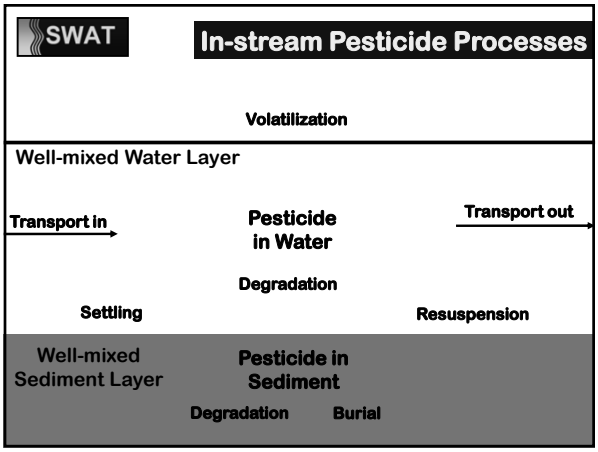
SWAT

In-stream Nutrient Processes



SWAT

In-stream Pesticide Processes



SWAT

Impoundments

- Water Balance
  - Inflow
  - Evaporation
  - Seepage
  - Withdrawals
  - Outflow
    - Spillway Control
    - Target Volume Approach
    - Missouri River Reservoir Operation

SWAT

Impoundments

- Nutrient Balance
  - Well-mixed System
  - Nitrogen & Phosphorus Loss Rates
  - 2 Settling Periods per Year
- Pesticide Balance
  - Well-mixed System
  - **Toxic balance developed at University of Colorado**

SWAT

User Options

- **PET:**
  - **Penman-Monteith, Priestly-Taylor, or Hargreaves**
- **Runoff:**
  - **Curve Number or Green & Ampt**
- **Channel Flow:**
  - **Variable Storage Coefficient or Muskingham-Cunge**
- **Channel Water Quality:**
  - **QUAL2E On-Off Switch**

More User Options

- **ARC GIS 9.3 or 10**
- **Map Windows (Public Domain GIS)**
- **SWAT-CUP (Calibration and Uncertainty Progra**
- **VIZSWAT (Output Vizualization)**
- **Manuals in English, Spanish, Chinese, Korean**
- **SWAT 2003, 2005, 2009, (2012)**

SWAT

SWAT Strengths

Upland Processes

- Comprehensive Hydrologic Balance
- Physically-Based Inputs
- Plant Growth – Rotations, Crop Yields
- Nutrient Cycling in Soil
- Land Management - BMP
  Tillage, Irrigation, Fertilizer, Pesticides, Grazing, Rotations, Subsurface Drainage, Urban-Lawn Chemicals, Street Sweeping

SWAT

SWAT Strengths

Channel Processes

- Flexible Watershed Configuration
- Water Transfer—Irrigation Diversions
- Sediment Deposition/Scour
- Nutrient/Pesticide Transport
- Pond, Wetland and Reservoir Impacts

SWAT

Collaborators

USDA Agricultural Research Service	Texas A&M University
USDA Natural Resources Conservation Service	EPA Office of Science and Technology
NOAA	Universities

SWAT

Conclusions

- **A product of over 45 years of USDA/Texas A&M model development**
- **Widely used for water quality, water supply, and climate change, carbon sequestration, and agricultural production assessments worldwide**
- **Over 1000's SWAT users and 30 active developers worldwide**
- **Annual meetings alternate in Asia and Europe**

SWAT

The End

http://swatmodel.tamu.edu

ARC SWAT

ARCGIS INTERFACE FOR SWAT

INTRODUCTION

OBJECTIVES

WATERSHED DELINEATION

HYDROLOGIC RESPONSE UNIT DEFINITION

WRITE INPUT TABLES FOR SWAT

EDIT SWAT INPUT

SWAT SIMULATION SETUP

APPENDIX: INSTALLING ARCSWAT

ArcSWAT

ArcGIS Interface for Soil and Water Assessment Tool (SWAT)

http://www.brc.tamus.edu/swat

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Blackland Research and Extension Center and Spatial Sciences Laboratory

Texas Agricultural Experiment Station

Texas A&M University

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Introduction

The ***Soil and Water Assessment Tool (SWAT)*** is a physically-based continuous-event hydrologic model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time. For simulation, a watershed is subdivided into a number of homogenous subbasins (hydrologic response units or HRUs) having unique soil and land use properties. The input information for each subbasin is grouped into categories of weather; unique areas of land cover, soil, and management within the subbasin; ponds/reservoirs; groundwater; and the main channel or reach, draining the subbasin. The loading and movement of runoff, sediment, nutrient and pesticide loadings to the main channel in each subbasin is simulated considering the effect of several physical processes that influence the hydrology. For a detailed description of the capabilities of the ***SWAT***, refer to *Soil and Water Assessment Tool User's Manual, Version 2000* (Neitsch et al., 2002), published by the Agricultural Research Service and the Texas Agricultural Experiment Station, Temple, Texas. The manual can also be downloaded from the ***SWAT*** Web site (www.brc.tamus.edu/swat/swatdoc.html#new).

Objectives

The objectives of this exercise are to (1) setup a SWAT project and (2) familiarize with the capabilities of SWAT.

Create a Project

ArcSWAT extension of ArcGIS 10 creates an ArcMap project file that contains links to your retrieved data and incorporates all customized GIS functions into your ArcMap project file. The project file contains a customized ArcMap Graphical User Interface (GUI) including menus, buttons, and tools. The major steps on how to create a SWAT project under then ArcMap environment are introduced below:

Step 1. Start ArcMap. Under the **Customize** menu of ArcMap View, click the **Extensions** button. You will see an extension entitled "SWAT Project Manager" and "SWAT Watershed delineator" under the extensions list (Figure 1). Turn on these two extensions.

Step 2. Go to the **Customize** menu of ArcMap, hover the mouse over the Toolbar button, a list of tools will appear. Click the ArcSWAT tool, the main interface of ArcSWAT will open

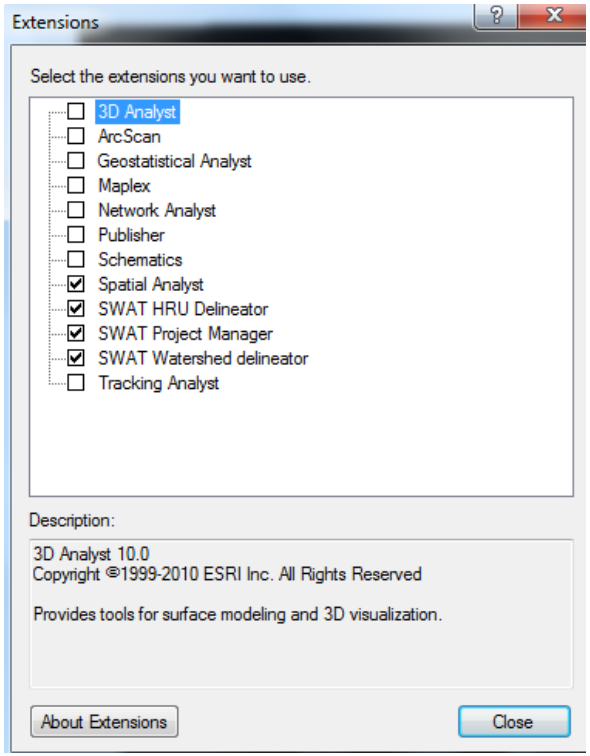


Figure 1 Extensions of ArcMap

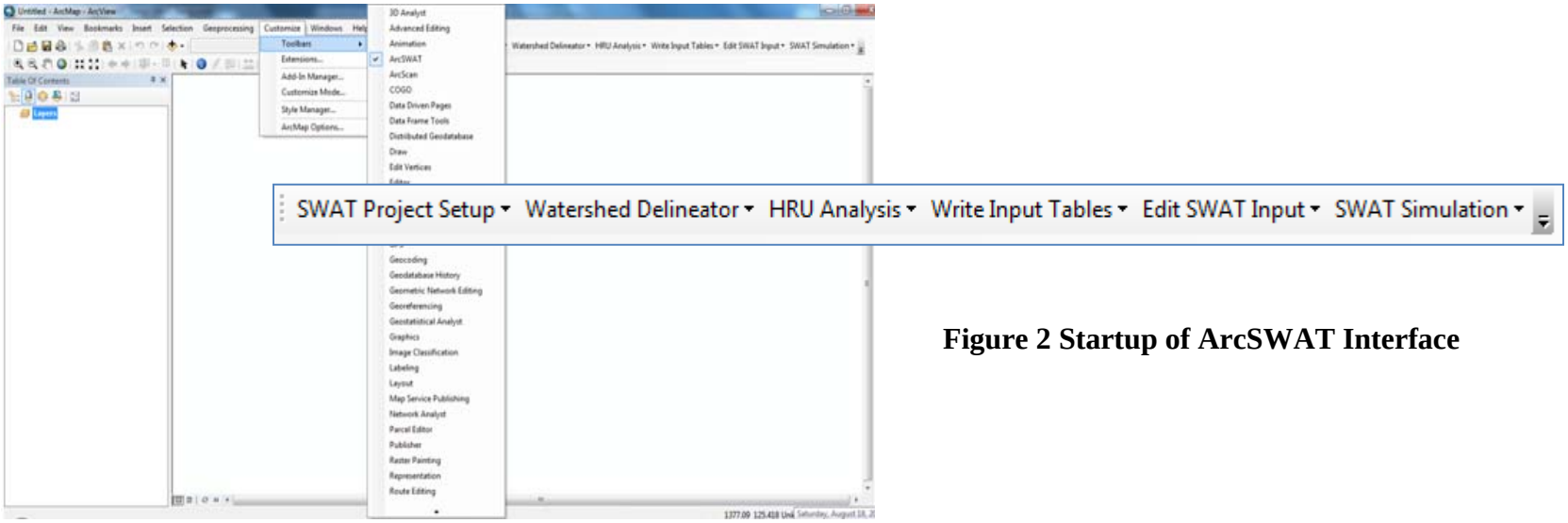


Figure 2 Startup of ArcSWAT Interface

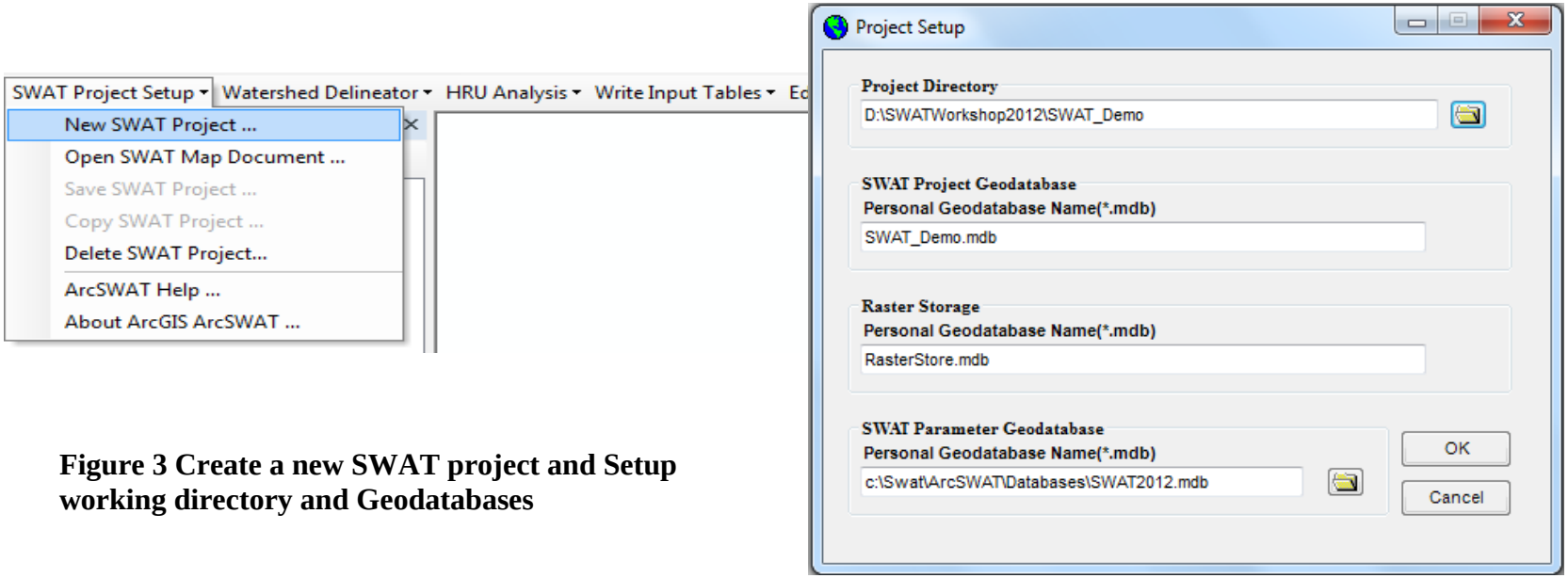


Figure 3 Create a new SWAT project and Setup working directory and Geodatabases

Step 3. Create a new SWAT project and Setup working directory and Geodatabases

- Click the **New SWAT Project** button under then **SWAT Project Setup** menu. In the prompted dialog entitled "**Project Set Up**" (Figure 3), Select a **Project Directory** for current project**.** The names of **SWAT Project Geodatabase** and **Raster Storage Geodatabase** are initialized automatically. These two Geodatabases will be created under the **Project Directory.**
- The **SWAT Parameter Geodatabase** stores the parameters that are needed for SWAT model run. The directory of this Geodatabase is provided by the interface, users should not change this value.
- Click **OK** after you setup a project. Then a new SWAT project will be created under the **Project Directory (**Figure 4**).** The SWAT project includes two folders, two geodatabases, and one <Project Directory>.mxd file. The < Project Directory >.mxd file is the file that is currently in use by the user.

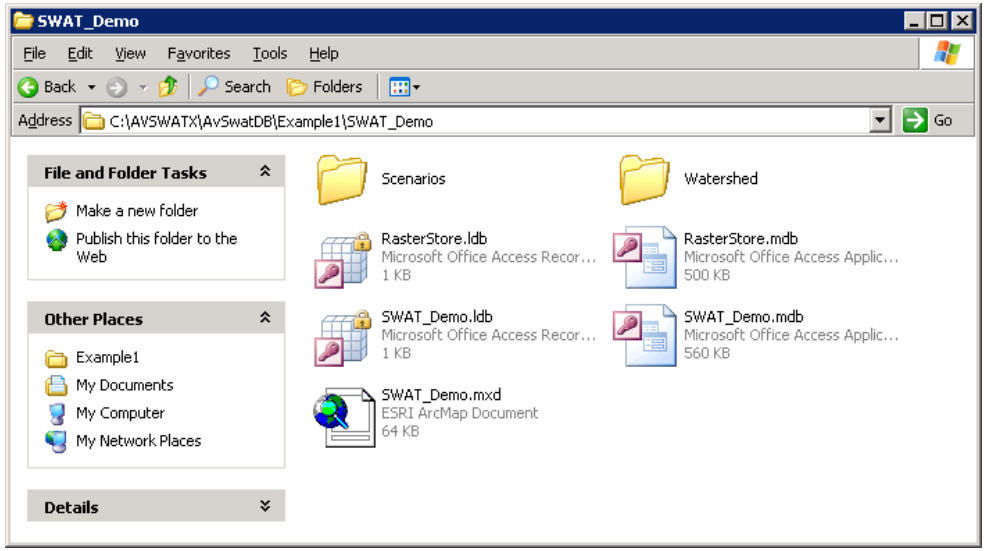


Figure 4 The structure of SWAT project directory

Watershed Delineation

After setup of a new SWAT project, activate the **Automatic Watershed Delineation** button under the **Watershed Delineator** menu by clicking this button. The **Watershed Delineation** tool will appear (Figure 2). The tool's functions are divided into five sections, namely: DEM setup, Stream Definition, Outlet and Inlet Definition, Watershed Outlet(s) Selection and Definition. This tool is used to create wateshed delineations using a combination of DEM, digitized network (RF1 or RF3, NHD or User defined), and other user inputs. The detailed procedures on how to use the **Watershed Delineation** tool are introduced in the following sections:

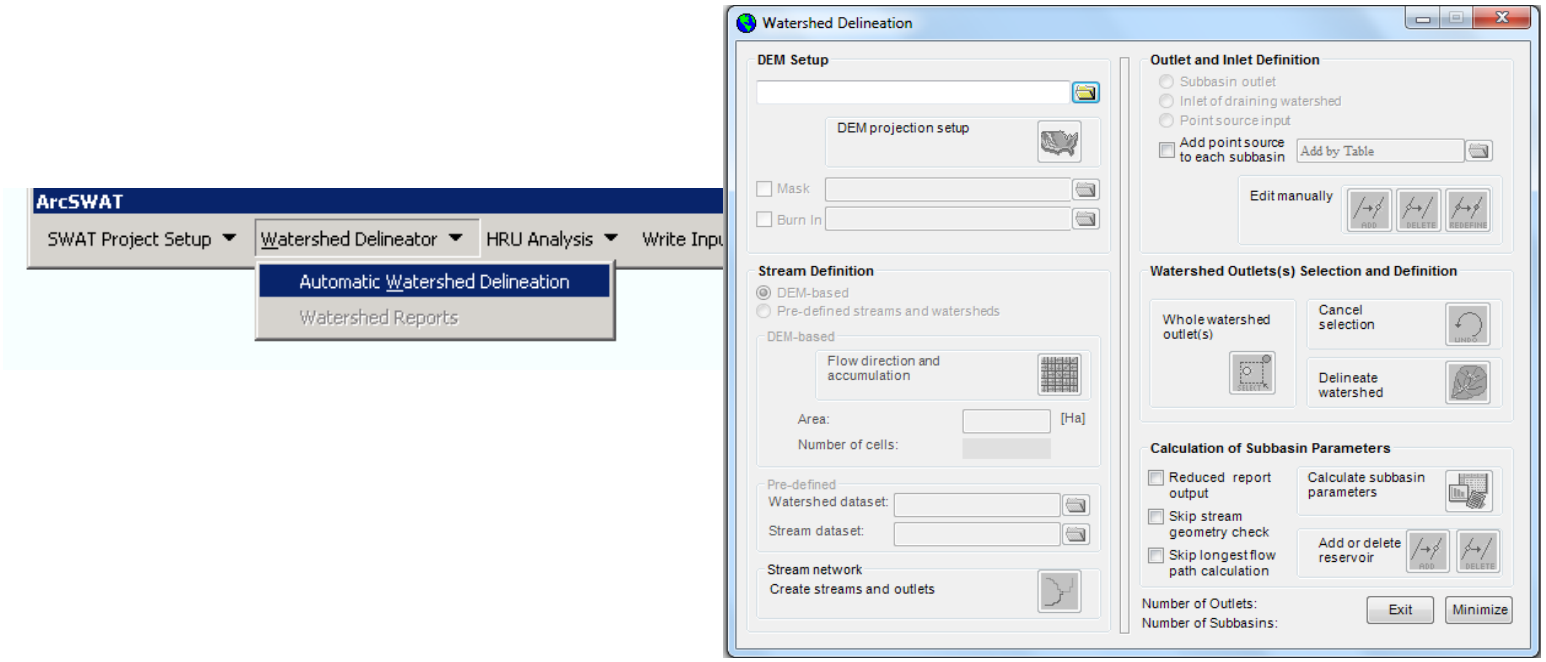


Figure 2 Watershed Delineation main dialog

Step 1: Add DEM Grid

1. Click the icon to add the DEM grid to be setup for modeling with SWAT. A dialog box (Figure 3) with options **Select from Watershed View** and **Load DEM grid from disk** is opened. Choose **Load DEM grid from disk** and select the **dem** grid located in your disk (the directory is "C:\AVSWATX\AvSwatDB\Example1" for this example) and click **ADD**. The selected dem will be resaved as **<Project Directory>\RasterStore.mdb\SourceDem, which is loaded into the ArcMap.**

   Note: the selected dem file must have an effective projection. If not, an error dialog will prompt.

2. After loading **dem**, the button will be activated. Using this button, the user can check the projection information of the **dem (**Figure 4**)**. The DEM properties box lets you verify that the DEM map properties are correct and make any needed changes. The DEM properties should correctly define the grid size and units. The user can change the Z unit to reflect the real situation.

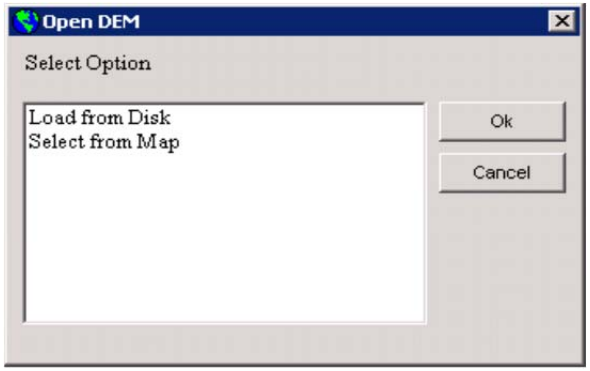


Figure 3 Projection properties of DEM

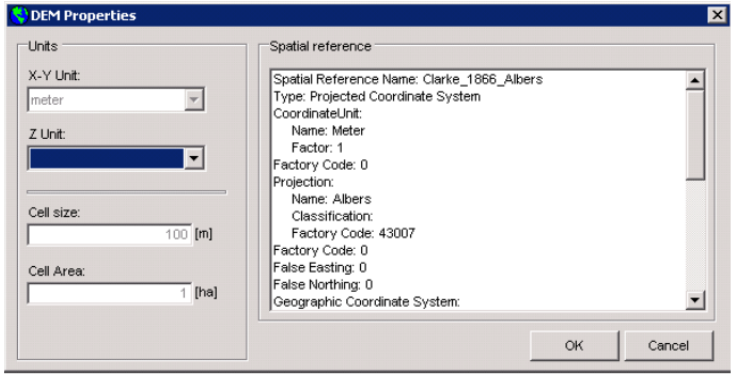


Figure 4 Projection properties of DEM

Step 2: Focusing on Watershed Area

The interface allows users to import or create a grid map that masks out a part of the DEM grid and/or a shape map that defines the stream network. These maps are not required but might speed the processing time for the GIS operations.

1. Click beside **Mask**, then three options are available to specify the watershed area of interest (Figure 5): **Load mask grid from disk**, **manually delineate** and **Select boundary theme from basins view**. Select the **Load mask grid from disk** option and click **OK**. Select the **mask** grid located in your disk, and click **ADD.** The selected dem will be resaved as **<Project Directory>\RasterStore.mdb\Mask,** which is loaded into the ArcMap (Figure 7).
2. If you selected the **Manually Delineate** option, then a toolset will appear and allow you draw polygon mask (Figure 6). A toolbar with three buttons, **DRAW**, **EDIT VERTEX** and **DELETE** appears. These tools provide the capability similar to drawing and editing a polygon theme in ArcMap.
   Click on the **DRAW** button to manually trace the boundary of the watershed area of interest using the mouse. Double click the mouse left button to complete the polygon. **EDIT Vertex** will allow you to adjust the boundary of the mask.
   The **DELETE** Button will allow you to select the entire polygon for deletion using the "Delete" function in your Keyboard. Click **APPLY** after you are satisfied with the manually drawn masking area. This will create a masking grid (**MASK**) and add the theme to the Watershed View.

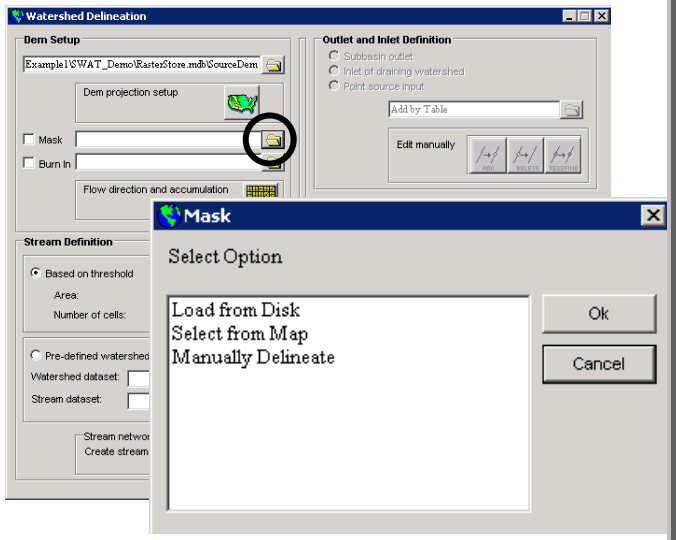


Figure 5 Options to define Mask

Figure 6 Toolset for Manually Mask Delineation

Note:
1. If a mask grid already exists, you can select Load mask grid from the disk option. The grid will be added to the Basins view and used for delineation.
2. A polygon theme already in the Basins View can be selected as a mask, using the Select boundary theme from the Basins view option.

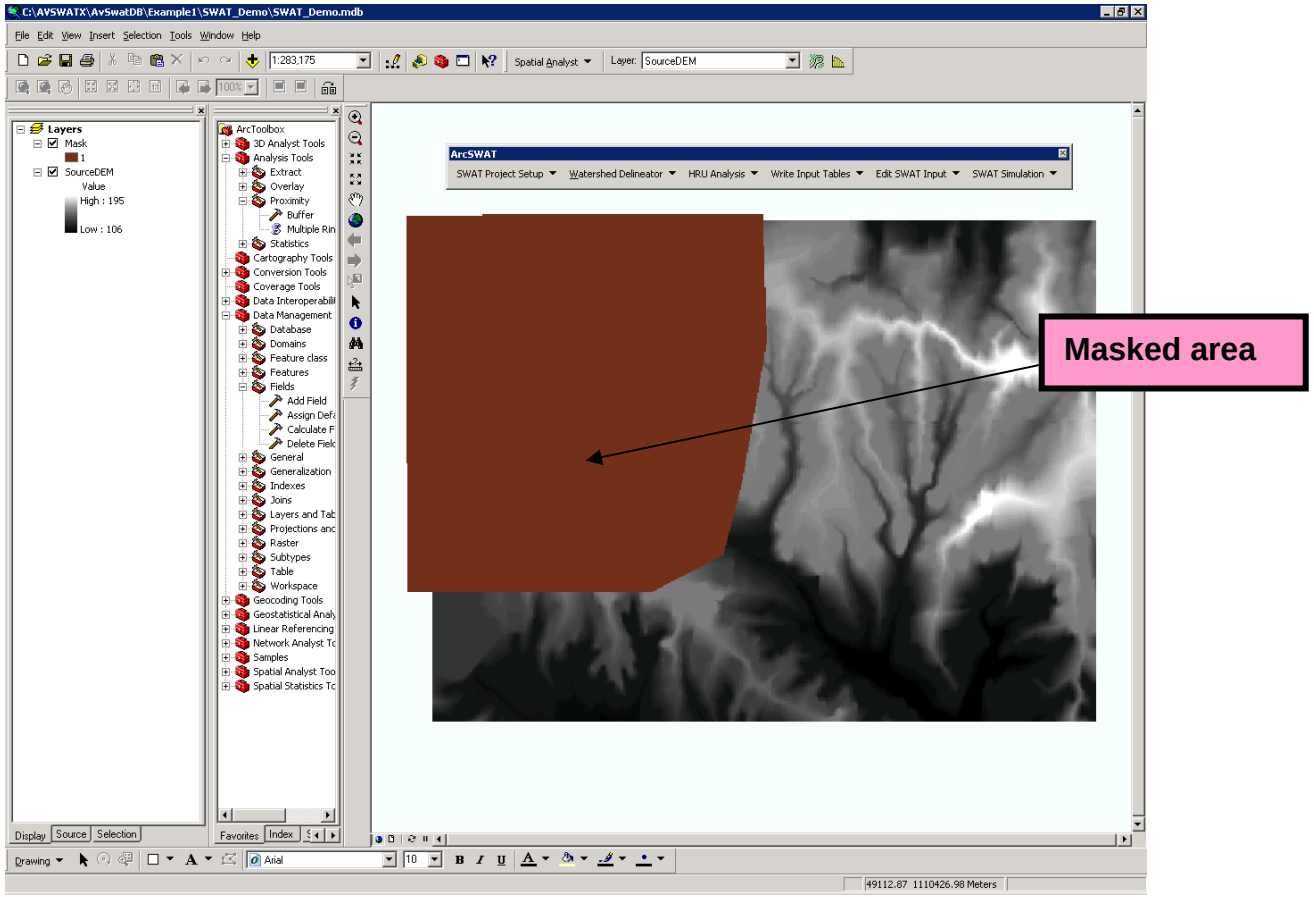


Figure 7 DEM grid added to ArcMap View with a mask area

Note:

- You can exit the main Watershed Delineation Dialog anytime and open it again by selecting **AUTOMATIC DELINEATION** from the WATERSHED **DELINEATOR** menu.

Step 3: Burning in a stream network

A stream network theme such as Reach File (V1 or V3) or National Hydrography Dataset (NHD) can be superimposed onto the DEM to define the location of the stream network.

Step 4: Stream Definition

(Note: For the Stream Definition function of the Watershed Delineator, There are two ways to define the watershed and stream network. In this section, the method based threshold area will be introduced, while another method based on pre-defined watershed will be introduced in Appendix I.)

1. In order to use the threshold method to delineate the watershed and stream network, the **Flow Direction and Accumulation** needs to be calculated by clicking the button. Stream definition defines both the stream network and subbasin outlets. A minimum, maximum, and suggested sub watershed area (in hectares) is shown in the drainage area box (Figure 8). You have the option of changing the size of the subbasins within the specified range of values. This function plays an important role in determining the detail of the stream network and the size and number of subbasins created. The threshold area defines the drainage area required to form the beginning of a stream.

Figure 8 Threshold area for stream and subbasin definition

2. After setting the threshold value of subbasin, then the user can delineate the stream network and outlets through clicking the button. The drainage network and stream juncture points, used to define subbasin outlets, are displayed on the DEM map grid (**Error! Reference source not found.**).

Note:

- NHD is an enhanced stream network at the scale of 1:100,000. It is based on USGS Digital Line Graph (DLG) hydrography data integrated with reach-related information from the EPA River Reach File version 3 (RF3).

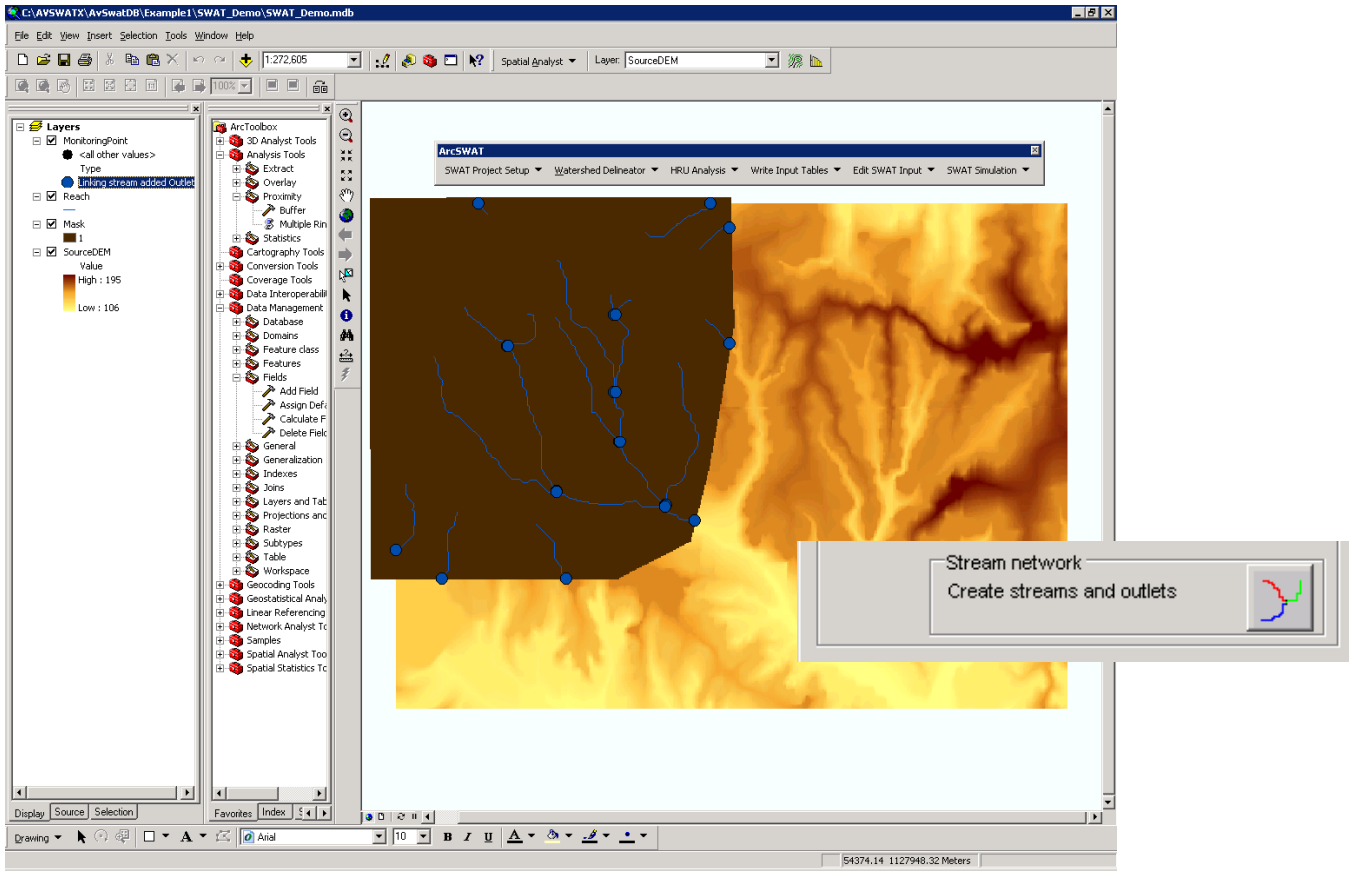


Figure 9 Drainage network and subbasin outlets

Next step is Outlet and Inlet Definition (

3. Figure 10). Before proceeding, you have a number of options: (1) change the threshold area and rerun the stream and outlet definition routine, (2) add outlet points by importing a table that contains the locations, (3) add outlet points manually, and (4) remove outlet points. Assuming the outlet and stream definition to be acceptable proceed to inlet definition for the study area. Inlets represent any point source loading into the study area or the inlets of drainage into the watershed from an upstream area.

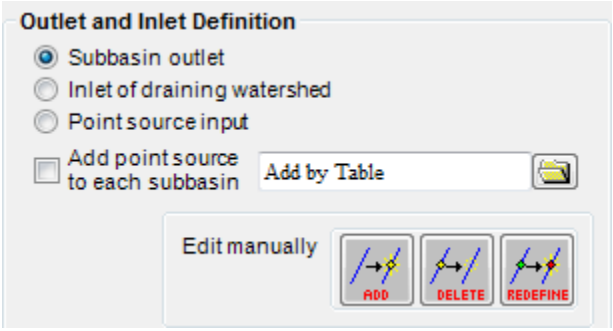


Figure 10 Options for defining Outlet and Inlet

Note

- By specifying the threshold area, we define the stream network for networking.
- It means that a minimum number of cells are required to start delineating the stream.
- The minimum threshold area is for the entire watershed, not for each sub watersheds that are going to be delineated.
- The suggested area given in this window is the average are that could be used.

Step 5: Main Watershed Outlet(s) Selection and Definition

In this step the users will select one or more outlet locations to define the boundary of the main watershed.

Click on the **SELECT** button to choose the watershed outlet. Draw a box covering the desired outlet locations will set the main **Watershed Outlets**. In this example, select 1 outlet at the downstream edge of the masked area (

1. Figure 11) and click the **Delineate Watershed** button . Select **YES** in the following dialog to continue with the delineation of main watershed and subbasins. A prompt box will appear to announce completion of the watershed and subbasin delineation.
2. The delineated watershed with subbasins will be added to the View. If the delineation is not satisfactory or if the user wants to select a different outlet for the watershed, click on the **Cancel Selection** button and repeat.

Click on the Calculate Subbasin Parameters button to estimate the subbasin parameters. This function calculates basic watershed characteristics from the DEM and sub-watershed themes. It also assigns the necessary subbasin identification. The results of the calculations are stored as additional fields in the streams and subbasins theme database files. Click OK to completion of watershed delineation dialog box.

3. Figure 12 shows the delineated watershed with subbasins.
4. Open the Reach or Watershed attribute tables to view the calculated characteristics.

** By holding the **SHIFT** key in your keyboard you can select more than one outlet. This feature allows adjacent watershed to be simulated at the same time using SWAT. Do not select an outlet at the upstream of another outlet. At least one outlet must be selected for delineation.

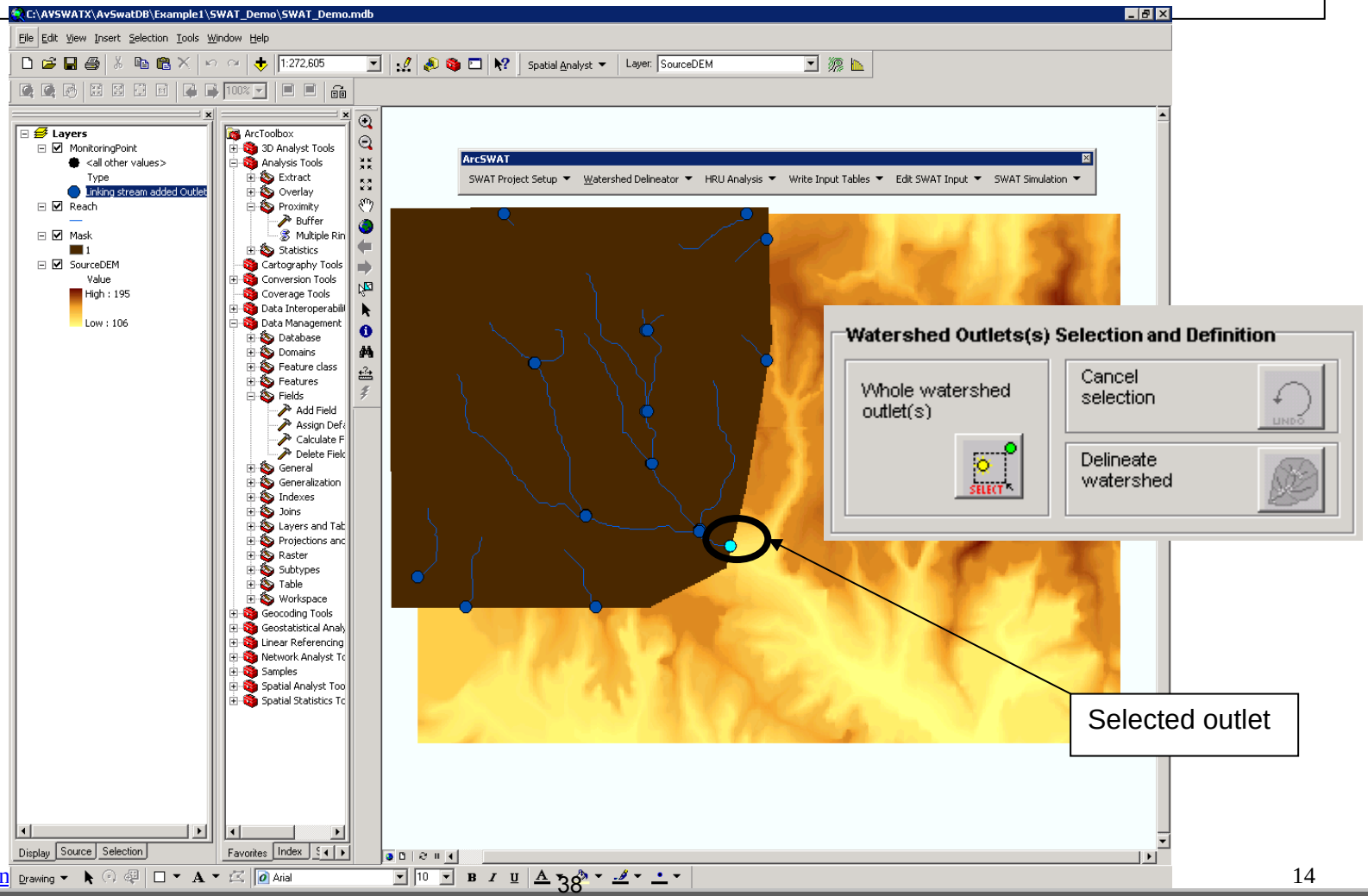


Figure 11 Main watershed outlet selection

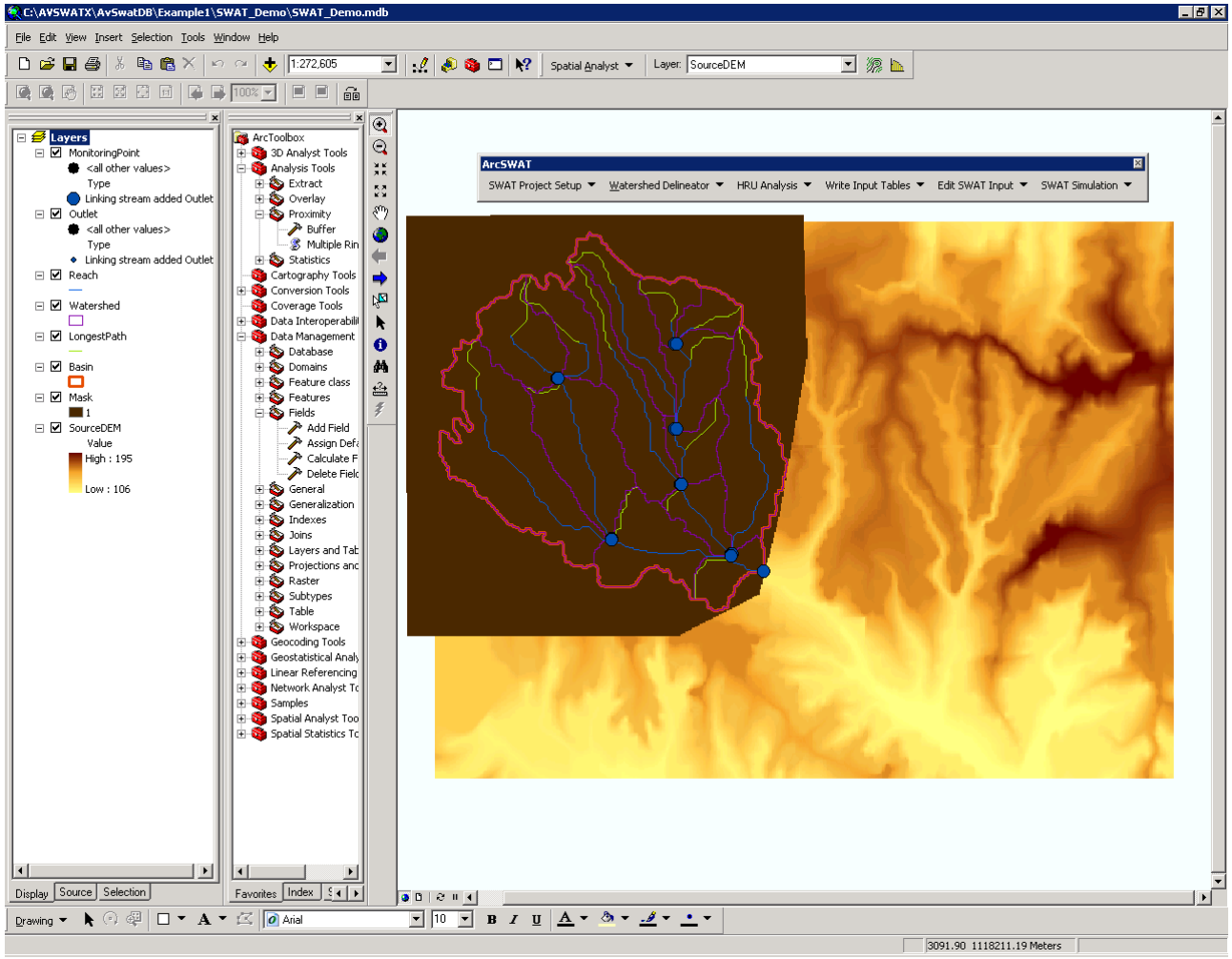


Figure 12 Delineated watershed and subbasins

Step 6: Reservoirs

The user can add or remove reservoirs to refine the delineation process. The procedure is similar to the process of manually adding or removing an outlet**. <u>In this exercise, we will not focus on adding or removing a reservoir.</u>** However the general procedure is given below for reference.

1. To add a reservoir, click on the **ADD** button and with the cross appearing as mouse pointer, click on the subbasin where the reservoir will be added. The reservoir will be placed at the outlet of the subbasin. A prompt box will be displayed asking for verification of the reservoir placement. If the wrong subbasin is listed, click **No** and repeat step 7(1). If the correct subbasin is listed, click **Yes**.
2. To remove a reservoir click on the **REMOVE** button. Draw a square around the reservoir to be removed by holding the left mouse button and moving the mouse. A prompt box will be displayed asking for verification of the reservoir removal. If the wrong subbasin is listed, click **No** and repeat step 7(2). If the correct subbasin is listed, click **Yes**.

Step 7: Exit the Watershed Delineation Dialog

Click **EXIT** in the watershed delineation main dialog

Step 8: View Topographic Report

Open the **Topographic Reports** through click the Watershed Reports Button under the **Watershed Delineator** menu from **Reports** of the project windows. You can view the area and percentage wise distribution of elevation for the entire watershed and each subbasin.

Land use, Soil and Slope Definition

The **Land Use, Soil and Slope Definition** option in the **HRU Analysis** menu allows the user to specify the land use, soil and slope themes that will be used for modeling using SWAT and NPSM. These themes are then used to determine the hydrologic response unit (HRU) distribution in each sub-watershed.

Both NPSM and SWAT require land use data to determine the area of each land category to be simulated within each subbasin. In addition to land use information, SWAT relies on soil data to determine the range of hydrologic characteristics found within each subbasin. **Land Use, Soil and Slope Definition** option guides the user through the process of specifying the data to be used in the simulation and of ensuring that those data are in the appropriate format. In particular, the option allows the user to select land use or soil data that are in either shape or grid format. Shapefiles are automatically converted to grid, the format required by ArcGIS to calculate land use and soil distributions within the subbasins of interest. Select the **Land Use / Soil / Slope Definition** option from the **HRU Analysis** menu. The **Land Use / Soil / Slope Definition** dialog box (Figure 13) will open. The detailed procedures on how to use the functions contained in this dialog were introduced below:

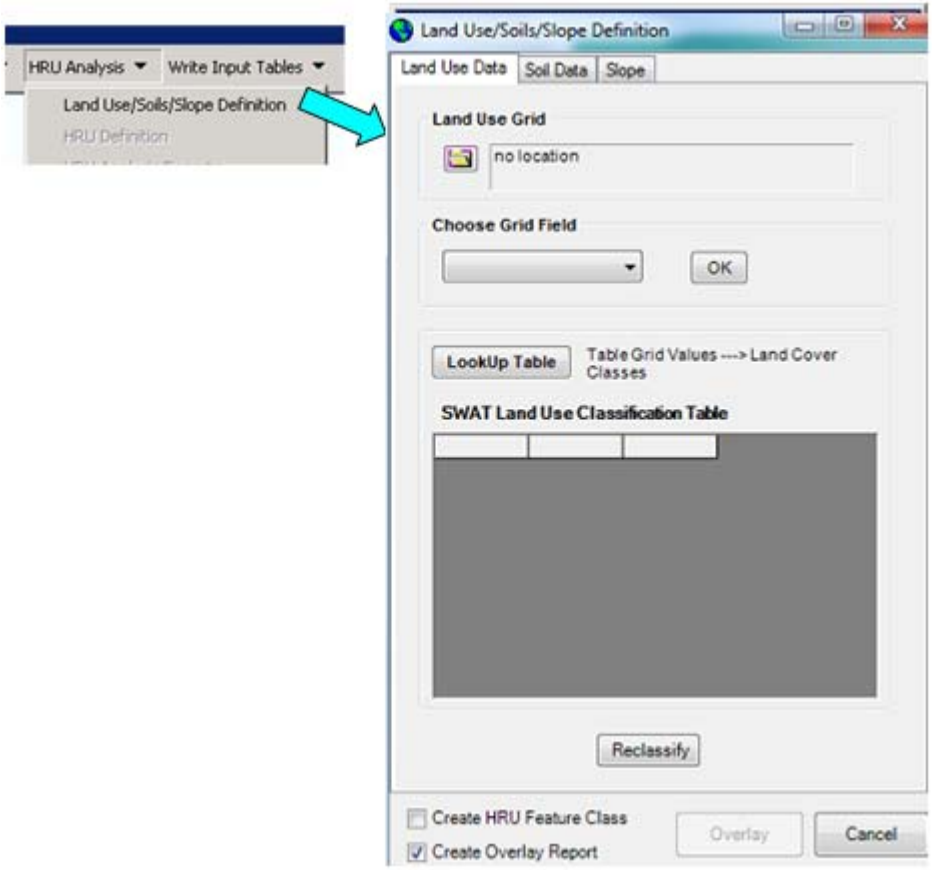


Figure 13 Dialog for Land Use / Soil / Slope Definition

Step 1: Define Land use theme

1. Select the land use data layer by clicking on the open file folder button next to "**Land Use Grid**."
2. A "Set the LandUse Grid" dialog box will appear (Figure 14). You will have the option to "**Select Land use layer(s) from the Map"** or "**Load Land Use dataset(s) from disk"**. Select the **Load Land Use dataset(s) from disk** option and click **Open**. Click **Yes** for the projection information dialog box.
3. Select the **Landuse** grid file in the **work directory** and click **Select**. A message box will indicate the successful loading of landuse theme.

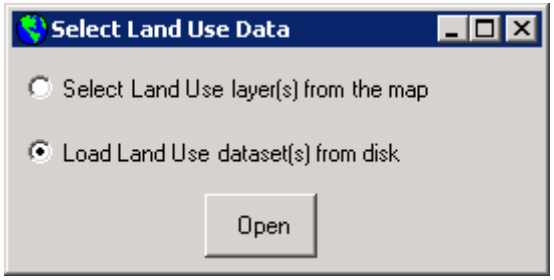
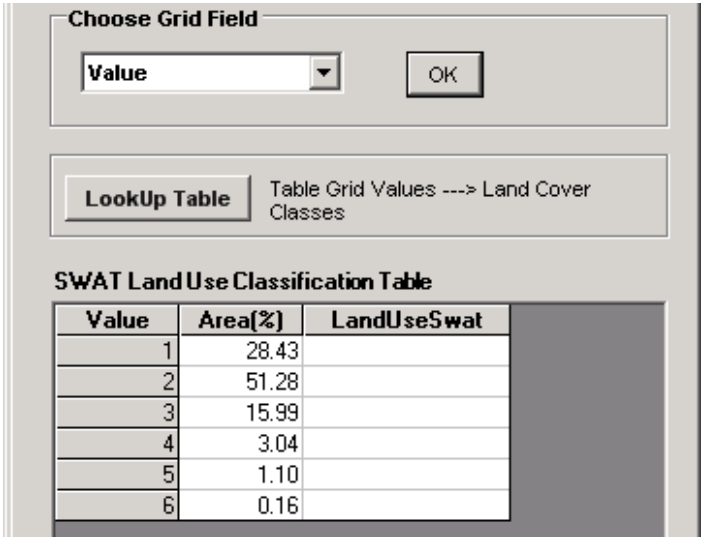


Figure 14 Dialog for options of selecting landuse dat

4. After loading the Landuse file into the map, choose the grid field which will be used as index to define different landuse types. In this example, the "**Value**" field is selected. Click **OK**, then a table titled "**SWAT LandUse Classification Table**" will be created automatically by the interface (Figure 15). The first column contains the unique values in the **Grid Field** chosen above. The second column contains the area of each type of landuse. And the third column contains the landuse names in the SWAT database corresponding to each index value.



Value	Area(%)	LandUseSwat
1	28.43	
2	51.28	
3	15.99	
4	3.04	
5	1.10	
6	0.16	

Figure 18 SWAT LandUse Classification Table

5. In order to fill correct values in the third column, the land use grid codes must be assigned a land cover/plant description. You may import a look-up table or manually assign a land cover/plant code. The interface includes tables that convert the USGS land use/land cover classification codes to SWAT land cover/plant codes. If the land use grid being used is classified by an alternate method, you must create a look-up table or enter the information manually.
6. Select the land use look-up table by clicking on the open "**Look-up Table**" button next to **"Table Grid Values –> Land cover classes**." A "Land Cover Lookup Table" dialog box will appear (Figure 19).
7. When the user has land use data and the corresponding four character land use code, the "**User Table**" option should be selected.
8. Select User defined lookup table in .txt or .dbf format (the ASCII .txt lookup table was shown in(Figure 21), then the SWAT LandUse Classification Table will be populated (Figure 16).
9. Click **Reclassify** button. Then Landuse map will be reclassified according the Lookup table. The reclassified landuse map is shown in Figure 18.

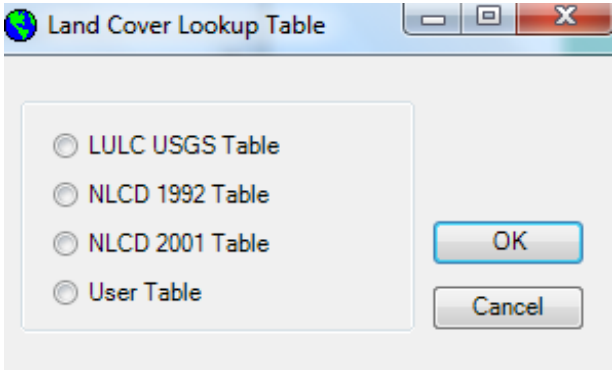


Figure 19 Land cover lookup table options

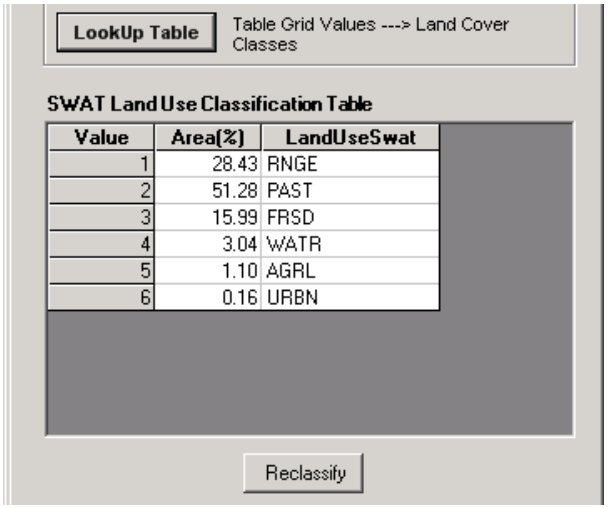


Figure 16 Populated SWAT LandUse Classification Table

Accessing “User Table” from the Landuse and soil definition dialog box:

- The user defined table has to be created in the format as shown in figure below:

ASCII (.txt) Table Format

An example land use look up file is:

```
"Value","Landuse"
1,RNGE
2,PAST
3,FRSD
4,WATR
5,AGRL
6,URBN
```

Figure 17 ASCII (.txt) table format of lookup table

Note:

1. To manually create a look-up table, double click on the “LandUseSwat” field next to the first category number in the dialog. A dialog box will appear listing the two database files from which a SWAT land type may be selected: Land Cover/Plant and Urban. Select the desired database file by clicking on it. Click **O**K. A dialog box will appear listing the available SWAT land cover codes or the available SWAT urban land type codes. Select the desired code from the list and click ok. Repeat this procedure for all the values in the grid.
2. If you do not find the desired land cover in the database, you will have to add the land cover class to the database too.

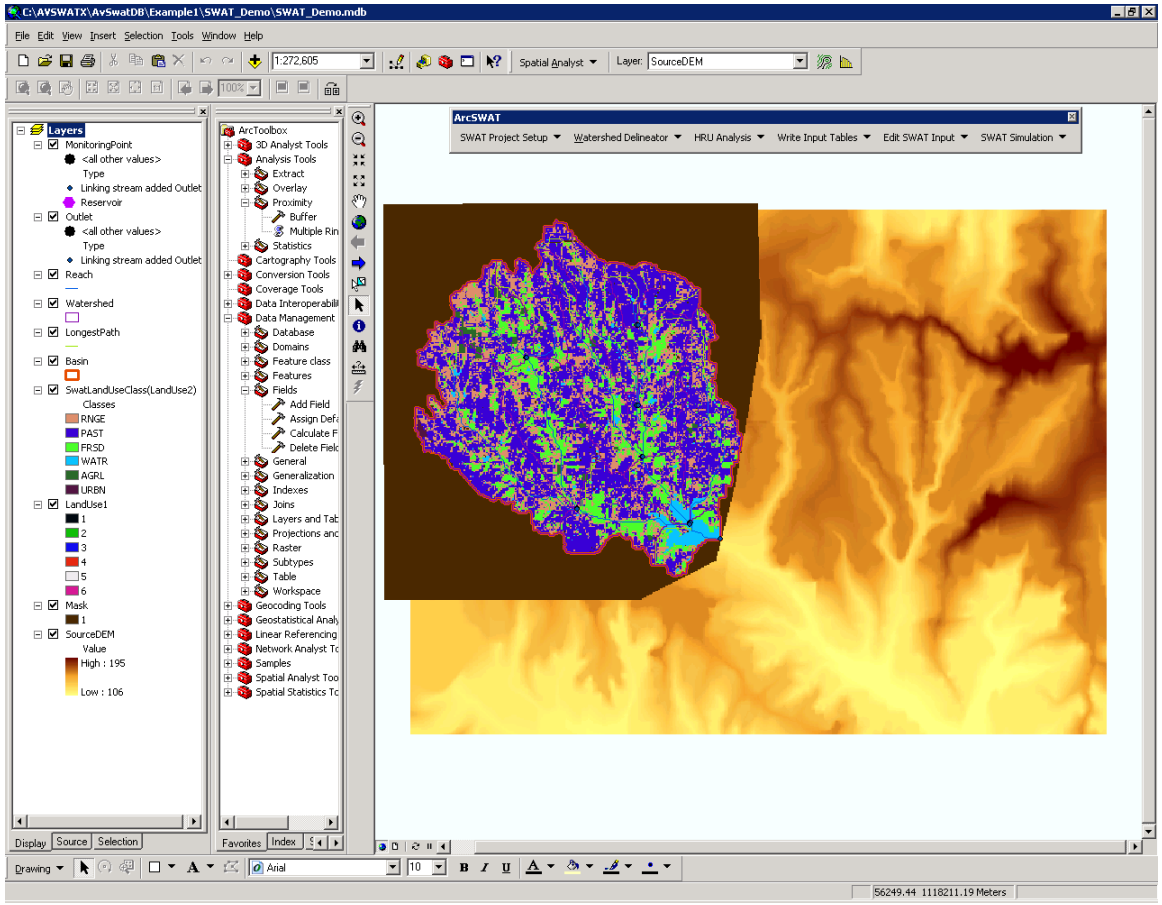


Figure 18 Reclassified land use grid

Step 2: Specify soils theme

1. Select the soils data layer by clicking on the open file folder button under "**Soil Grid**" in the "**Soil Data**" tab (Figure 19).
2. A "Select Soils Data" dialog box appears. You have the option to **Select Soil layer(s) from the Map** or **Load Soils dataset(s) from disk or Load ArcSWAT US STATSGO from disk**. Select the Soil map from the disk and load it to the map. A message box will indicate the successful loading of the soil grid theme.
3. After loading the **Soil** file into the map, choose the field which will be used as the index to define different soil types. In this example, the "**Value**" field is selected. Click **OK**, then a table titled "**SWAT Soil Classification Table**" will be created automatically by the interface. The first column contains the unique values in the **Grid Field** chosen above. The second column contains the area of each soil type. And the third column contains the soil names in the SWAT database corresponding to each index value, which need to be filled through a Lookup table.

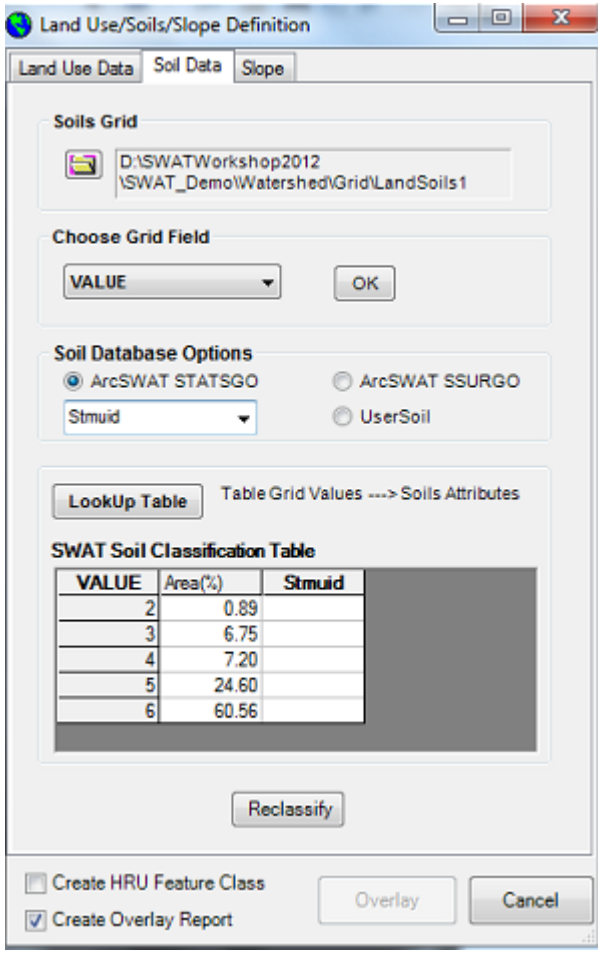


Figure 19 Interface for setting the soil data

The soil map grid must be linked to the U.S. soils database (provided with the interface) or to the User Soils (customized) database. Under "Options," click the button beside the method used to link the soils map grids to the soils data. There are five options available:

- **Stmuid**: State STATSGO polygon number, dominant soil phase
- **S5id**: Soils5ID number for USDA soil series data

- **Name**: Name of soil in User Soils database
- **Stmuid + Seqn**: State STATSGO polygon number and sequence number of soil phase
- **Name + Stmuid**: State STATSGO polygon number and soil series name

4. Select **Stmuid,** then load look up values for the soil grid file and click the **Reclassify** button for soils grid. The reclassified soils grid (Figure 20) is shown in the map.

Note:

- SSURGO soil data can also be used with SWAT. SWAT – SSURGO processing tool is available in http://lcluc.tamu.edu/ssurgo/ .

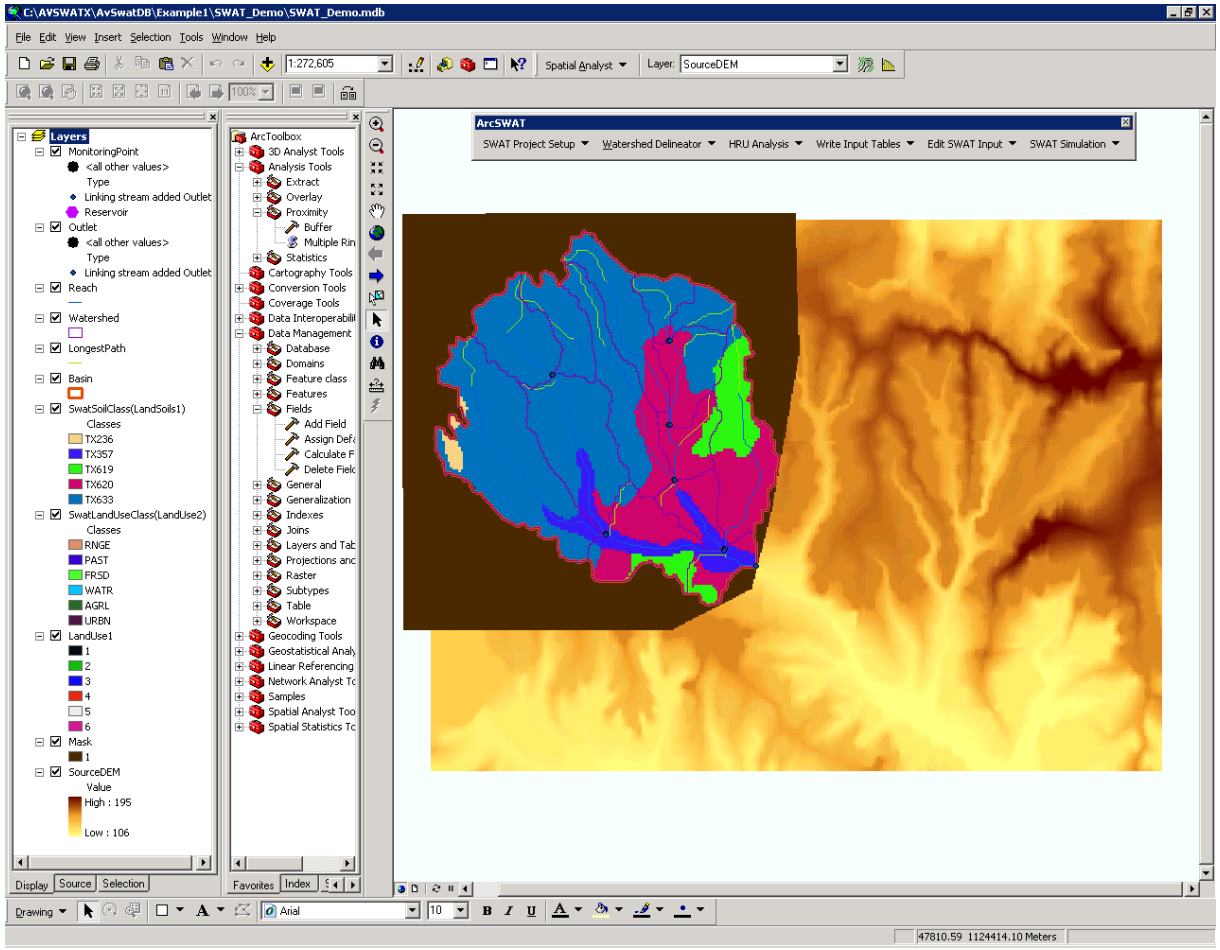


Figure 20 Soils grid theme reclassified by State MUID class

Note:

1. You can manually reclass the soils grid using a procedure similar to the manual reclassification of land use grid.
2. User defined lookup tables in database or text format can also added by click on the "OPEN FOLDER"

Step 3: Specify slope theme

Slope is an important factor that determines the water, sediment and nutrients movement. In this new version interface, a new function is added to take slope into account to delineate HRU. The general procedures for defining a slope theme will be introduced below.

1. Click the "**Slope"** tab, then the interface for defining slope theme appear (Figure 21). There are two options for slope discretization: "**Single Slope**" and "**Multiple Slope**" The "**Single Slope**" option denotes that the mean value of slope will be used for for the whole watershed, whilethe "**Multiple Slope**" option will allow slope be classified into several level.

   If the "**Multiple Slope**" option was selected, the user need to define the "**Number of Slope Classes",** and the range (**Lower Limit and Upper Limit**) of each slope class. At last the slope classification results will be stored in the "**SWAT Slope Classification Table**". Click "Reclassify", the classified slope layer will be added to the map (Figure 26).

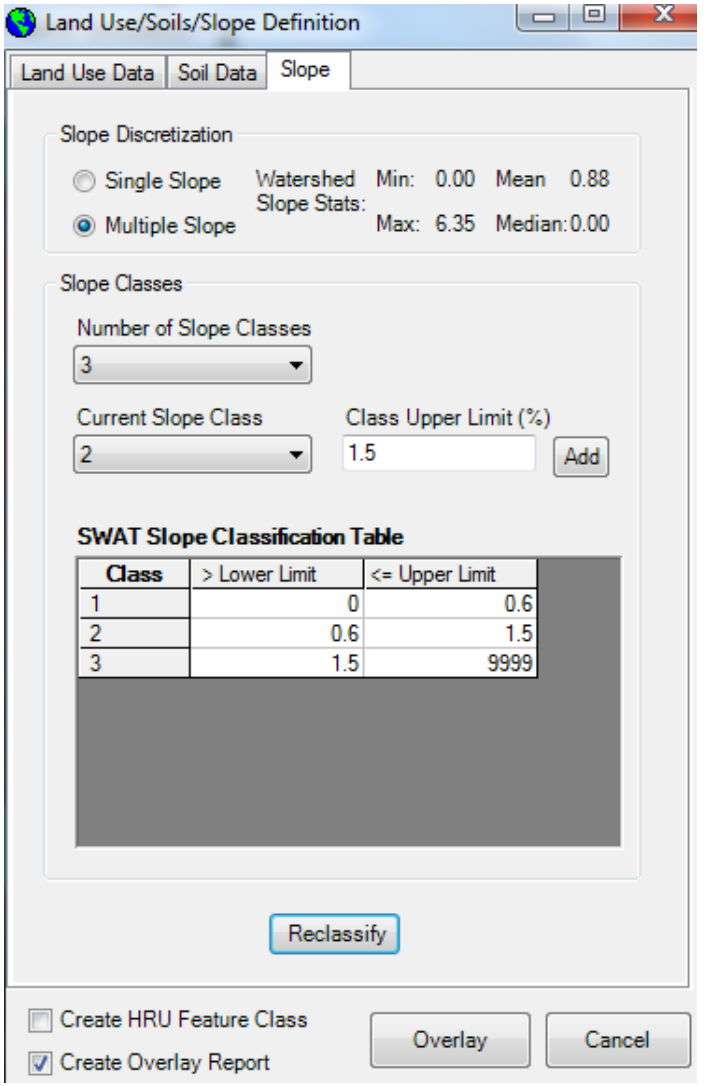


Figure 21 Populated SWAT Slope Classification Table

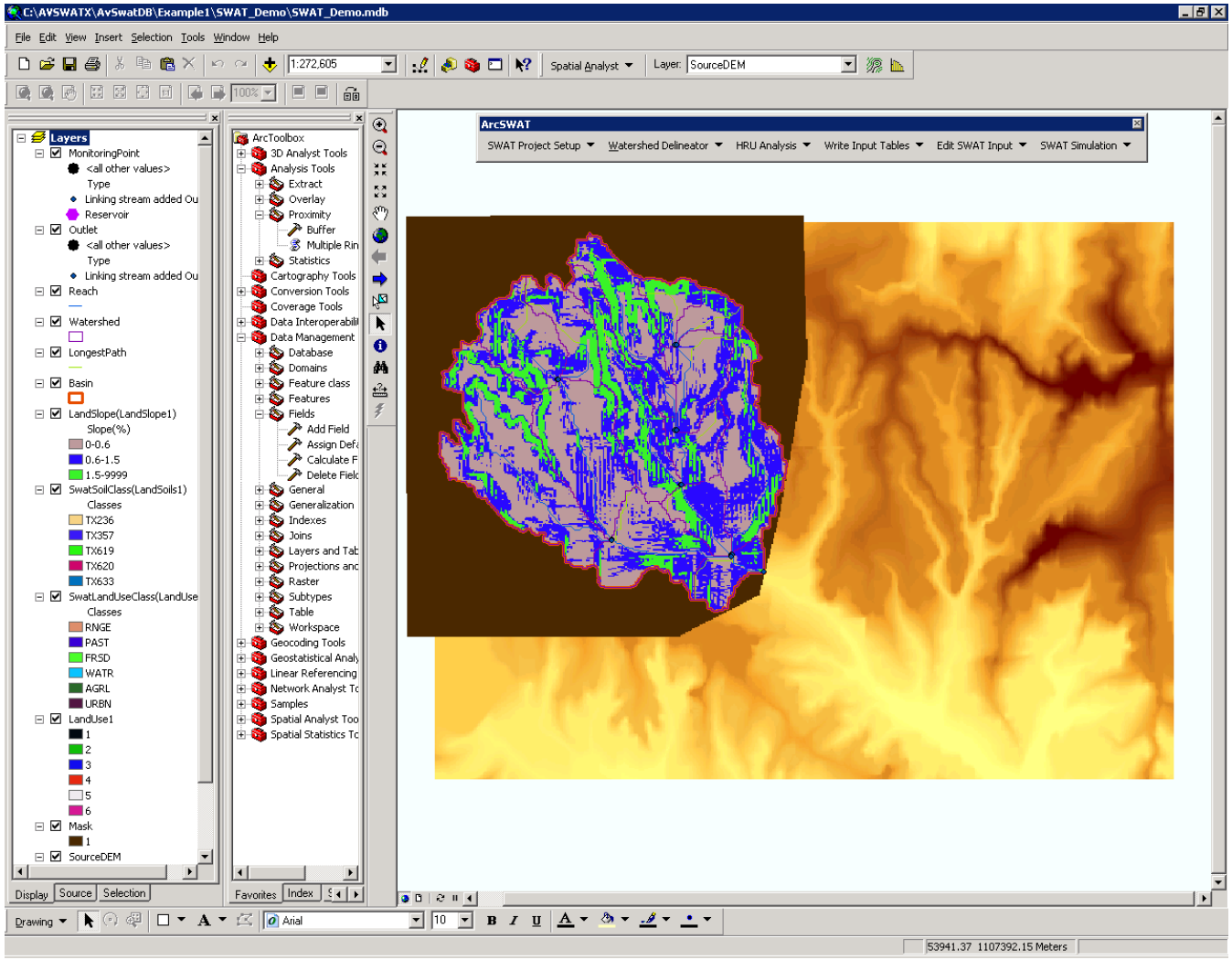


Figure 22 Slope grid theme reclassified by user defined criteria

Step 4: Overlay land use, soil and slope layers

When the land use, soil and slope layers have all been classified, the **OVERLAY** button will be activated. Click this button; all the three grid layers will be overlaid. When the overlay process is completed, an “Info” message box will appear. Click **OK** to proceed the delineation of hydrologic response units (HRUs). Figure 23 shows the units with unique combination of landuse, soil, and slope within each subbasin. This layer will be used later in defining HRU.

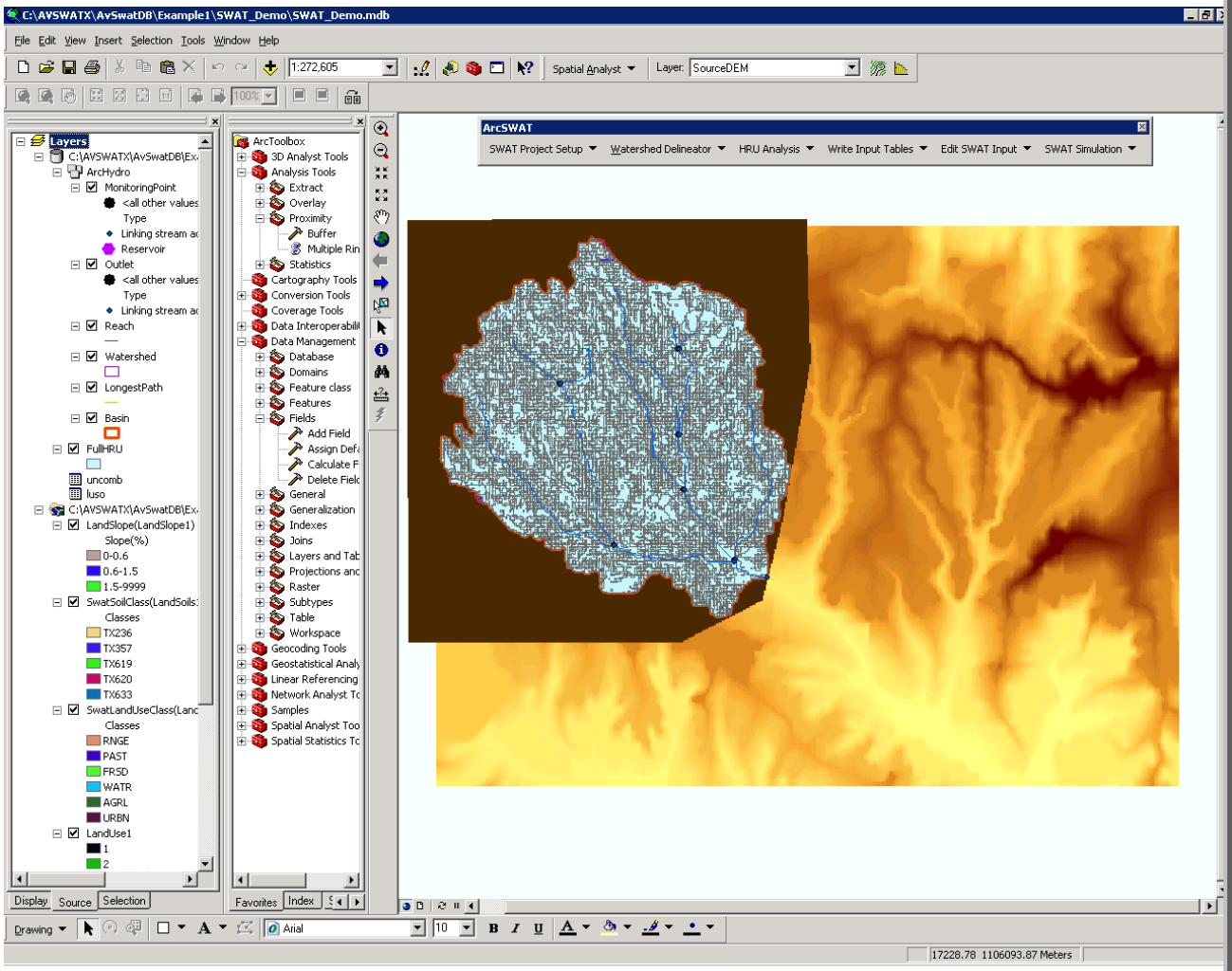


Figure 23 Shape file layer of the units with unique combination of landuse, soil and slope within each subbasin

Step 5: View land use, soil and slope distribution report

View the area and percentage distribution of each land use and soil class within each subbasin by clicking the **HRU Analysis Reports** button under the **HRU analysis** menu

Hydrologic Response Unit Definition

Before executing SWAT, the distribution of hydrologic response units (HRUs) within the watershed must be determined based on the land use, soil and slope layers specified in the previous step. The interface allows the user to specify criteria to be used in determining the HRU distribution. One or more unique land use/soil/slope combination(s) (hydrologic response units or HRUs) can be created for each subbasin.

Subdividing the watershed into areas having unique land use, soil and slope combinations enables the model to reflect differences in evapotranspiration for various crops and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases accuracy and gives a much better physical description of the water balance.

Click the **HRU Definition** button under the **HRU Analysis** menu. This will open a "**HRU Definition**" dialog (Figure 24). The user has two options in determining the HRU distribution: assign a single HRU to each subbasin or assign multiple HRUs to each subbasin. If a single HRU per subbasin is selected, the HRU is determined by the dominant land use/soil/slope combination within each subbasin. If multiple HRUs are selected, the user may specify the several criteria for the land use, soil and slope data that will be used to determine the number and type of HRUs in each subbasin. The procedures on how to use this tool are introduced below:

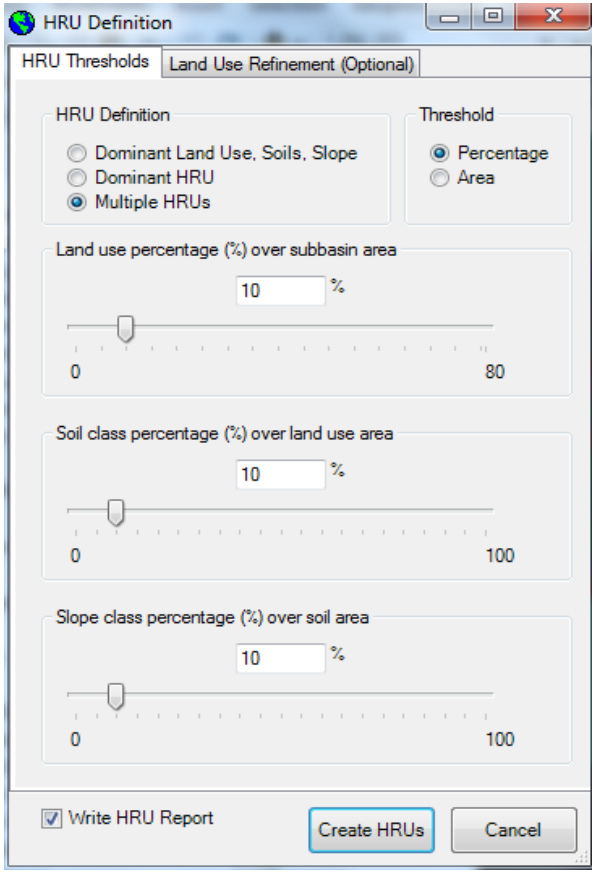


Figure 24 HRU definition dialog

Step 1: Hydrologic Response Unit Definition

1. Select the **Multiple Hydrologic Response Units** option. Modify the threshold land use/soil/slope area percentage (%) over subbasin area to define how detailed the watershed will be represented. Select the desired threshold values for soil, land use and slope (for example 10% for land use/soil/slope)**.**
2. Now you can click the "**Create HRUs**" button to delineate HRU distribution. Also you can go to the Land Use Refinement tap to specify more detailed criteria. There are two ways to refine the definition of HRU. The first one is to split one land use type into two or several sub land use types. For example the AGRL land use type can be split into two sub types: AGRL (50%) and AGRR (50%). The other option is to set one land use type exempt, which mean that this type of land use will exempt of the area threshold value set in previous steps. In this example, the settings of these two functions are shown in Figure 25.
3. After creating HRUs, the distribution report for the HRUs can open through clicking the **HRU Analysis Reports** button under the **HRU Analysis** menu.
4. If the distribution is not satisfactory, repeat the preceding steps, altering the land use and soil sensitivities, until a satisfactory distribution is obtained.

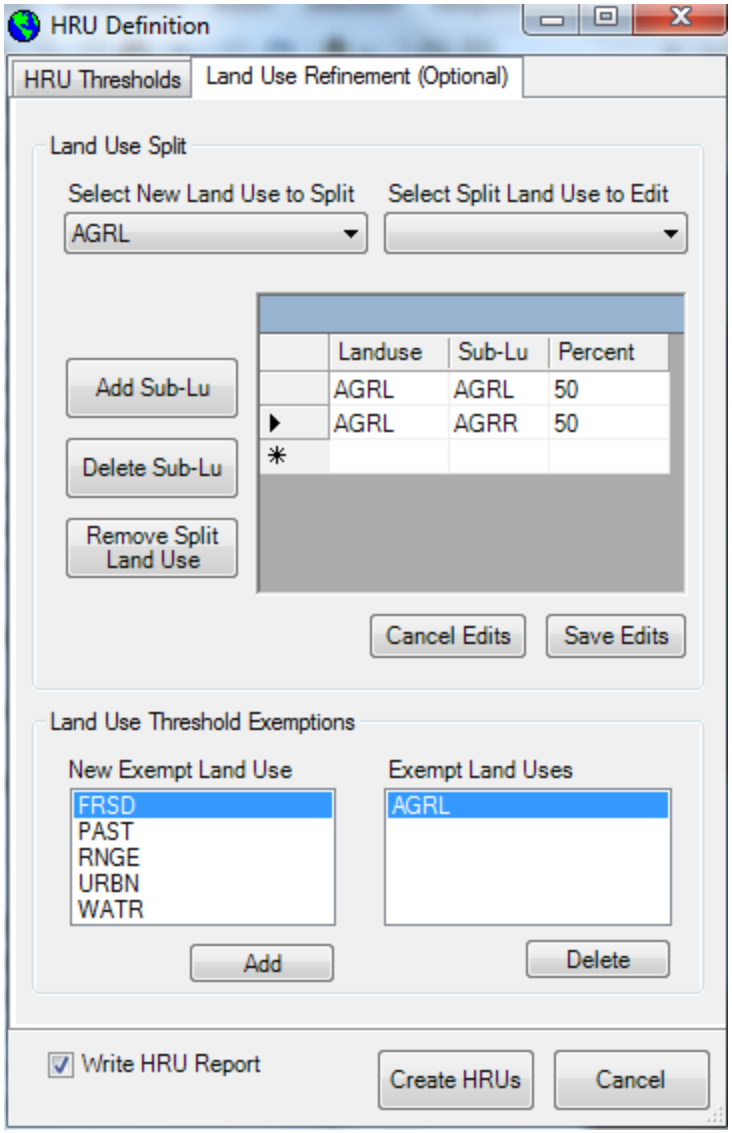


Figure 26 HRU definition dialog, land use refinement

Note for HRU distribution

- Selecting Multiple Hydrologic response units option allows us to eliminate minor land uses in each subbasin.
- For example, if we set the threshold for Landuse (%) over subbasin area to 15% landuses that occupy less that 15% of subbasin area would be eliminated and the HRU will be created for landuses that occupy greater than 15% of the subbasin area.
- The same holds for Soil and slope layer.

Soil and Water Assessment Tool (SWAT)

The following are the key procedures necessary for modeling using SWAT.

- Create SWAT project
- Delineate the designated watershed for modeling
- Define land use/soil/slope data grids
- Determine the distribution of HRUs based on the land use and soil data
- Define rainfall, temperature and other weather data
- Write the SWAT input files- requires access to data on soil, weather, land cover, plant growth, fertilizer and pesticide use, tillage, and urban activities.
- Edit the input files – if necessary
- Setup and run SWAT – requires information on simulation period, PET estimation method and other options
- View SWAT Output

Now we have completed the first three procedures. In this tutorial we will concentrate on preparing the rest of the input data for SWAT, running the model, and viewing the output from the model.

Note

- Spatial analyst is the main tool that will be used in SWAT. Without this, SWAT simply can't be used.
- General info about SWAT: All SWAT input and output are in Metric units (MKS)

Write Input Tables for SWAT

This menu contains functions to build database files that include information needed to generate default input for the SWAT model. The commands on the menu need to be implemented only once for a project. However, if the user modifies the HRU distribution after building the input database files, these commands must be reprocessed again.

Step 1: Define Weather data

1. Select the **Weather Stations** button under the **Write Input Tables** menu. A "Weather Data Definition" dialog is opened (Figure 27). This dialog will allow the user to define the input data for rainfall, temperature and other weather data. For weather data, you have the option of simulating the data in the model or to read from data tables. If no observed weather data is available, then information can be simulated using a weather generator based on the data from 1041 weather stations around the US or combination of WBAN (Weather Bureau Army Navy) and Cooperative stations for four 30-year periods stored in a database or custom weather data can be input through a database table. The weather generator data must be defined before you can continue to define the other data, like precipitation and temperature.

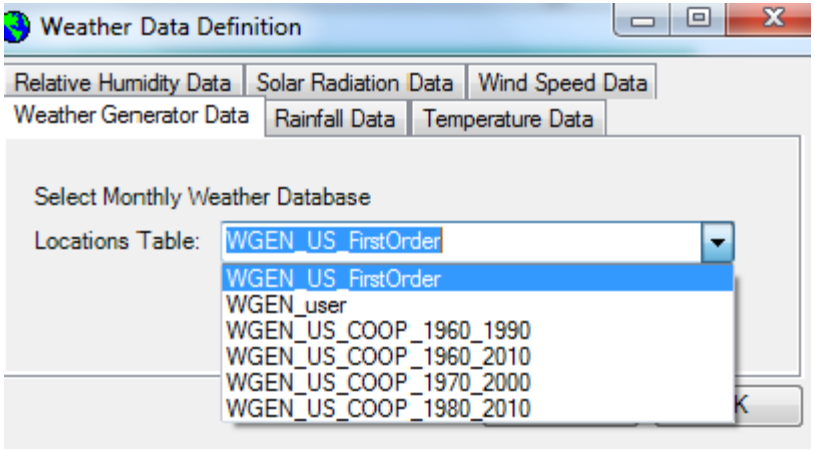


Figure 27 Weather Data definition dialog

2. Select the "WGEN_US_FirstOrder" option for Weather Generator Data to add the weather simulation database automatically.
3. Under the "Rainfall data" tab, select the "Raingages" option for rainfall data. Browse to the **Work Directory** and choose the file **pcpfork.txt** and click **Add.**

4. Under the “Temperature data” tab, select the “Climate Stations” radio button option for temperature data. Browse to the **Work Directory** and choose the file **tmpfork.txt** and click **Add.**

5. After selecting the rainfall, temperature and weather generator data, click **OK** to generate the SWAT weather input data files. The locations of weather generator, rainfall and temperature gages will be displayed in the map view (Figure 28).
6. A message box will indicate successful generation of SWAT weather input database.

At this point you have the option to generate all the input data files using the **WRITE ALL** option under the **INPUT** menu or generate each input file separately. The input files needed are:

- Watershed Configuration file (.fig)
- Soil data (.sol)
- Weather generator data (.wgn)
- General HRU data (.sub)
- Soil chemical input (.chm)
- Stream water quality input (.swq)
- Pond input (.pnd)
- Management Input (.mgt)
- Main channel data (.rte)
- Ground water data (.gw)
- Water use data (.wus)

Note

In the new version of ArcSWAT (2012), the user can modify the weather data files later without rewriting the input tables. In the previous version (2009) the input files needed to be rewritten after weather data modification and the model parameterizations set to the default values.

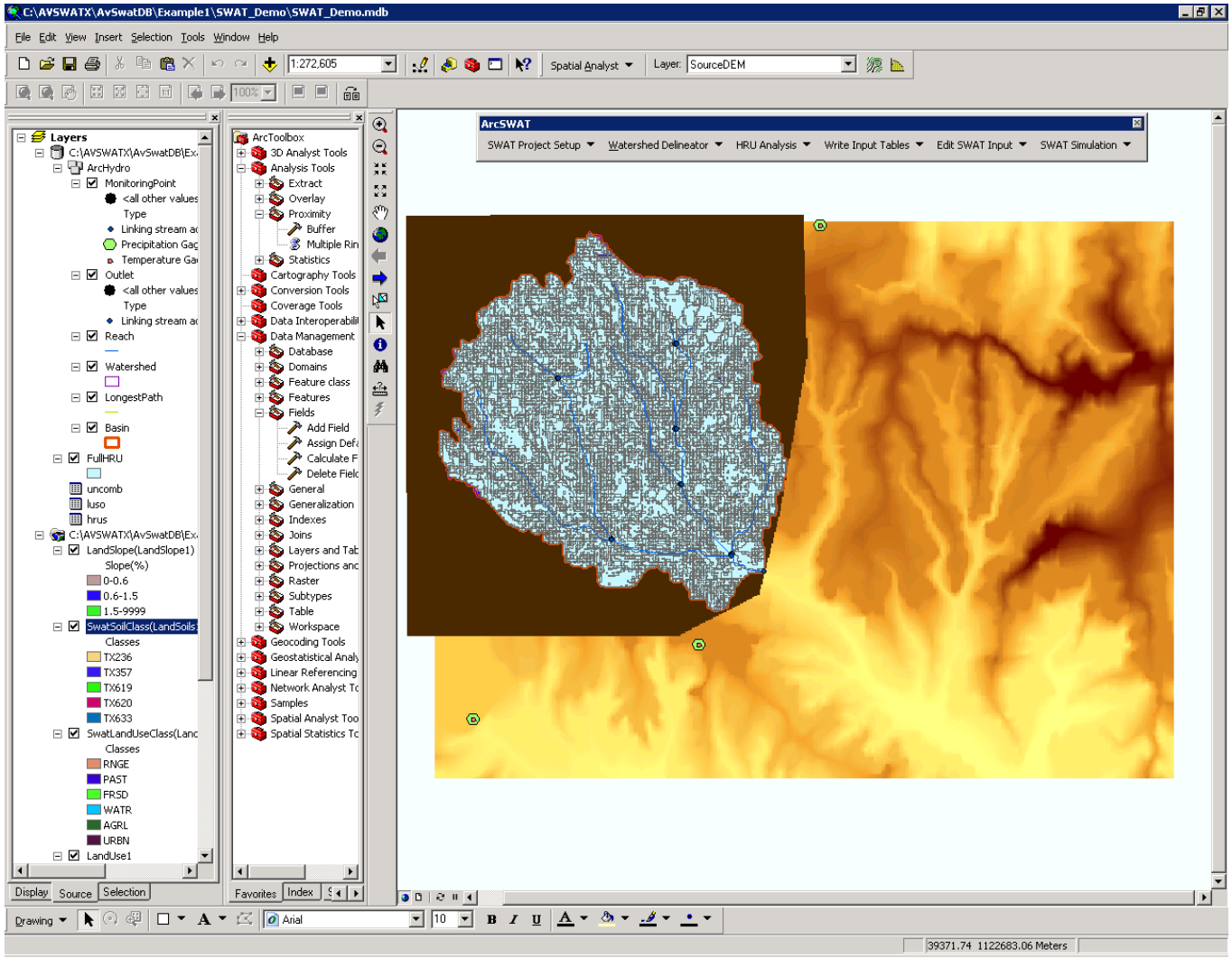


Figure 28 Location of weather stations

Step 2: Write All (Figure 29)

1. Select the **Write SWAT Database Tables** option under the **Write Input Tables** menu.
2. A "Current Status of Input Data" dialog appears. This window shows the list of input files to be generated and the status of input file generation. Click **Select All** and **Create Tables**.
3. For the management input file generation a message prompt verifies if the US weather database is sufficient to estimate the Plant Heat Units. Click **Yes** if the study area is within US.
4. A message box indicates the successful completion of input files generation.

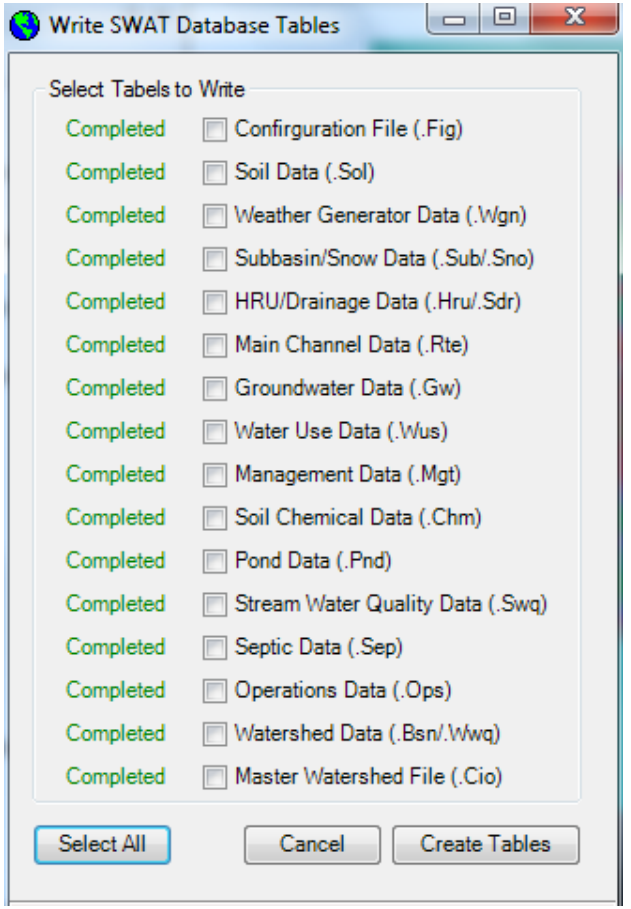


Figure 29 Write all input files status dialog

Edit SWAT Input

The commands listed under the **Edit SWAT Input** menu bring up dialog boxes that allow you to alter default SWAT input data. The **Edit SWAT Input** menu can be used to make input modifications during the model calibration process. In this exercise **you are not required** to edit any input information.

However a general procedure is given to familiarize you with the SWAT input files and editing capabilities in ArcSWAT.

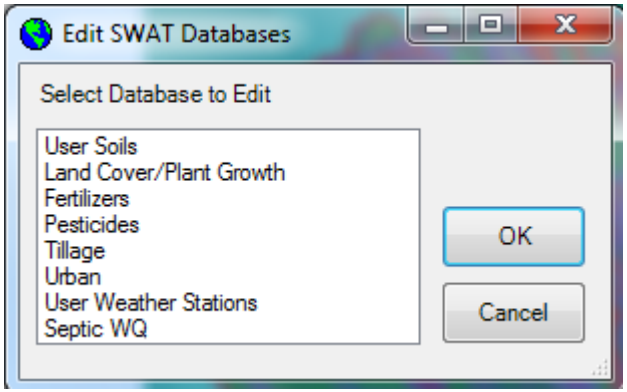


Figure 30 List of SWAT databases

Step 1: Editing Databases

1. Select the **Edit Databases** button under the **Edit SWAT Input** menu. You will be given a list of options to choose the databases to be edited (Figure 30).

Step 1-1: Edit Soils database (Figure 31)

1. Select **User Soils** option, and click **OK**.
2. "**User Soils Edit**" dialog box with a list of abbreviated soil names appears. Click on a soil name to edit the entire soil profile data or individual soil layer information.
3. You can also add new soil into the database by clicking on the **Add New** button in the bottom of the "Add and Edit User Soil" dialog box.
4. Click **EXIT** after completion of editing the database. A prompt box will give you the option to save or ignore the changes made to soils database.

By using a procedure similar to editing soils database, the **Database** option under the **Edit Input** menu you can edit or add information to the weather, land cover/plant growth, fertilizer, pesticide, tillage, and urban area databases.

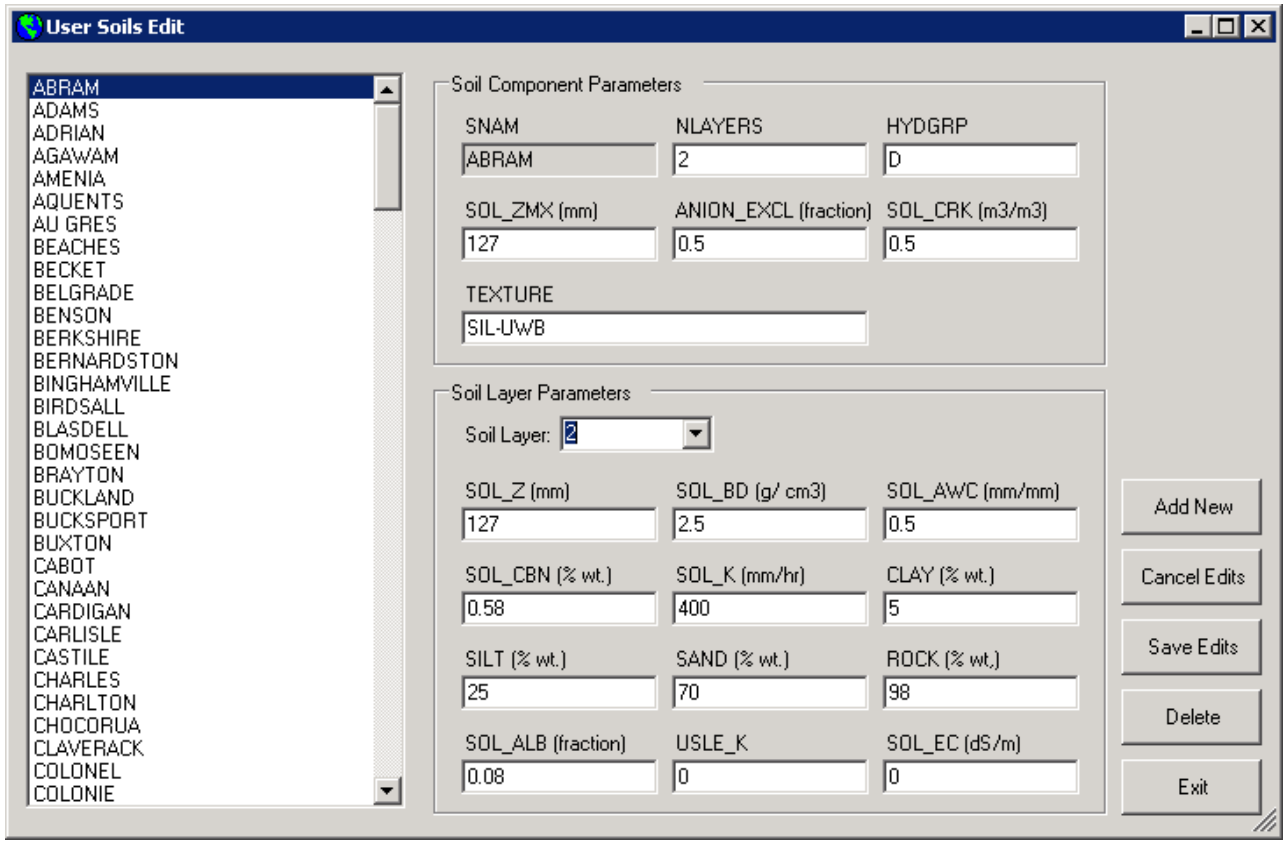


Figure 31 Edit soils database dialog

Note:

- Moving the mouse pointer near an object (text box, radio button etc.,) in any of the edit input dialog box will display a short description of the parameter contained in the object.

Step 2: Edit Point Discharge Inputs

1. Select the **Point Sources Discharges** option under the **Edit SWAT Input** menu. "Edit Point Source Inputs" dialog box (Figure 32) with a list of subbasins containing point discharges will appear.
2. Click on the subbasin number whose point discharge database needs to be edited. A "Point Discharges Data" dialog box appears with the list of attributes of the point data. The dialog box allows the input of point source data in one of four formats: constant daily loadings, average annual loadings, average monthly loadings, and daily loadings.
3. Choose a format by clicking the button next to the format to be used. The default point source data format option is constant daily loadings. If you select this format, you will have the option of either inputting average daily flow (m^3/s), sediment loading (tons), and organic N, organic P, NO_3, mineral P loadings (all in kg), three conservative metals, and 2 categories of bacteria or load PCS data directly. If you select the "Annual Records" option you will be prompted to load the data from disk by clicking on the open folder button or from PCS by clicking on the Load PCS button. If you select the "Monthly Records" or "Daily Records" option you will be prompted to load data from the disk. Click **OK** to complete the editing of point discharges database for a subbasin.

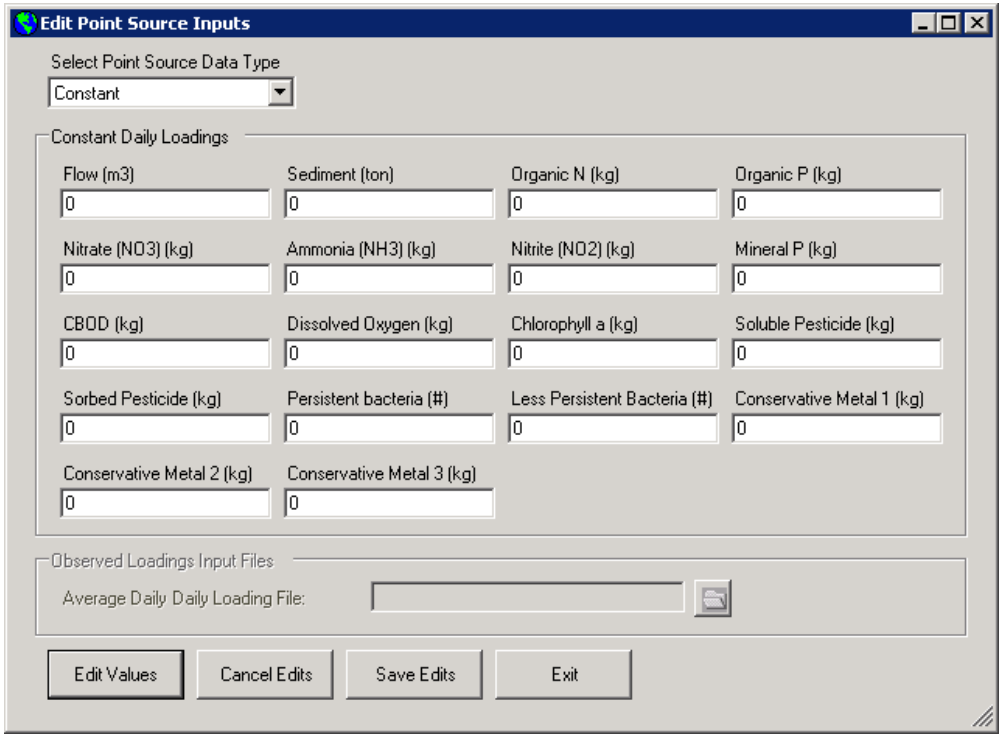


Figure 32 Edit Point Discharge Inputs Dialog

4. If you wish to edit the point sources in another subbasin, select it from the list in the "Edit Point Source Inputs" dialog box. Click **Exit** to complete editing of point discharges database in all subbasins.

Step 3: Edit Inlet Dischargers Input

1. Select the **Inlet Discharges** option under the **Edit Input** menu
2. If there are any inlet dischargers in the project, "Edit Inlet Input" dialog box with a list of subbasins containing inlet dischargers will appear (Figure 33).
3. You will be able to modify the inlet input information using a procedure similar to editing the point dischargers database
4. The dialog box allows the input of inlet discharge data in one of four formats: constant daily loadings, average annual loadings, average monthly loadings, and daily loadings. Choose a format by clicking the button next to the format to be used.
5. The default inlet discharge data format option is constant daily loadings. If you select this format, you will be prompted to input average daily flow (m^3), sediment loading (tons), and organic N, organic P, NO_3 and mineral P loadings.
6. If you choose "Annual Records", "Monthly Records" or "Daily Records" option you will be prompted to load the data from the disk.
7. Click **OK** to complete the editing of inlet discharges for a subbasin.

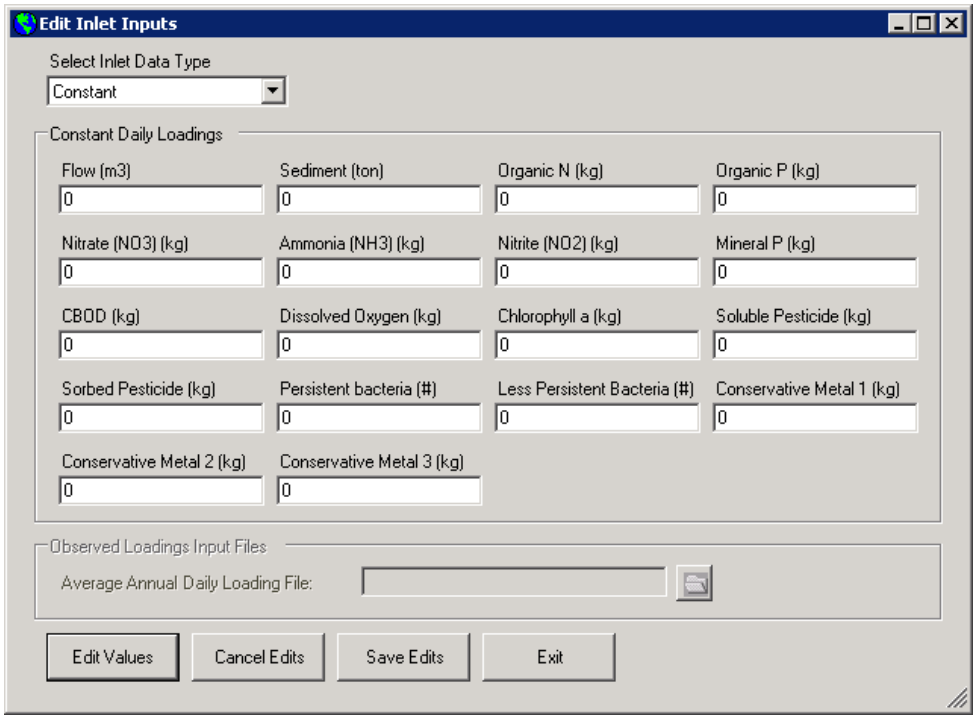


Figure 33 Edit Inlet Discharge Inputs Dialog

8. If you wish to edit the inlets in another subbasin, select it from the list in the "Edit Inlet Discharger Input" dialog box. Click **Exit** to complete editing of inlet dischargers input in all subbasins
9. Since there are no inlet dischargers defined in this tutorial you will get a message "**No Inlet Discharges in the Watershed**"

Step 4: Edit Reservoir Input

1. To edit the reservoirs, on the **Edit Input** menu, select **Reservoirs**. A dialog box will appear with a list of the subbasins containing reservoirs.
2. To edit the reservoirs within a subbasin, click on the number of the subbasin in the "Edit Reservoirs Inputs" dialog box.
3. Since there are no reservoirs defined in this project you will get a message "**No Reservoirs in the Watershed**".

Step 5: Edit Subbasins Data

1. To edit the subbasin input files, select the **Subbasins Data** option under the **Edit Input** menu. "Edit Subbasin Inputs" dialog box will appear (Figure 37).

   This dialog box contains the list of subbasins, land uses, soil types and slope levels within each subbasin and the input files corresponding to each subbasin/land use/soil/slope combination. To select an input file, select the subbasin, land use, soil type and slope that you would like to edit. When you select a subbasin, the combo box of land uses, soil types, and slope levels will be activated in sequence. Specify the subbasin/land use/soil combination of interest by selecting each category in the combo box.

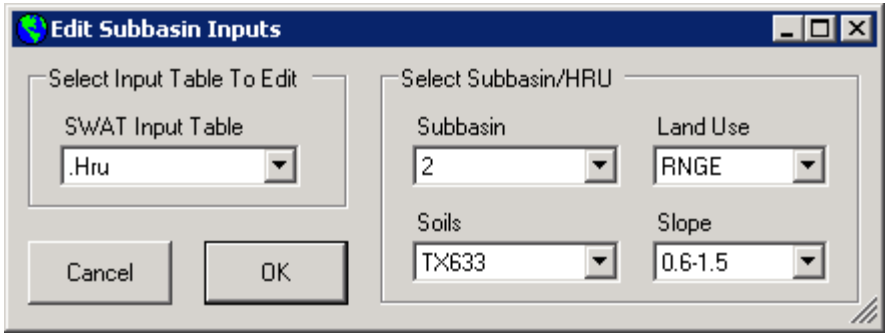


Figure 34 Edit Subbasin Inputs main dialog

2. To edit the soil physical data, click on the .sol extension, and select the subbasin number, landuse type, soil type and slope level. Then the OK button is activated. Click **OK**; a new dialog box will appear (Figure 35). Click the **Edit Values** button; all the boxes are activated and the user can revise the default values.
3. The interface allows the user to save the revision of current .sol file to other .sol files. Three options are available: 1) extend edits to current HRU, which is the default setting, 2) extend edits to all HRUs, or 3) extend edits to selected HRUs. For the third option, the user needs to specify the subbasin number, landuse type, soil type and slope levels for the HRUs that the user wants to apply current .sol file parameters.

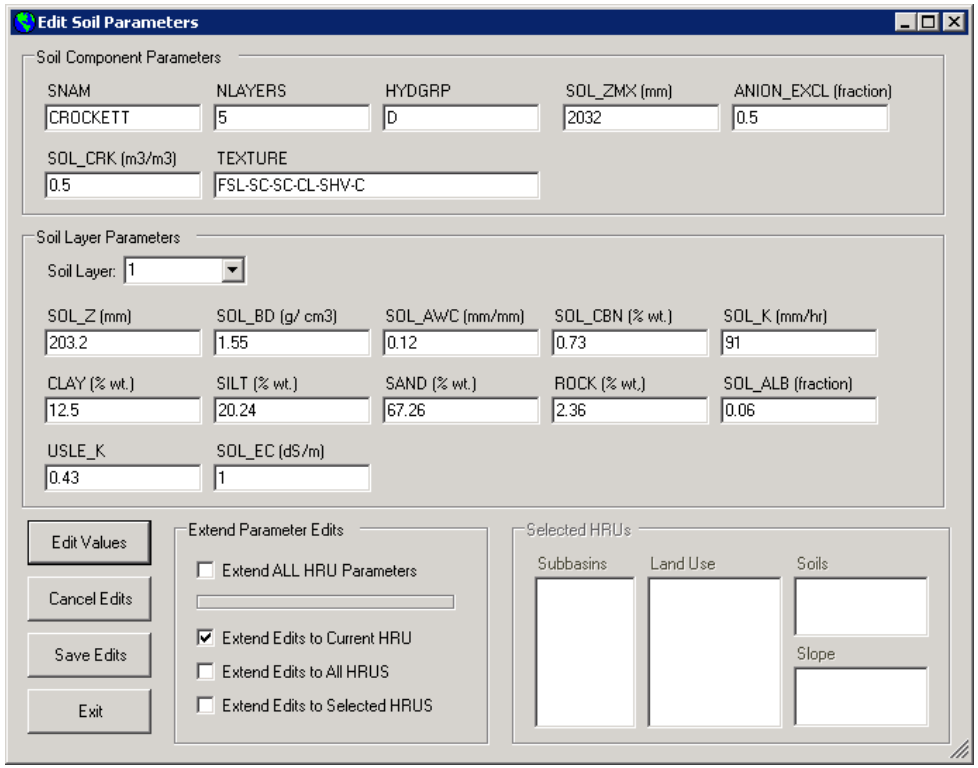


Figure 35 Edit soil input file dialog

4. To edit the weather generator data click on the .wgn extension. For the .wgn file you only need to select the subbasin number, and then the OK button will be activated. Click OK; a new dialog box (Figure 36) will appear which will allow you to modify the data in .wgn file. Similar to .sol file, the interface also allow the user to extend the current edits to other subbasins. The user can select to 1) extend edits to current Subbasin, which is the default setting, 2) extend edits to all Subbasins, or 3) extend edits to selected Subbasins.

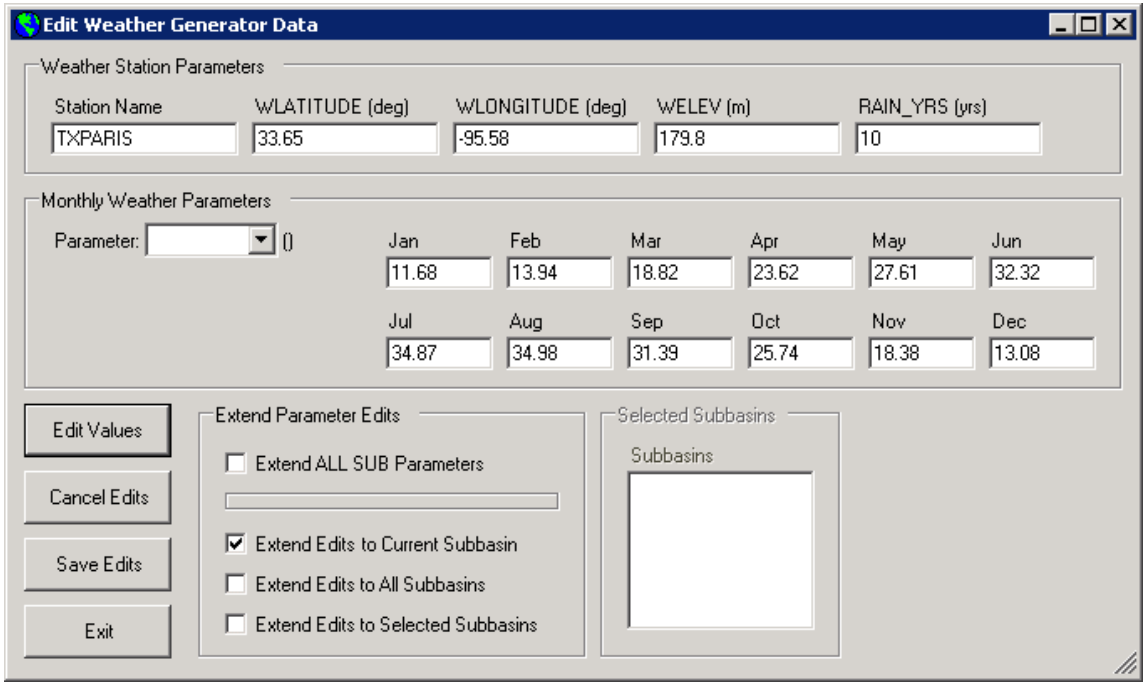


Figure 36 Edit weather generator input file main dialog

5. To edit general subbasin data, click on the .sub extension in the “Select Input File”. Select the subbasin number and click OK, then a new dialog box will appear displaying the existing general subbasin data for the selected subbasin (Figure 37). To modify data, activate all fields by clicking **Edit Values** button. For the elevation band parameters, the user can choose ELEVB, ELEVB_FR and SNOEB in the combo box beside the Elevation Band, and then change the parameter values for each band. In this version (ArcSWAT2012) the user can modify the snow parameters over the elevation bands while in the previous version the snow parameters were constant across the entire watershed. Also, the user can choose RFINC, TMPINC, RADINC, HUMINC in the combo box aside of Weather Adjustment, then change the parameter values for each month. Once you have made all editing changes, click the **OK** button. The interface will save all changes and return you to the “Edit Subbasin Inputs” box. The user can select to 1) extend edits to current Subbasin, which is the default setting, 2) extend edits to all Subbasins, or 3) extend edits to selected Subbasins. For selecting multiple subbasins, hold the Shift key when clicking the preferred subbasin numbers.

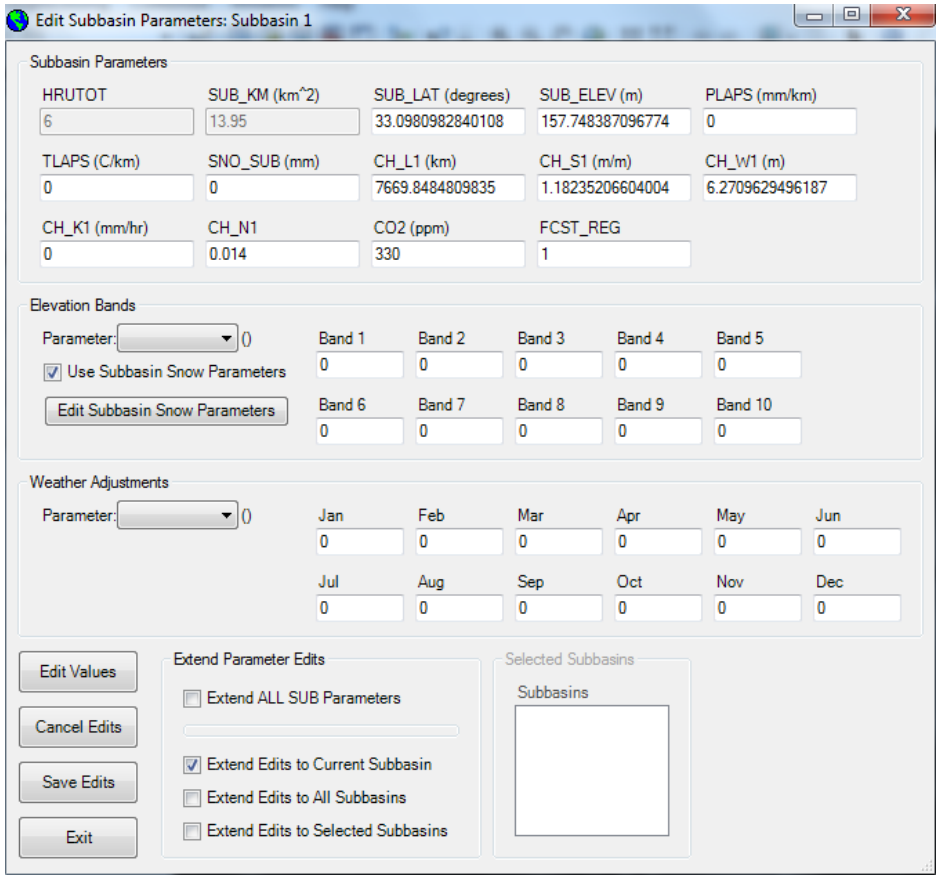


Figure 37 Edit Subbasin (Sub) dialog

6. To edit general HRU data, click on the .hru extension in the “Select Input File” section of the “Edit Subbasin Inputs” dialog box (Figure 38). A new dialog box will appear displaying the existing general HRU data for the selected subbasin. To modify data, activate a field by positioning the cursor over the text box and clicking. Once a cursor appears in the field, make the desired changes. Once you have made all editing changes, click the **OK** button. If you do not want to copy the edited HRU generator data to other data sets, click **No** on the prompt dialog. In this version of ArcSWAT two new modules: Carbon and Urban BMP, and Drainage parameters can be modified in the HRU scale by user.

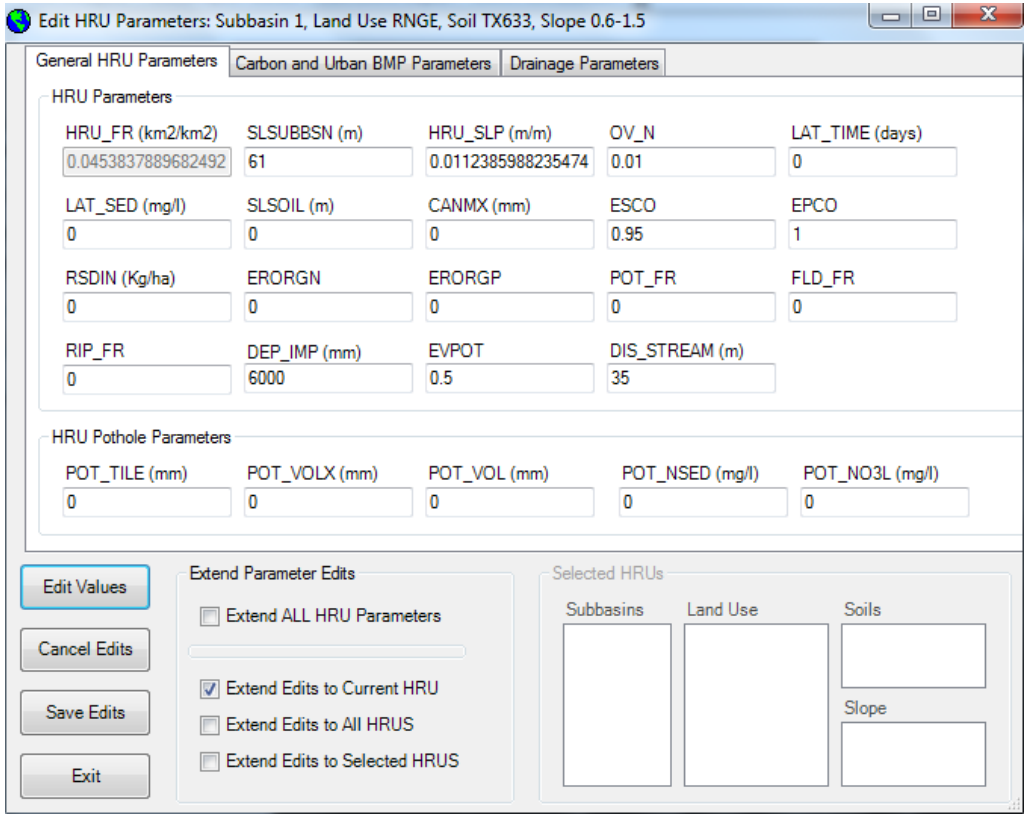


Figure 38 Edit Hydrologic Response Units (HRU) dialog.

7. To edit the main channel input file, click on the .rte in the “Select Input file” section of “Edit Subbasin Inputs” dialog box. A new dialog box (Figure 39) will appear with the existing main channel data for the selected subbasin. Click **Edit Values** button to activate all the textboxes to all user’s modification. Also the user can extend current edits to other basins with three types of options.

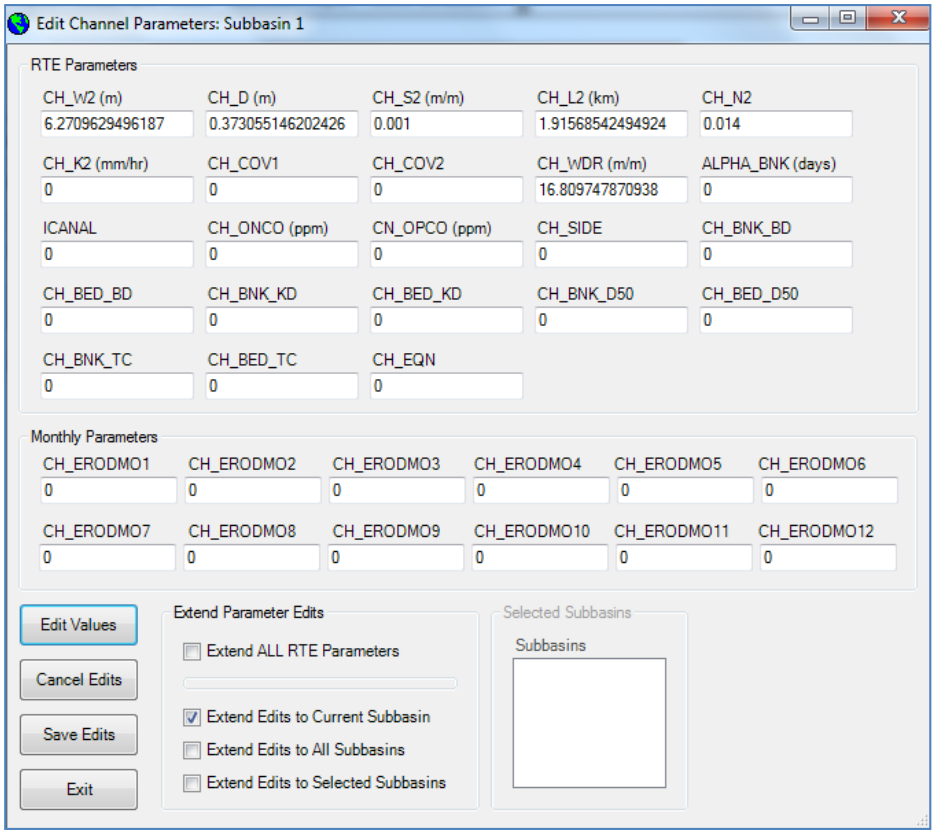


Figure 39 Edit Main channel input data dialog

8. To edit the ground water input file, click on the .gw in the “Select Input file” section of “Edit Subbasin Inputs” dialog box. In the dialog box that opens (Figure 40) with the existing data, make modifications by clicking **Edit Values** button to activating all textboxes. Similarly, after the modification, the user has three options to Save Edits to other HRUs.

9. To edit the consumptive water use input data, click on the .wus in the “Select Input file” section of “Edit Subbasin Inputs” dialog box. In the dialog box (Figure 41) that opens with the existing data, click **Edit Values** button, then the user can modify the data. Also the current edits can be saved to other subbasins.

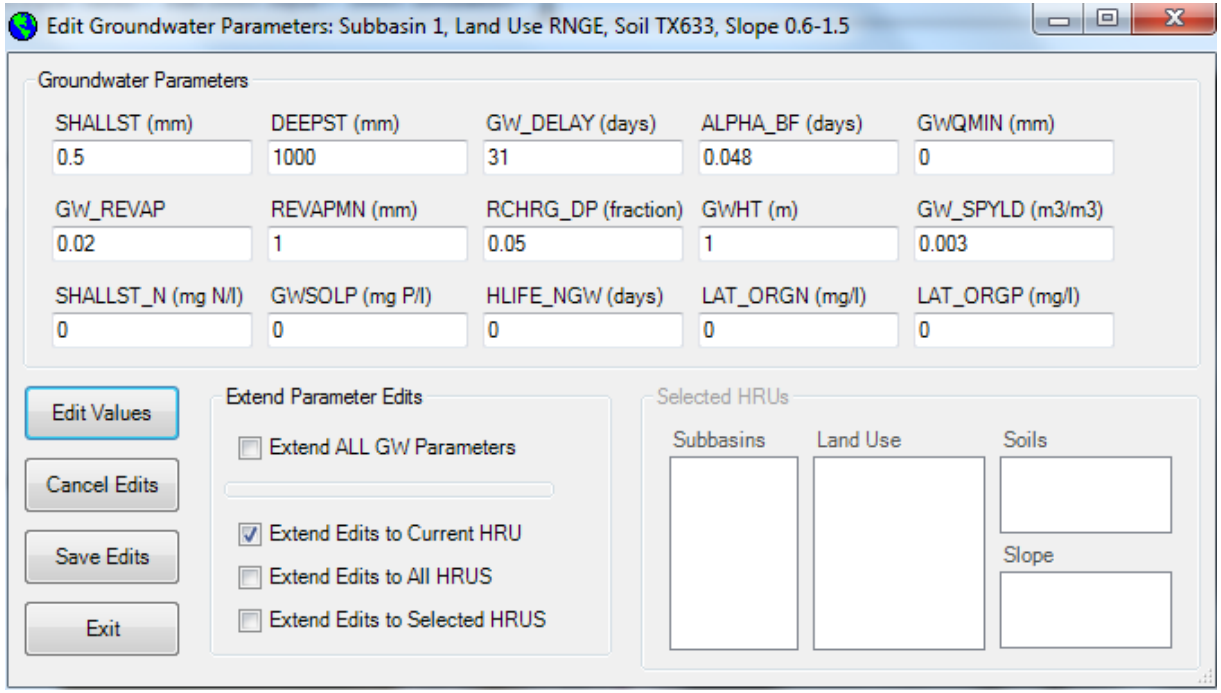


Figure 40 Edit Ground Water input data dialog

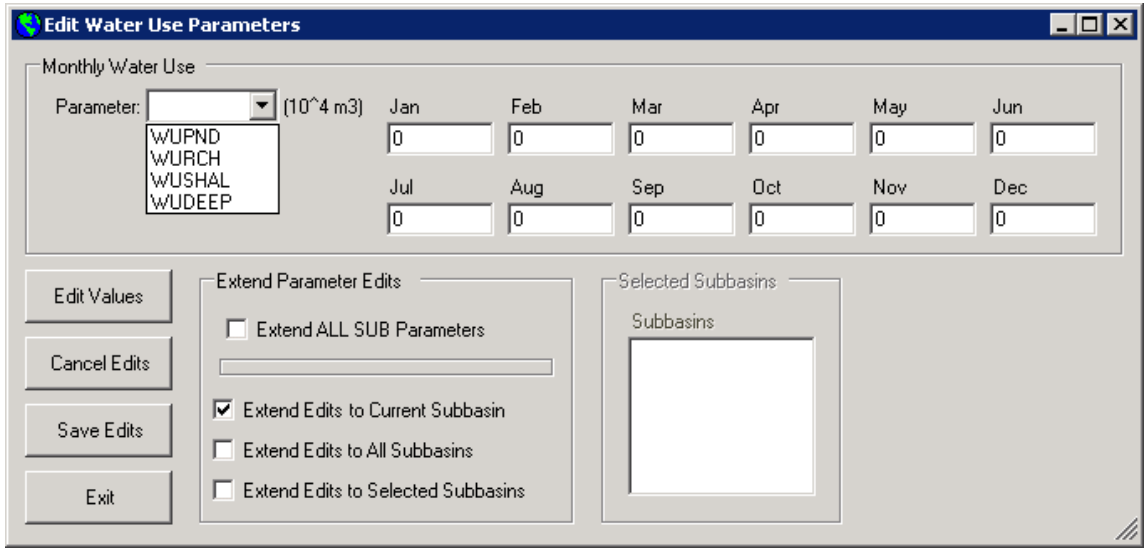


Figure 41 Edit water use input data dialog

10. To edit the management file input data, click on the .mgt in the "Select Input file" section of "Edit Subbasin Inputs" dialog box. A new dialog box (Figure 42) will appear and display the management data editor. This dialog has two tabs: General Parameters and Operations. In the first tab the user can modify the general parameters concerned with Initial Plant Growth, General Management, Urban Management, Irrigation Management, and Tile Darin Management. In the second tab, the user can arrange the detailed management options on the current HRU. The management operations can be scheduled by Date or by Heat Units. The settings of the management operations can also be extended to other HRUs that the user has defined.

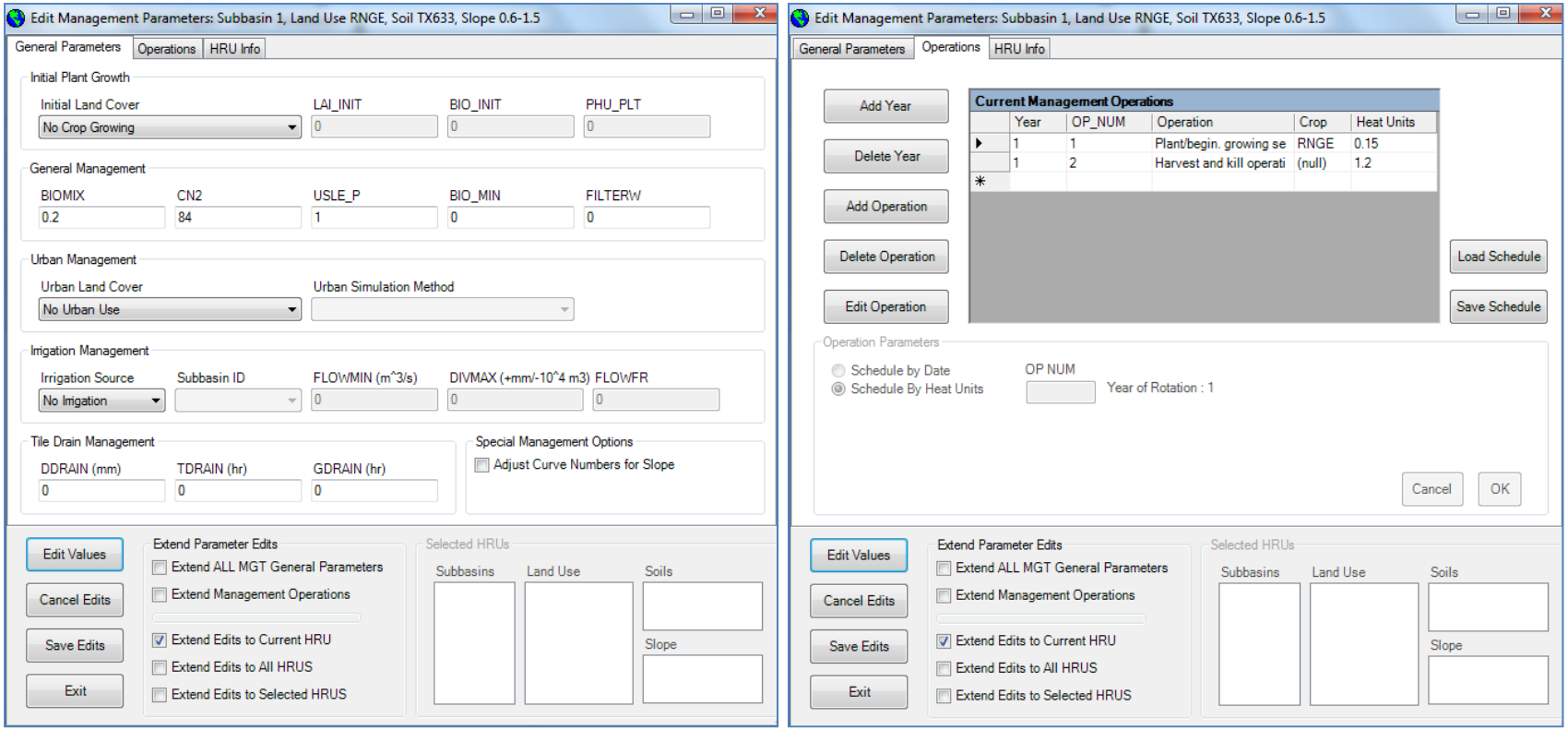


Figure 42 Edit management input file main dialog

11. To edit the soil chemical data click on the .chm in the “Select Input file” section of “Edit Subbasin Inputs” dialog box. A new dialog box (Figure 43) will appear displaying the Soil Chemical data editor. To modify the displayed data, click the **Edit Values** button to activate all the textboxes. After the modification of Soil Chemical Data, the user also can extend the modification to other user specified HRUs.

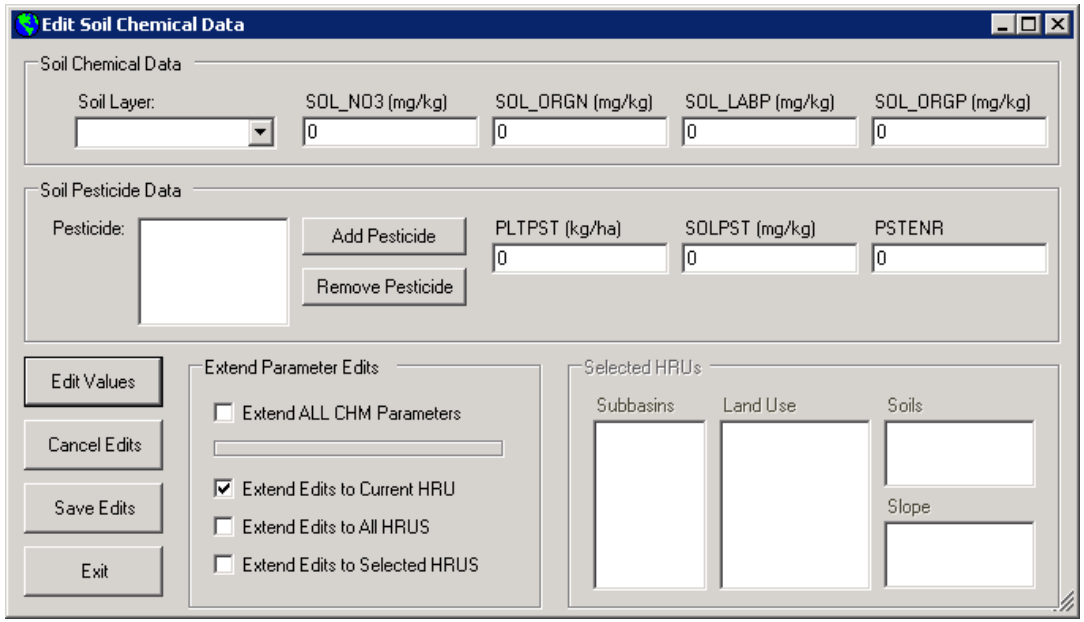


Figure 43 Soil chemical input data editor

12. To edit pond data click on the .pnd in the “Select Input file” section of “Edit Subbasin Inputs” dialog box. A new dialog box (Figure 44) will appear displaying the pond data editor. To modify the displayed data, click the **Edit Values** button to activate all the textboxes. After the modification of pond data, the user also can extend the modification to other user specified Subbasins.

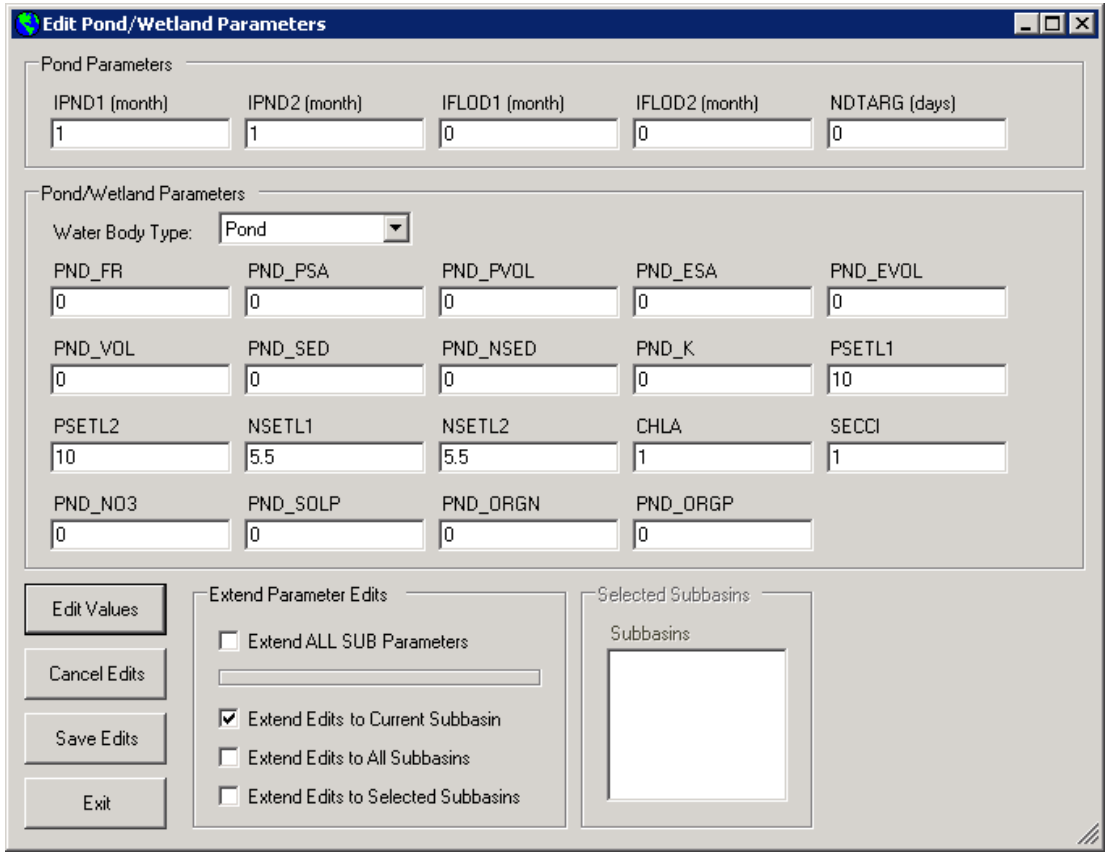


Figure 44 Dialog to edit pond input data file

13. To edit stream water quality input data file click on the .swq in the “Select Input file” section of “Edit Subbasin Inputs” dialog box. A new dialog box (Figure 45) will appear displaying the stream water quality input data editor. To modify the displayed data, click the **Edit Values** button to activate all the textboxes. After the modification of stream water quality input data, the user also can extend the modification to other user specified Subbasins.

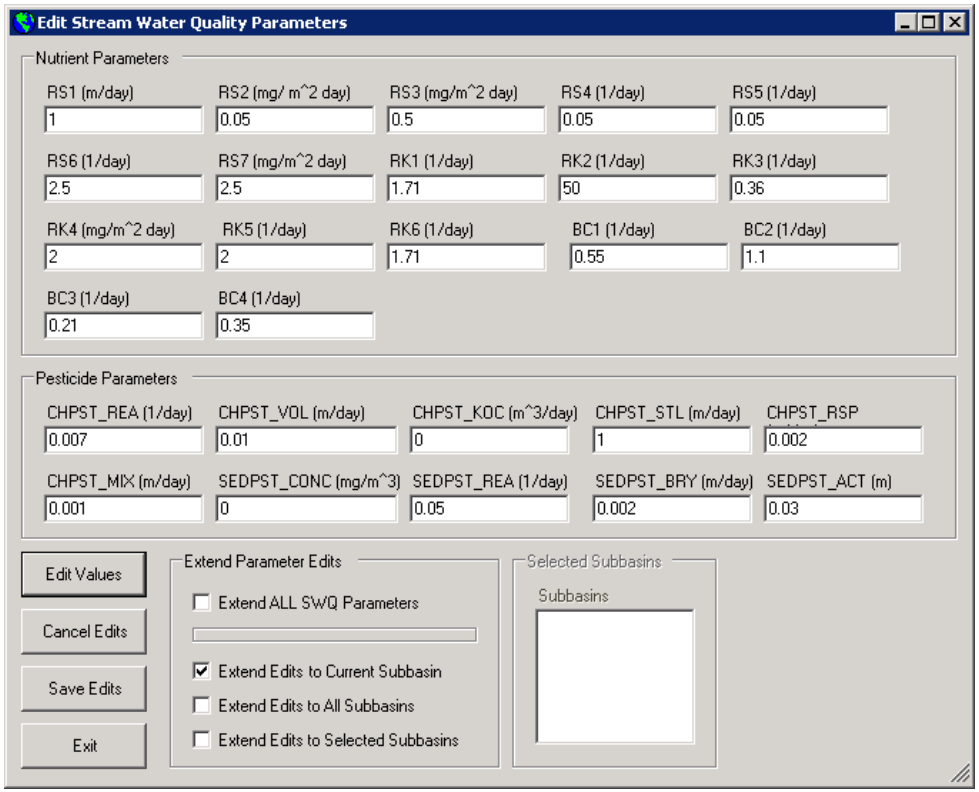


Figure 45 Stream water quality input data editor

14. To edit septic input data file click on the .sep in the “Select Input file” section of “Edit Subbasin Inputs” dialog box. A new dialog box (Figure 45) will appear displaying the septic input data editor. To modify the displayed data, click the **Edit Values** button to activate all the textboxes. After the modification of septic input data, the user also can extend the modification to other user specified Subbasins.

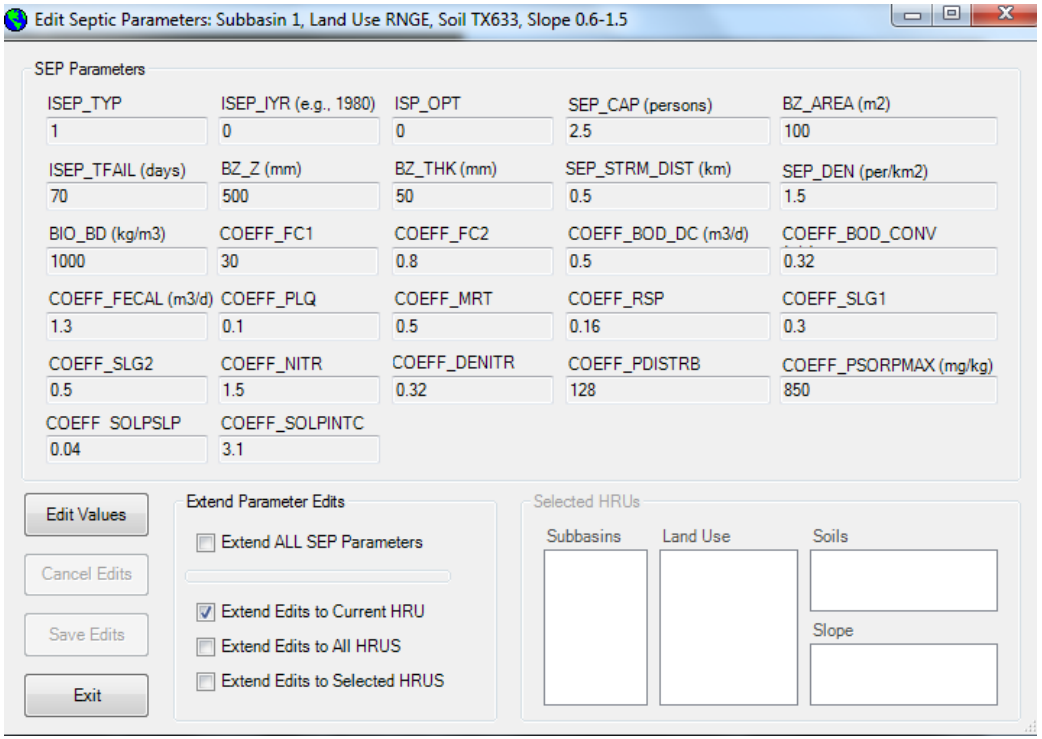


Figure 46 Septic input data Editor

15. To edit Operations input data file click on the .sep in the “Select Input file” section of “Edit Subbasin Inputs” dialog box. A new dialog box (Figure 45) will appear displaying the septic input data editor. To modify the displayed data, click the **Edit Values** button to activate all the textboxes. After the modification of septic input data, the user also can extend the modification to other user specified Subbasins.

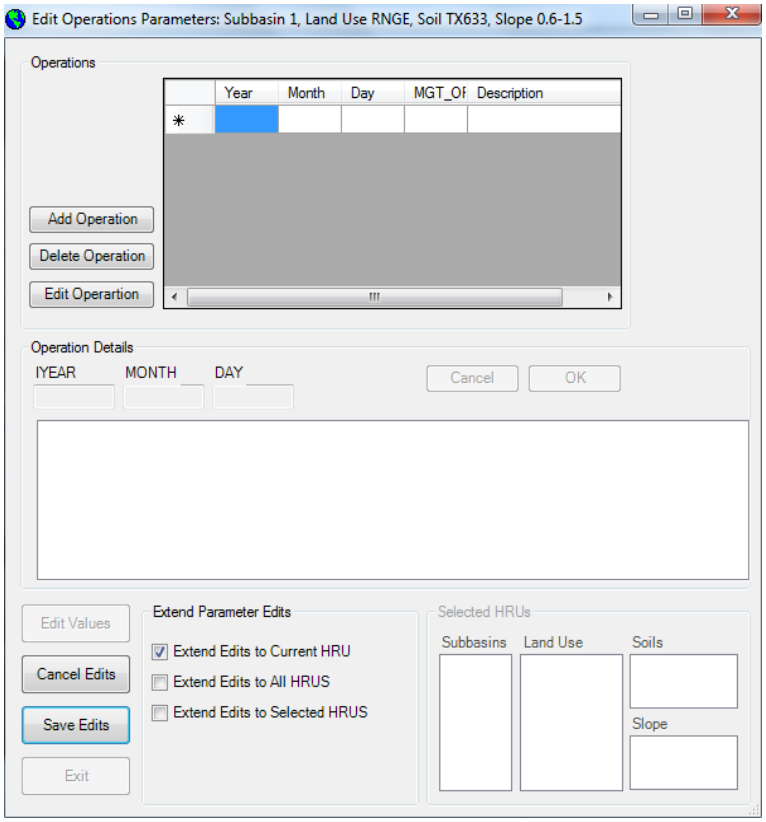


Figure 50 Operations parameters Editor

Step 6. Edit Watershed Data

1. Go to the **Watershed Data** item under the **Edit SWAT Input** menu, and click the General Data (.BSN) button, then a new dialog (**Error! Reference source not found.**) will appear.

This interface allows you to modify the parameters concerned with three major groups:

1) Water Balance, Surface Runoff, and Reaches,

2) Nutrients and Water Quality, and

3) Basin-wide Management. After revision of the parameters, click Save Edits.

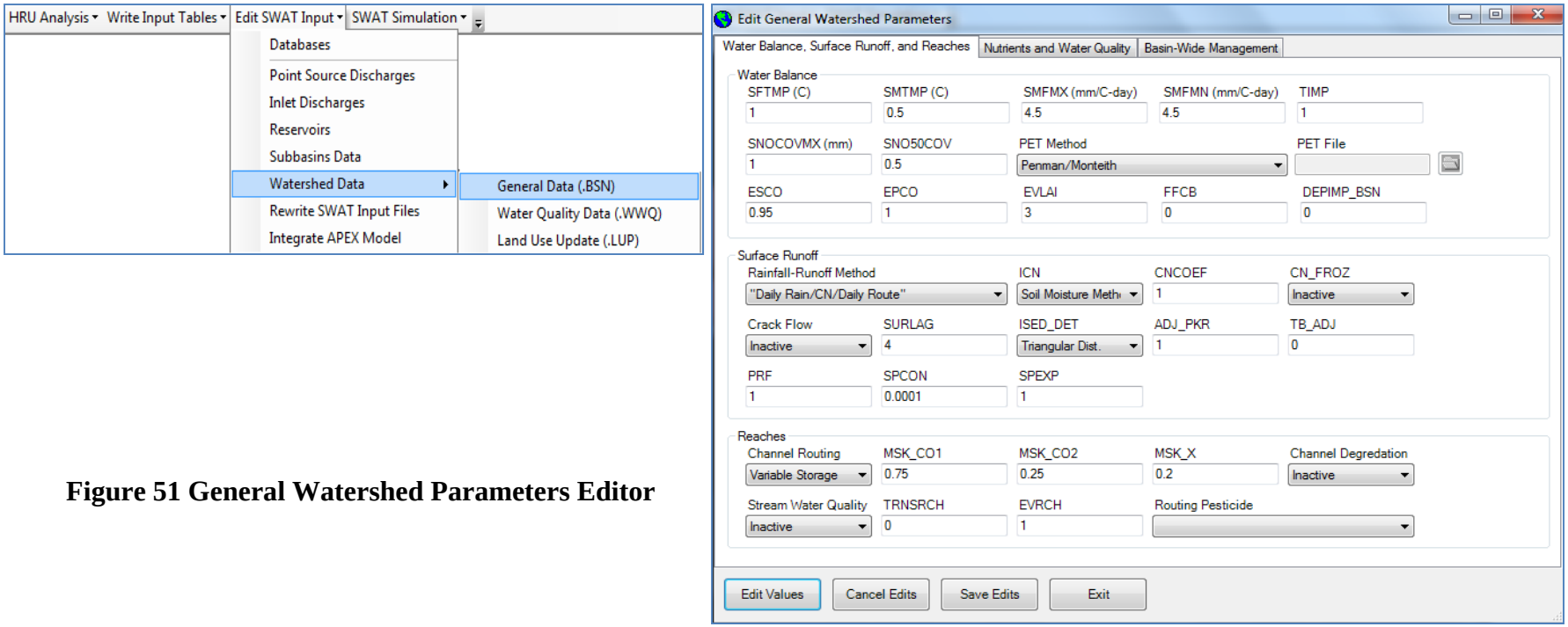


Figure 51 General Watershed Parameters Editor

2. Go to the **Watershed Data** item under the **Edit SWAT Input** menu, and click the Water Quality Data (.WWQ) button, then a new dialog (Figure) will appear. This interface allows you to modify the parameters concerned with Watershed Water Quality Simulation. After revision of the parameters, click Save Edits.

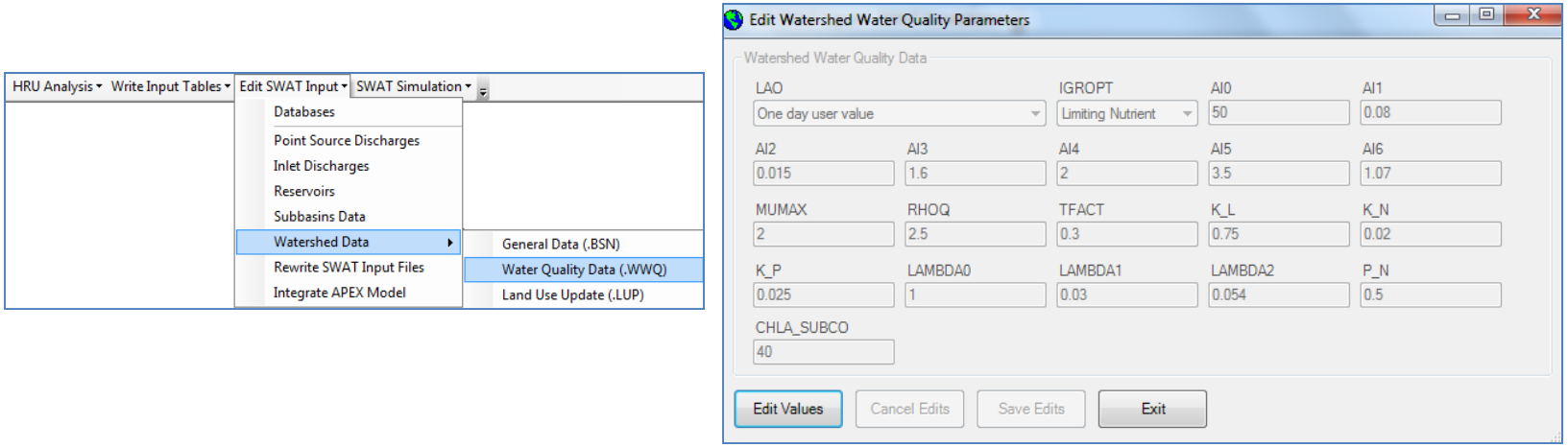


Figure 52 Watershed Water Quality Parameters

3. Go to the **Watershed Data** item under the **Edit SWAT Input** menu, and click the Land Use Update (.LUP) button, then a new dialog (Figure) will appear. This interface allows you to modify the parameters concerned with Watershed Water Quality Simulation. After revision of the parameters, click Save Edits.

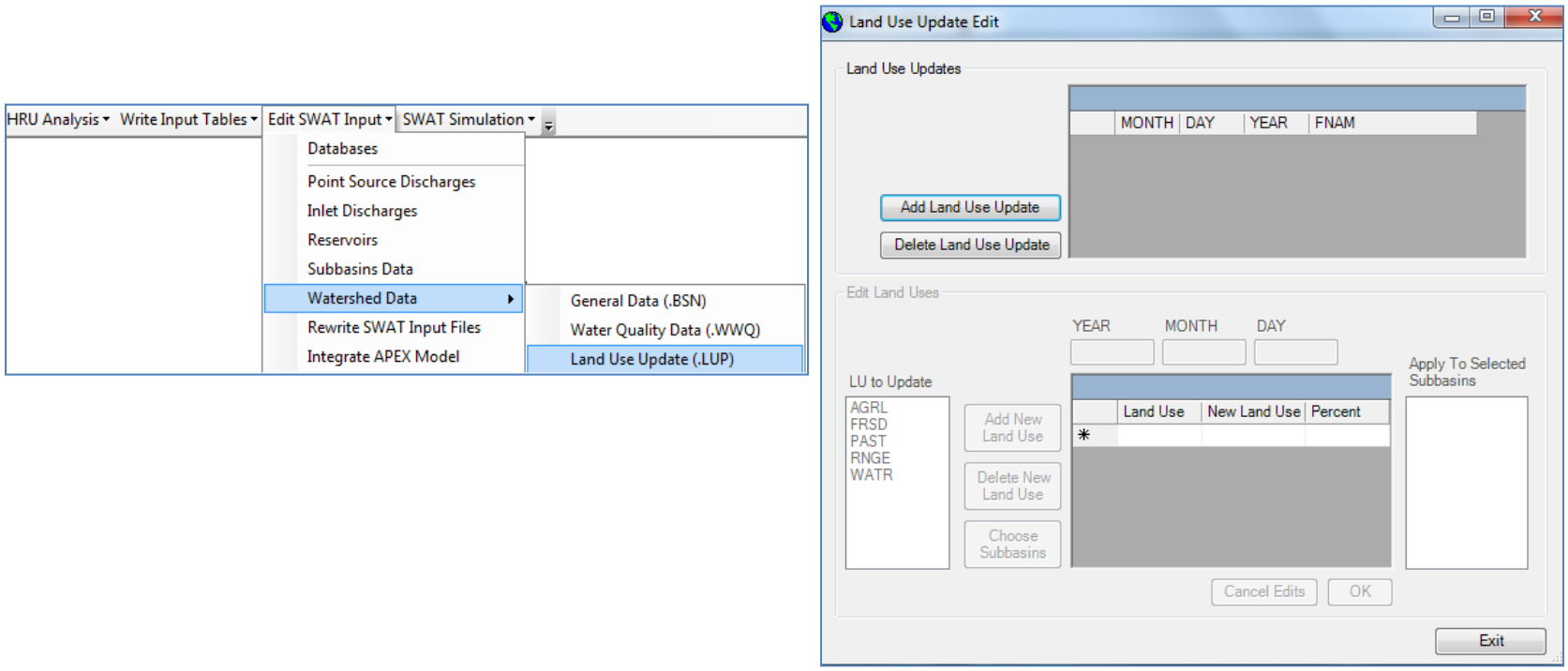


Figure 53 Watershed Land Use Update

Step 7. Integrate APEX Model

The Integrate APEX Model commands allow the user to specify subbasins within the current SWAT model that they wish to simulate using an existing APEX model. To use this option, the APEX model must have been set up with the ArcGIS APEX interface using the option to link integrate the APEX model with an existing SWAT model. In addition the APEX model must be run independently of the SWAT model. Choosing the Integrate APEX Model option will open a new dialog that will allow the user to define the subbasins and associated APEX model inputs (Figure 54).

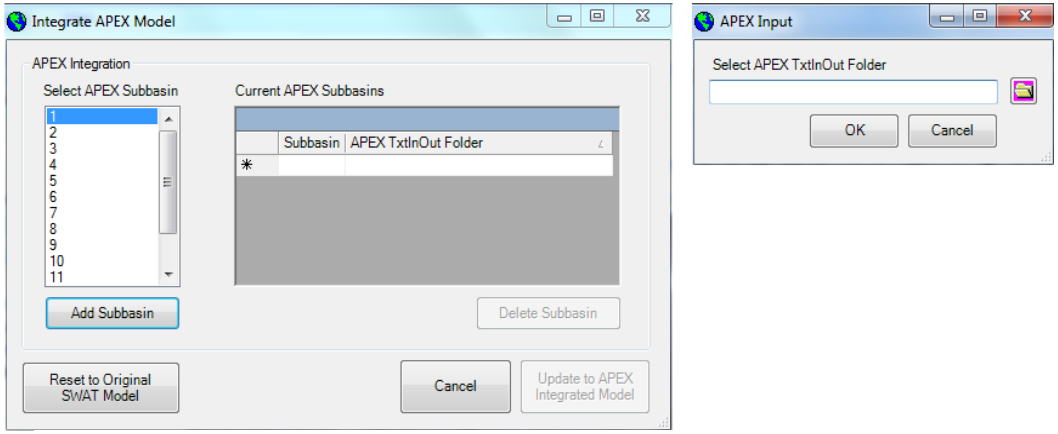


Figure 54. APEX Model input file main dialog

1. Select the subbasind that you want to simulate using APEX form the select APEX Subbasin list box and click Add Subbasin (Figure 54)
2. Brows the appropriate APEX TxtInOut folder that contain the input and output of the APEX model and click the OK button.
3. Browse to the appropriate folder and click the OK button on the APEX Input dialog. The folder path selected will be written into the Current APEX Subbasin table.
4. To re-write the SWAT model fig.fig file to incorporate the APEX model for the selected subbasin, click the Update to APEX Integrated Model button.
5. To reset the fig.fig for the current SWAT model back to original model click to Reset to Original SWAT Model button.

SWAT Simulation Setup

SWAT simulation menu contains commands that setup and run SWAT simulation. To build SWAT input files and run the simulation, proceed as follows:

Step 1: Setup data and Run SWAT

1. Select the **Run SWAT** command under the **SWAT Simulation** menu. It will open a dialog box (Figure 55) that will allow you to set up the data for SWAT simulation.

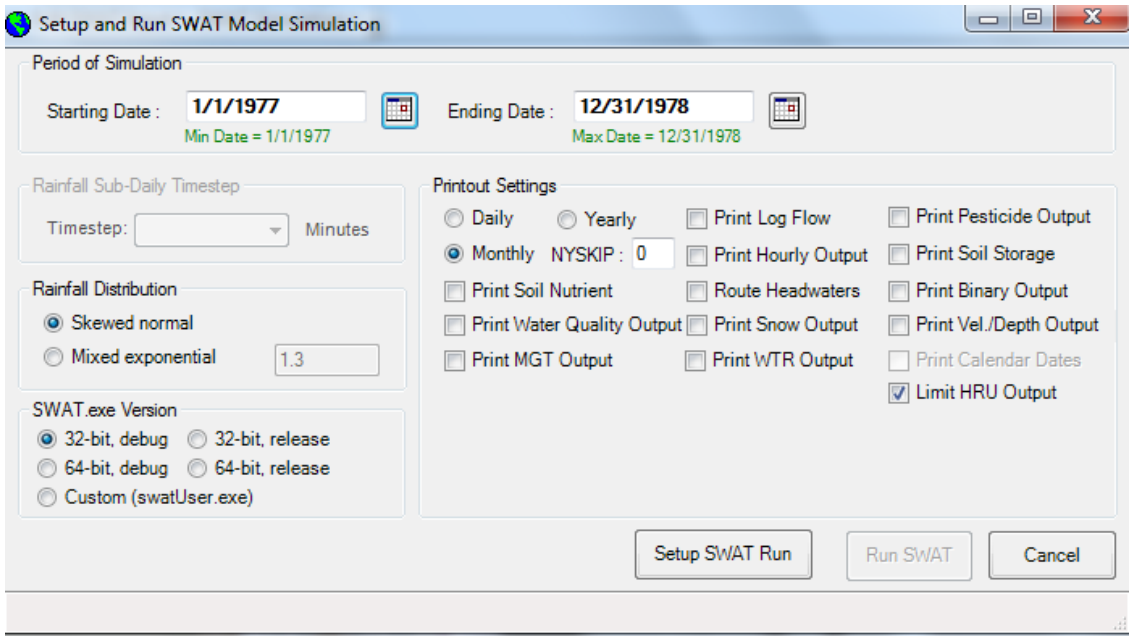


Figure 55 SWAT data setup and simulation dialog

2. Select the **1/1/1977** for the "**Starting date**" and **12/31/1978** for the "**Ending date**" option. If you are using simulated rainfall and temperature data, both these fields will be blank and you have to input the information manually.
3. Choose "monthly" option for **Printout Frequency**
4. Keep the rest at the default selections.
5. After all the parameters have been set, click the **Setup SWAT Run** button in the "Run SWAT" dialog box (Figure) to build the SWAT CIO, COD, PCP.PCP and TMP.TMP input files. Once all input files are setup, the **Run SWAT** button is activated in the bottom right of the Run SWAT dialog.
6. Click the button labeled **Run SWAT**. This will run the SWAT executable file. A message box will indicate the successful completion of SWAT run.

Step 2: Read SWAT Output

1. On the SWAT Simulation menu, click Read SWAT Output (Figure 56).
2. A dialog box will be brought up (Figure 57)

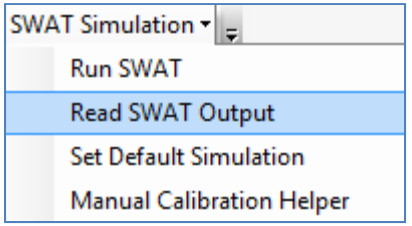


Figure 56. SWAT Simulation menu

3. To view the “Output.std” file, click the Open output.std button.
4. To view the “Output.std” file, click the Open output.std button.
5. To import selected SWAT files into an Access database, check the checkboxes associated with the output files of interest, and then click the **Import Files to Database** button. The selected output files will be converted to Access database tables in the “workdirectory\SWAT_Demo\Scenarios\Default\TablesOut\SwatOutput.mdb”.
6. To perform simple check to identify potential model problems, click the “SwatCheck” button.
7. Now, save the current SWAT simulation as “Sim1”
8. Type in a name (e.g. Sim1) for the current run
9. The button **Save Simulation** is activated now. You need to save the current setting of the SWAT project to another folder. Click the **Save Simulation** button, and input “Sim1” as the name of current SWAT Run. Click OK. Then the interface will copy the files under **“workdirectory\SWAT_Demo\Scenarios\Default**” to **“workdirectory\SWAT_Demo\Scenarios\Sim1**”. And a dialog will appear to notify you that the current SWAT run has been saved as “Sim1” (**Error! Reference source not found.**).

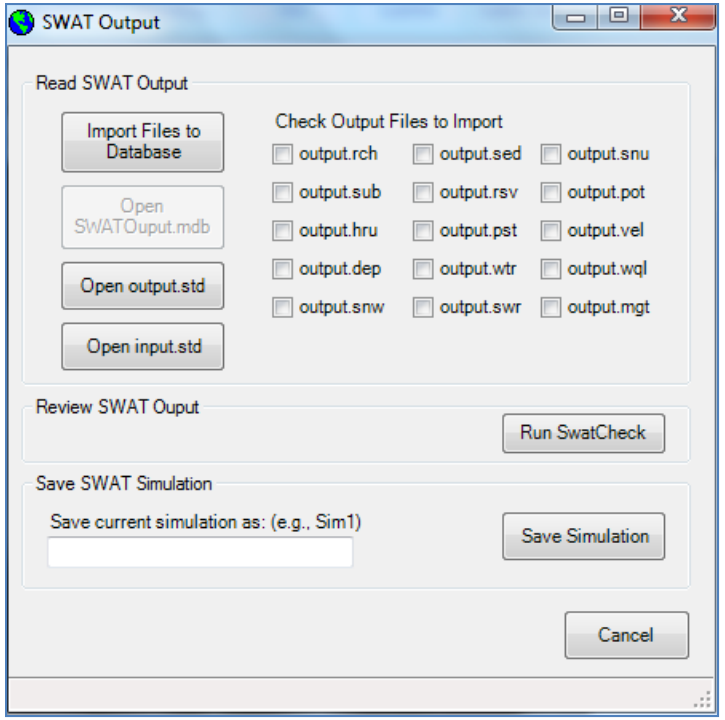


Figure 57. Dialog of saving SWAT run

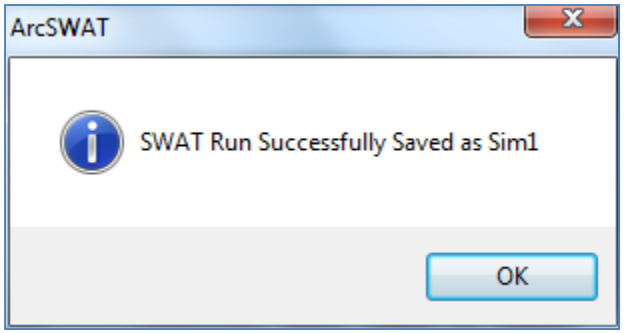


Figure 58. Dialog of successfully saved SWAT run

Step 3: Set Default Simulation

To choose saved simulation (Sim1) to be set as the current default simulation and input dataset, proceed as follows:

1. On the **SWAT Simulation** menu, click **Set Default Simulation** (Figure 59).
2. A dialog box will be displayed (Figure 60)
3. Choose a saved simulation "Sim1" from the **Select Simulation** box to set as the default simulation and click the **Copy to Default** button. The current SWAT project geodatabase and the contents of the "Default\TxtInOut\" folder are overwritten with the geodatabase found in the "TablesIn\" folder and the "TxtInOut\" folder contents from the selected simulation respectively. A dialog will appear to notify you that the current SWAT run will be replaces by the saved simulation "Sim1" (**Error! Reference source not found.**).

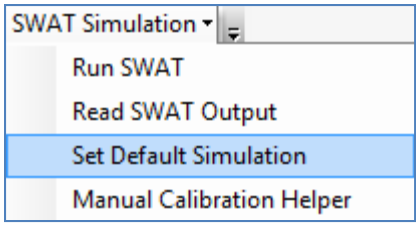


Figure 59. SWAT Simulation menu

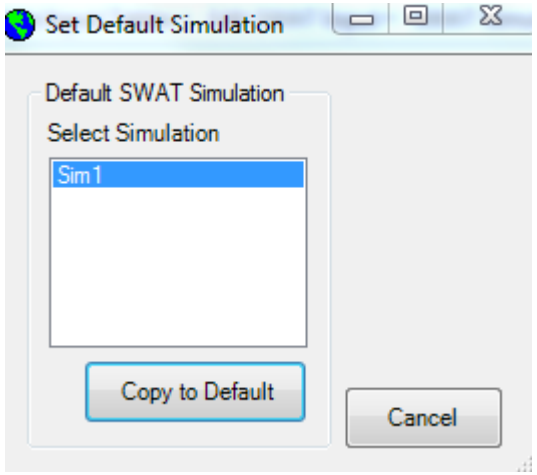


Figure 60. SWAT Simulation menu

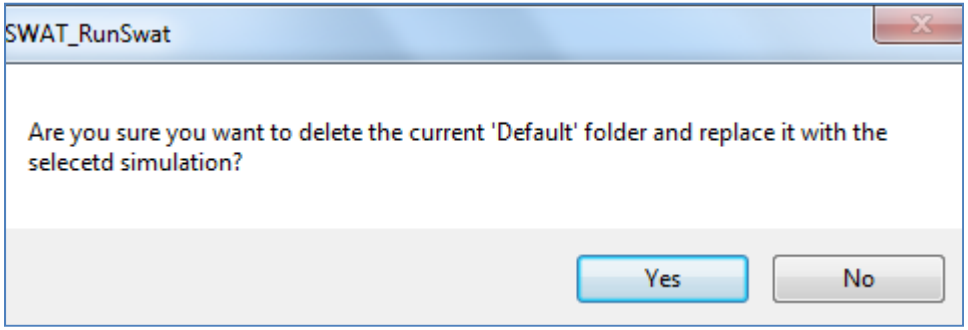


Figure 61. Replacing the default simulation with the saved simulation

Step 4: Manual Calibration Helper

This dialog provides a simple method for making adjustments to parameters across a user-defined group of HRUs or subbasins during the manual calibration process.

1. On the **SWAT Simulation** menu, click **Manual Calibration Helper** (Figure 62).
2. A dialog box will be displayed (Figure 63)
3. A parameter to adjust is selected by choosing a parameter from the **Select Parameter** combo box.
4. Select a mathematical operation (Multiply By, Add, Replace Value) in the **Mathematical Op** combo box.
5. Enter in a value to multiply by, add or replace in the **Value** box.
6. Specify the subbasins or HRUs that the parameter adjustment will apply. In Figure 63, the parameter adjustment has been chosen to be applied to all "PAST" HRUs of Subbasin 1. Click **Update Parameter.**
7. When completed a message will appear indicating the changes have been made.

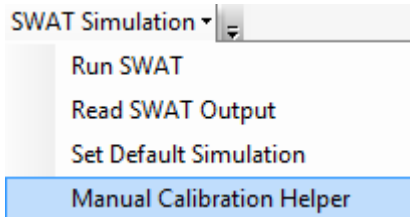


Figure 62. SWAT Simulation menu

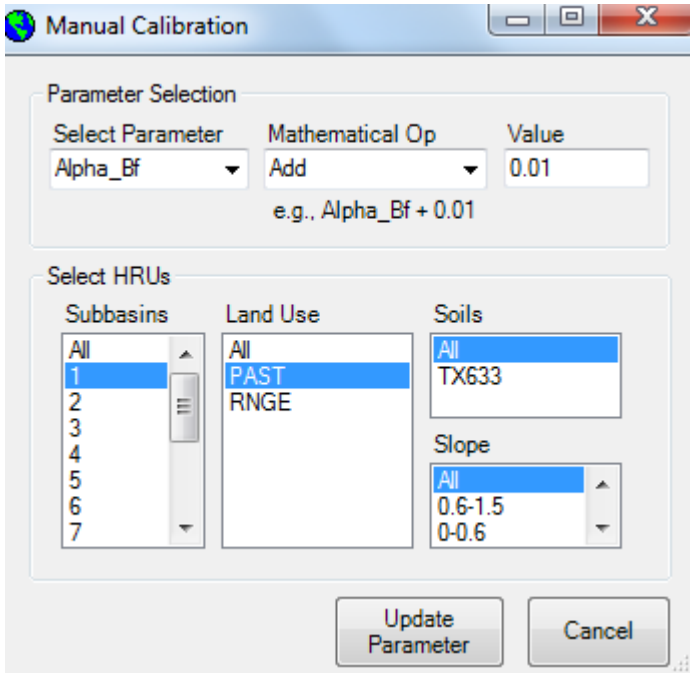


Figure 63. Dialog of Manual Calibration

Note:

- The user is responsible for keeping track of the changes made to parameters when using the Manual Calibration Helper. It is possible to make unrealistic parameter modifications using this tool, particularly for a novice user. It is always recommended to save a SWAT simulation prior to making significant changes to parameter values during calibration.

Appendix: Installing ArcSWAT

System Requirements

The SWAT2012/ArcSWAT 2012.10_0.1 Beta8 Interface requires:

Hardware:

- Personal computer using a Pentium IV processor or higher, which runs at 2 gigahertz or faster
- 1 GB RAM minimum
- 500 megabytes free memory on the hard drive for minimal installation and up to 1.25 gigabyte for a full installation (including sample datasets and US STATSGO data)

Software (ArcSWAT 2012.10_0.1 for ArcGIS 10 version):

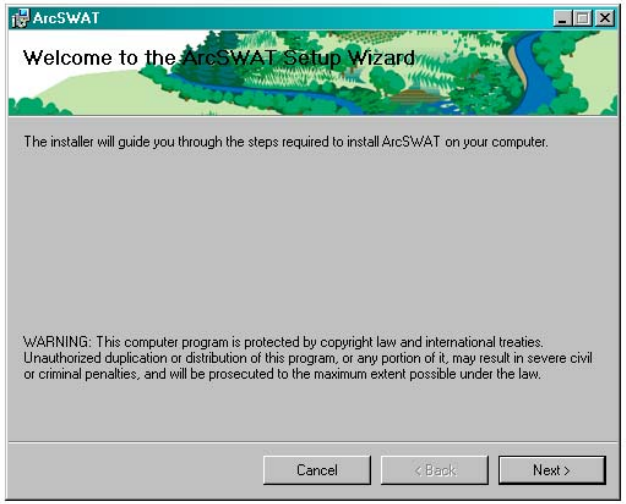
- Microsoft Windows XP, or Windows 2000 operating system with most recent kernel patch*****
- ArcGIS-ArcView 10 with service pack 5 (Build 4400)
- ArcGIS Spatial Analyst 10 extension
- ArcGIS Developer Kit (usually found in C:\Program Files\ArcGIS\DeveloperKit\)
- ArcGIS DotNet support (usually found in C:\Program Files\ArcGIS\DotNet\)
- Microsoft .Net Framework 2.0
- Adobe Acrobat Reader version 7 or higher

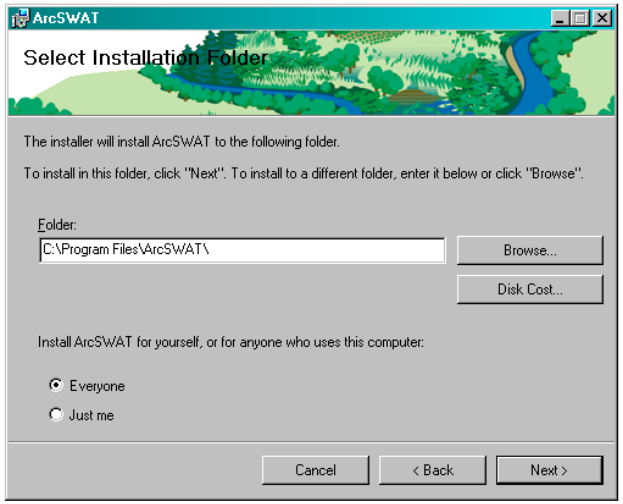
Microsoft constantly updates the different versions of windows. This interface was developed with the latest version of Windows and may not run with earlier versions. Patches are available from Microsoft.

Using the ArcSWAT Setup Wizard:

After downloading the ArcSWAT program, open the ArcSWAT_Install_1.0.0 folder. Click the

icon to begin installation. Follow the installation wizard instructions.

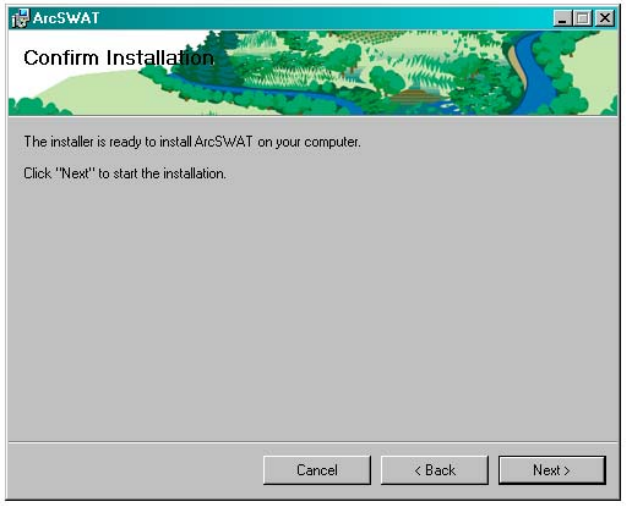


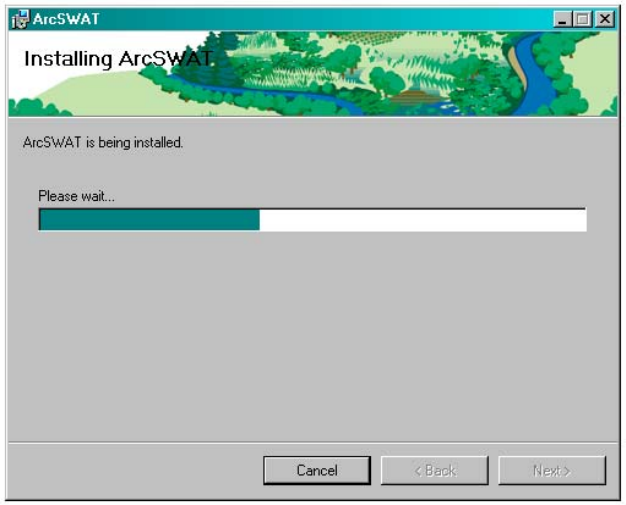


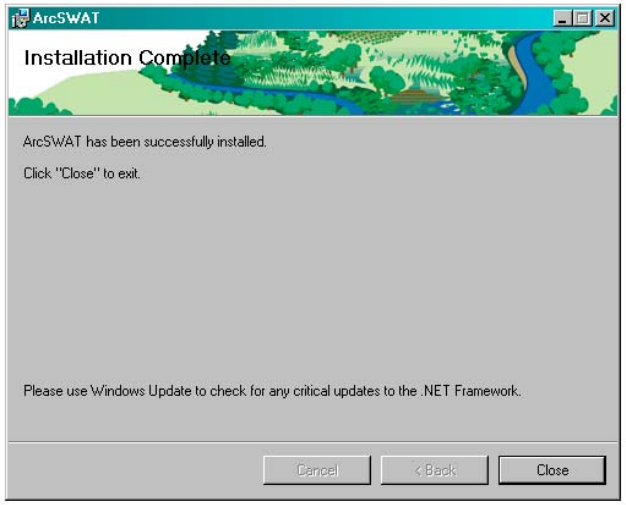
Select the appropriate folder location for the program, preferably the computer's main hard drive. Click the **Disk Cost** button to ensure enough disk space for installation.

Indicate if program access will be for everyone who uses the computer or just the installer.

Follow the wizard instructions until installation is completed successfully.







Make sure the SWAT_US_Soils.zip file is also downloaded and unzipped under ArcSWAT\databases directory

Note:

- After installation is complete, check that the downloaded data is located in the correct location: **C:\Program Files\ArcSWAT\Databases** and contains both the **SWAT2012.mdb** and **SWAT_US_Soils.mdb** databases.

Additional information on ArcSWAT installation:

What are the build numbers for all the recent releases of ArcGIS?

http://support.esri.com/index.cfm?fa=knowledgebase.techArticles.articleShow&d=30104

You need ArcGIS Desktop 10 Service Pack 5:

http://support.esri.com/en/downloads/patches-ServicePacks/view/productid/159/metaid/1892

How to install ArcGIS 10 with .NET support?

1. Insert the ArcView or ArcGIS Desktop installation disk.

2. Select Install ArcGIS Desktop.

3. Select Modify.

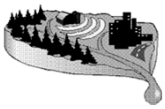
4. Expand Applications; verify that '.NET Support' is installed. If you see a red X, click on the X and select 'Entire feature will be installed' and then follow the rest of the wizard.

Section 3

SWAT Calibration Techniques

SWAT

SWAT Calibration Techniques



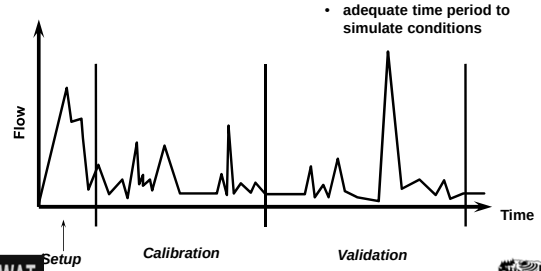
Calibration, Validation & Verification

- **CALIBRATION:** model testing with known input and output used to adjust or estimate factors
- **VALIDATION:** comparison of model results with an independent data set (without further adjustment).
- **VERIFICATION:** examination of the numerical technique in the computer code to ascertain that it truly represents the conceptual model and that there are no inherent numerical problems

SWAT

Calibration/Validation Periods

- distinct time period
- similar range of conditions
- adequate time period to simulate conditions



SWAT

Model Configuration

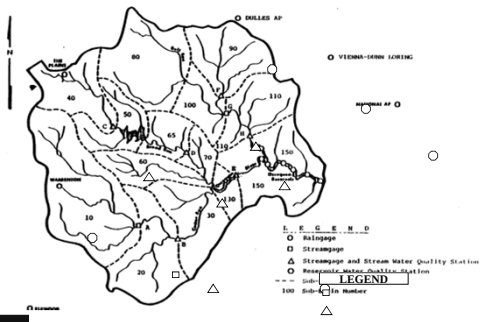
- Land use categories
  - land use types in watershed, existing and future land uses, management techniques employed, management questions
- Subwatersheds
  - location, physical characteristics/soils, gaging station locations, topographic features, management questions.
- Reaches
  - topographic features, stream morphology, cross-section data available

Calibration Issues:

- individual land use parameter determination
- location of gaging station data
- location of water quality monitoring information
- available information on stream systems

SWAT

Model Configuration
Calibration Points Example



SWAT

Calibration/Validation Procedures

- Hydrology - first and foremost
- Sediment - next
- Water quality - last (nitrogen, phosphorus, pesticides, DO, bacteria)

- Check list for model testing
  - water balance - is it all accounted for?
  - time series
  - annual total - stream flow & base flow
  - monthly/seasonal total
  - frequency duration curve
  - sediment and nutrients balance

SWAT

Calibration Time Step

- Calibration sequence
  - annual water balance
  - seasonal variability
  - storm variability
    - time series plot
    - frequency duration curve
  - baseflow
  - overall time series

SWAT

Calibration/Validation Statistics

- Mean and standard deviation of the simulated and measured data
- Slope, intercept and regression coefficient/coefficient of determination
- Nash-Suttcliffe Efficiency

SWAT

Calibration/Validation Common Problems

- too little data - too short a monitoring period
- small range of conditions
  - only small storms
  - only storms during the spring...
- prediction of future conditions which are outside the model conditions
- calibration/validation does not adequately test separate pieces of model
  - accuracy of each land use category prediction
- calibration adjustments destroy physical representation of system by model
- adjustment of the wrong parameters

SWAT

Calibration/Validation Suggested References

- Neitsch, S. L., J. G. Arnold, J. R. Kiniry and J. R. Willams. 2001. Soil and Water Assessment Tool – Manual, USDA-ARS Publications. pp: 341-354. http://www.brc.tamus.edu/swat/manual.
- 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. J. American Water Resources Association 37(5): 1169-1188.
- Srinivasan, R., T. S. Ramanarayanan, J. G. Arnold and S. T. Bednarz. 1997. Large area hydrologic modeling and assessment: Part II - Model application. J. American Water Resources Association 34(1): 91-102.
- Arnold, J.G., R. S. Muttiah, R. Srinivasan and P. M. Allen. 2000. Regional estimation of baseflow and groundwater recharge in the upper Mississippi basin. J. Hydrology 227(2000): 21-40.

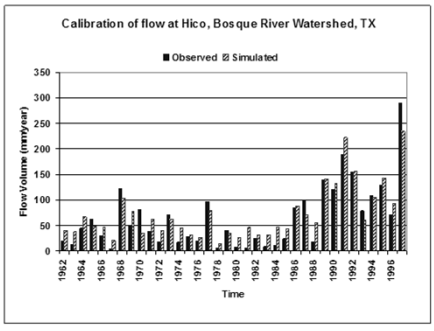
SWAT

Hydrology Calibration Summary

- Key considerations
  - Water balance
    - overall amount
    - distribution among hydrologic components
  - Storm sequence
    - time lag or shifts
      - time of concentration, travel time
    - shape of hydrograph
      - peak
      - recession
      - consider antecedent conditions

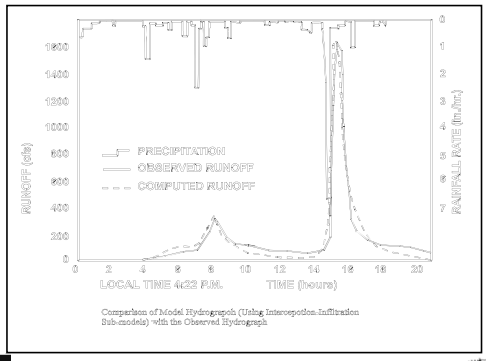
SWAT

Example Calibration Plot



SWAT

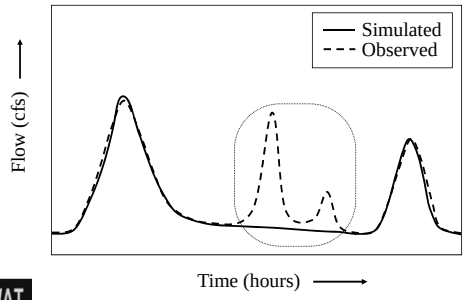
Example Calibration Plot



Comparison of Model Hydrograph (Using Interception-Infiltration Sub-models) with the Observed Hydrograph

SWAT

Hydrologic Calibration Scenario 1

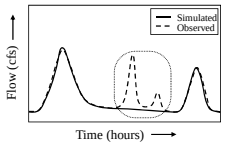


SWAT

Hydrologic Calibration

Model failed to simulate some peak flows

- **Rainfall station is not representative**
- **Localized storm -no response**
- **Malfunctioning gages (precipitation or flow)**

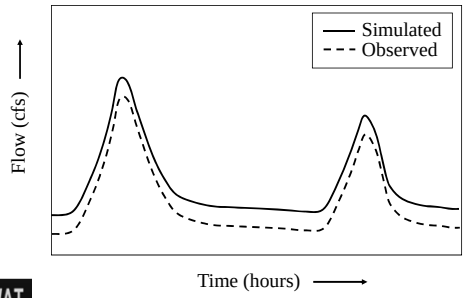


Solutions

- **Use precipitation data from representative meteorological stations**
- **Carefully review precipitation and flow data for the particular duration**

SWAT

Hydrologic Calibration Scenario 2

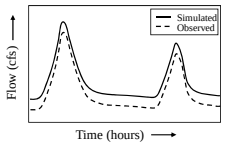


SWAT

Hydrologic Calibration

Model consistently over predicts the flow

- **High Surface flow**



Solutions

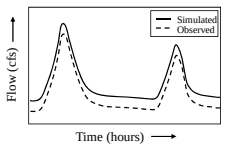
- **Decrease curve number for different land uses (CN in .mgt)**
- **Soil available water (SOL_AWC in .sol)**
- **Soil evaporation compensation factor (ESCO in *.bsn)**

SWAT

Hydrologic Calibration

Model consistently over predicts the flow

- **High base flow**
- **Too little evapotranspiration**

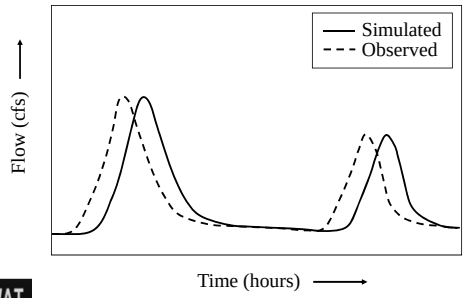


Solutions

- **Increase deep percolation loss (Adjust threshold depth of water in shallow aquifer required for the base flow to occur) (GWQMN in .gw)**
- **Increase groundwater revap coefficient (GW_REVAP in .gw)**
- **Decrease theshold depth of water in shallow aquifer for revap to occur (REVAPMN in .gw)**

SWAT

Hydrologic Calibration Scenario 3

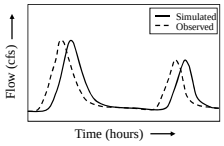


SWAT

Hydrologic Calibration

Simulated flow follows the observed pattern but lags the actual flow consistently

- **Time of concentration is too long**
- **Less than actual slope for overland flow**
- **Over estimated surface roughness**

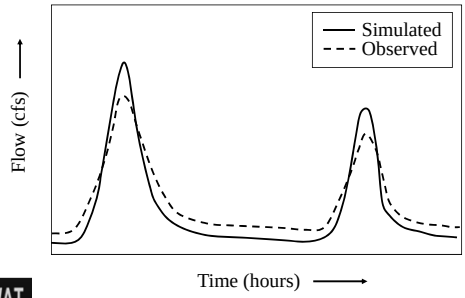


Solutions

- **Adjust slope for over land flow (SLOPE in .hru)**
- **Adjust Manning's roughness coefficient (OV_N in .sub or .rte)**
- **Adjust the value of overland flow length (SLSUBBSN in .sub or .hru), if necessary**

SWAT

Hydrologic Calibration Scenario 4

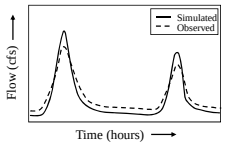


SWAT

Hydrologic Calibration

Simulated flow over predicts peak flows but under predicts all other times

- **Too little base flow**
- **Too high surface runoff**



Solutions

- **Adjust infiltration**
- **Adjust interflow**
- **Adjust base flow recession parameter**

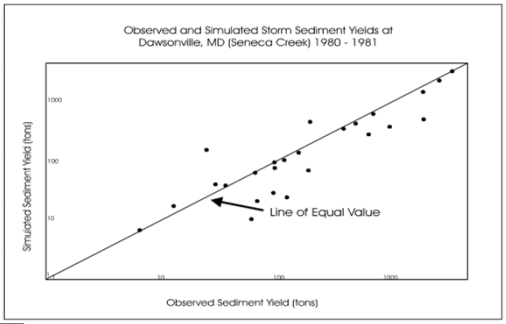
SWAT

Sediment Calibration Summary

- **Key considerations**
  - **Sources of sediment loadings**
    - **Loadings from HRUs/Subbasins**
    - **Channel degradation/deposition**
  - **Sediment loading distribution**
    - **overall amount**
    - **Seasonal loading**
      - **distribution by storm sequence**
        - **rising and falling limb of hydrograph**
        - **peak concentration**

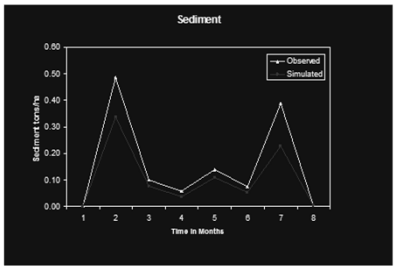
SWAT

Example Calibration Plot



SWAT

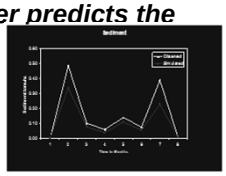
Sediment Calibration Scenario 1



SWAT

Sediment Calibration

Model consistently under predicts the sediment



- Low sediment yield

Solutions

- Calibrate HRU/Subbasin Loadings
  - Adjust USLE crop management factor (P) (USLE_P in .mgt)
  - Adjust USLE slope length factor (LS) (SLSUBBSN in .sub or .hru)
  - Adjust the slope of HRUs (SLOPE in .hru)
  - Adjust crop practice factor (C) for land use (USLE_C in crop.dat)
  - Verify tillage operations in *.mgt files and adjust crop residue coefficient (RSDCO) and bio-mixing efficiency (BIOMIX) in .bsn
- Calibrate Channel degradation/deposition
  - Linear and exponential parameters used for channel sediment routing (SPCON and SPEXP in .bsn)
  - Channel erodibility facor (CH_EROD in .rte)
  - Channel cover factor (CH_COV in .rte)

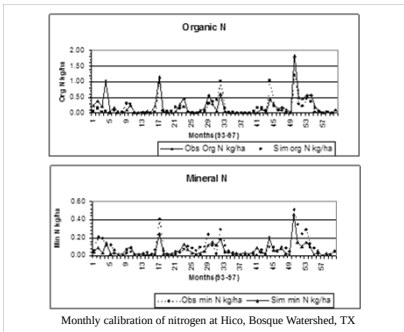
SWAT

Nutrients Calibration Summary

- Key considerations
  - Sources of nutrients loadings
    - Loadings from HRUs/Subbasins
    - In-stream processes
  - Nutrient loading distribution
    - overall amount
    - Seasonal loading
      - distribution by storm sequence
        - rising and falling limb of hydrograph
        - peak concentration

SWAT

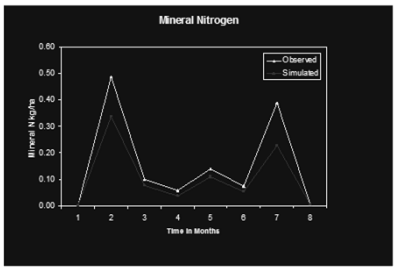
Example Calibration Plot



Monthly calibration of nitrogen at Hico, Bosque Watershed, TX

SWAT

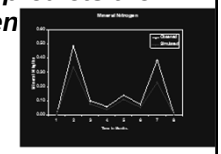
Mineral Nitrogen Calibration Scenario 1



SWAT

Mineral Nitrogen Calibration

Model consistently under predicts the mineral nitrogen



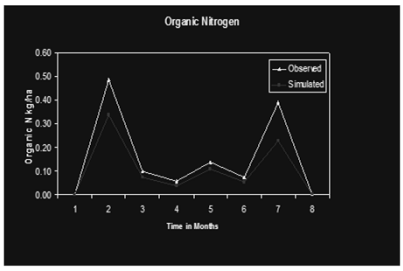
- **Low mineral nitrogen loading**

Solutions

- **Calibrate mineral nitrogen loadings**
  - **Adjust initial concentration of the nutrient in soils (SOL_NO3 in .chm)**
  - **Verify fertilizer application rates and adjust fertilizer application fraction to surface layer as 0.20 (FRT_LY1 in .mgt)**
  - **Verify tillage operations in *.mgt files and adjust crop residue coefficient (RSDCO) and bio-mixing efficiency (BIOMIX) in .bsn**
  - **Adjust nitrogen percolation coefficient (NPERCO in .bsn)**
- **Calibrate in-stream mineral nitrogen processes**
  - **Adjust fraction of algal biomass that is as nitrogen for water quality (AI1 in.wwq)**

SWAT

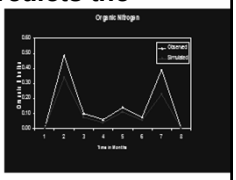
Organic Nitrogen Calibration Scenario 1



SWAT

Organic Nitrogen Calibration

Model consistently under predicts the organic nitrogen



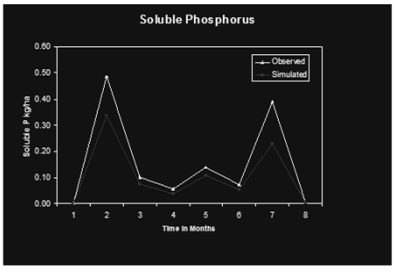
- **Low Organic nitrogen loading**

Solutions

- **Calibrate organic nitrogen loadings**
  - **Adjust initial concentration of the nutrient in soils (SOL_ORGN in .chm)**
  - **Verify fertilizer application rates and adjust fertilizer application fraction to surface layer as 0.20 (FRT_LY1 in .mgt)**
- **Calibrate in-stream organic nitrogen processes**
  - **Adjust fraction of algal biomass that is as nitrogen for water quality (AI1 in.wwq)**

SWAT

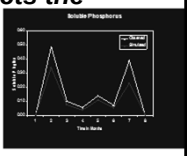
Soluble Phosphorus Calibration Scenario 1



SWAT

Soluble Phosphorus Calibration

Model consistently under predicts the soluble phosphorus



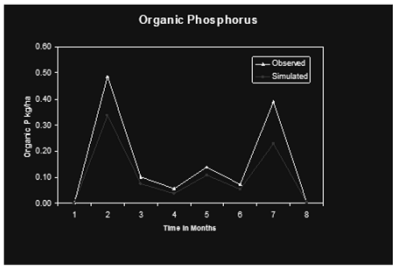
- **Low soluble phosphorus loading**

Solutions

- **Calibrate soluble phosphorus loadings**
  - **Adjust initial concentration of the nutrient in soils (SOL_MINP in .chm)**
  - **Verify fertilizer application rates and adjust fertilizer application fraction to surface layer as 0.20 (FRT_LY1 in .mgt)**
  - **Verify tillage operations in *.mgt files and adjust crop residue coefficient (RSDCO) and bio-mixing efficiency (BIOMIX) in .bsn**
  - **Adjust phosphorus percolation coefficient (PPERCO in .bsn)**
  - **Adjust phosphorus soil partitioning coefficient (PHOSKD in .bsn)**
- **Calibrate in-stream soluble phosphorus processes**
  - **Adjust fraction of algal biomass that is as phosphorus for water quality (AI2 in.wwq)**

SWAT

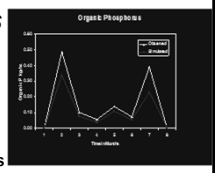
Organic Phosphorus Calibration Scenario 1



SWAT

Organic Phosphorus Calibration

Model consistently under predicts the organic phosphorus



- **Low organic phosphorus loading**

Solutions

- **Calibrate organic phosphorus loadings**
  - **Adjust initial concentration of the nutrient in soils (SOL_ORGP in .chm)**
  - **Verify fertilizer application rates and adjust fertilizer application fraction to surface layer as 0.20 (FRT_LY1 in .mgt)**
- **Calibrate in-stream organic phosphorus processes**
  - **Adjust fraction of algal biomass that is as phosphorus for water quality (AI2 in.wwq)**

SWAT

SWAT Publications

Validation of SWAT on a Large River Basin with Point and Nonpoint Sources

Information to Run SWAT Model

SSURGO Processing for ArcSWAT

Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
VOL. 37, NO. 5 AMERICAN WATER RESOURCES ASSOCIATION OCTOBER 2001

VALIDATION OF THE SWAT MODEL ON A LARGE RIVER BASIN WITH POINT AND NONPOINT SOURCES[1]

C. Santhi, J. G. Arnold, J. R. Williams, W. A. Dugas, R. Srinivasan, and L. M. Hauck[2]

ABSTRACT: The State of Texas has initiated the development of a Total Maximum Daily Load program in the Bosque River Watershed, where point and nonpoint sources of pollution are a concern. Soil Water Assessment Tool (SWAT) was validated for flow, sediment, and nutrients in the watershed to evaluate alternative management scenarios and estimate their effects in controlling pollution. This paper discusses the calibration and validation at two locations, Hico and Valley Mills, along the North Bosque River. Calibration for flow was performed from 1960 through 1998. Sediment and nutrient calibration was done from 1993 through 1997 at Hico and from 1996 through 1997 at Valley Mills. Model validation was performed for 1998. Time series plots and statistical measures were used to verify model predictions. Predicted values generally matched well with the observed values during calibration and validation ($R^2 \geq 0.6$ and Nash-Suttcliffe Efficiency ≥ 0.5, in most instances) except for some underprediction of nitrogen during calibration at both locations and sediment and organic nutrients during validation at Valley Mills. This study showed that SWAT was able to predict flow, sediment, and nutrients successfully and can be used to study the effects of alternative management scenarios.
(KEY TERMS: watershed management; total maximum daily load; erosion; sedimentation; phosphorus loading; dairy manure management.)

INTRODUCTION

The United States Environmental Protection Agency (USEPA) reported nutrient enrichment as the major cause for impairment of lakes and other water bodies in the United States (USEPA, 1994). USEPA's water quality inventory report of 1996 indicated that 40 percent of the surveyed rivers, lakes, and estuaries were polluted relative to their designated uses (USEPA, 1998). To restore the quality of these water bodies, the Total Maximum Daily Load (TMDL) process was established by section 303(d) of the Clean Water Act (CWA). A TMDL quantifies pollutant sources and maximum allowable loads to the contributing point and nonpoint sources so that the water quality standards are attained to protect drinking water, aquatic life, and other water uses (USEPA, 1998). Once the necessary pollutant reduction levels are identified through establishment of TMDLs, control measures such as best management practices (BMPs) are to be implemented.

The Texas Natural Resource Conservation Commission (TNRCC) is implementing TMDL projects in Texas in cooperation with the Texas State Soil and Water and Conservation Board (TSSWCB). Of the 386 classified water bodies, 147 have been listed on the 1998 303(d) list. One of these projects is in the Bosque River Watershed in North Central Texas, where phosphorus from confined animal-feeding operations is a concern (TNRCC, 1999). Runoff from cropland and urban areas (nonpoint sources) and effluent from wastewater treatment plants (WWTPs) (point sources) are other pollution sources in this watershed.

Water quality simulation models can assist with TMDL development through simulating loads to receiving water bodies under various BMPs. Models in combination with observational data from historical and current monitoring programs will provide the information for TMDL waste/load allocations and implementation strategies. In this study, the hydrologic/water quality model, Soil Water Assessment Tool

[1]Paper No. 00044 of the *Journal of the American Water Resources Association.* **Discussions are open until June 1, 2002.**
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(SWAT) was used to study the effect of different BMPs in reducing the pollution. The objective of this paper is to describe the calibration and validation of the SWAT model for flow, sediment, organic, and mineral nutrients in the Bosque River Watershed. The model was then used to study the impact of different BMPs on the Bosque River Watershed and identify suitable BMPs for achieving water quality targets (Santhi *et al.,* 2000).

MATERIALS AND METHODS

SWAT Model Description

SWAT is a hydrologic/water quality model developed by United States Department of Agriculture - Agricultural Research Service (USDA-ARS) (Arnold *et al.,* 1998). It is a continuous time model that operates on a daily time step. The objective in model development was to predict the impact of management on water, sediment, and agricultural chemical yields in large ungaged basins. To satisfy the objective, the model (a) is physically based (calibration is not possible on ungaged basins); (b) uses readily available inputs; (c) is computationally efficient to operate on large basins in a reasonable time; and (d) is continuous in time and capable of simulating long periods for computing the effects of management changes. SWAT uses a command structure for routing runoff and chemicals through a watershed. Commands are included for routing flows through streams and reservoirs, adding flows, and inputting measured data from wastewater treatment plants. The subbasin/subwatershed components of SWAT can be placed into eight major components – hydrology, weather, erosion/sedimentation, soil temperature, plant growth, nutrients, pesticides, and land management. Erosion and sediment yield are estimated for each subbasin with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). The channel sediment routing equation uses a modification of Bagnold's sediment transport equation (Bagnold, 1977) that estimates the transport concentration capacity as a function of velocity.

$$CY_u = SPCON*V^{SPEXP} \quad (1)$$

where, CY_u is sediment transport concentration capacity in g/m^3; SPCON is the concentration capacity in g/m^3 at a velocity of 1 m/s; V is flow velocity in m/s; and SPEXP is a constant in Bagnold's equation. The model either deposits excess sediment or reentrains sediment through channel erosion depending on the sediment load entering the channel.

The nitrogen processes modeled by SWAT and the various pools of nitrogen in the soil are shown in Figure 1 (Arnold *et al.,* 1998; USDA-ARS, 1999). Plant use of nitrogen is estimated using the supply and demand approach (Williams *et al.,* 1984). Daily plant demand is a function of plant biomass and biomass N concentration. Available nitrogen in the soil (root depth) is supplied to the plant. When demand exceeds supply, there is a nutrient stress. Masses of NO_3-N contained in runoff, lateral flow and percolation are estimated as products of the volume of water and the average concentration of nitrate (NO_3-N) in the soil layer. Organic N transport with sediment is calculated with a loading function developed by McElroy *et al.* (1976) and modified by Williams and Hann (1978) for application to individual runoff events. The loading function estimates daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment yield, and an enrichment ratio (that is, the ratio of organic N in sediment to organic N in soil and typically ranging from two to four). The phosphorus processes modeled by SWAT and the various pools of phosphorus in the soil are depicted in Figure 2 (USDA-ARS, 1999). Plant use of phosphorus is estimated using the supply and demand approach similar to nitrogen. The loss of dissolved phosphorus in surface runoff is based on the concept of partitioning pesticides into solution and sediment phases as described by Leonard and Wauchope (1980). The amount of soluble P removed in runoff is predicted using labile P concentration in the top 10 mm of the soil, the runoff volume and a phosphorus soil partitioning factor (that is, the ratio of P attached to sediment to P dissolved in soil water and typical values range from 100 to 175 depending on the soil). Sediment transport of P is simulated with a loading function as described in organic N transport.

Instream nutrient dynamics have been incorporated into SWAT (Ramanarayanan *et al.,* 1996) using the kinetic routines from an instream water quality model, QUAL2E (Brown and Barnwell, 1987). However, the QUAL2E routines were not explicitly used in this study. The North Bosque River is a phosphorus limited system and dominated by large amounts of attached algae (periphyton) as opposed to suspended algae. The in-stream kinetics formulation for SWAT does not include a periphyton component, a common limitation of many in-stream water quality models. In addition, inadequate monitoring information exists to quantify the periphyton biomass distribution in the river. To overcome these limitations, a first-order decay kinetic function was developed for the nutrient of concern in the study (phosphorus) and to characterize the microbial transformation of in-stream soluble P to organic P rather than the more traditional approach involving algae growth and phosphorus

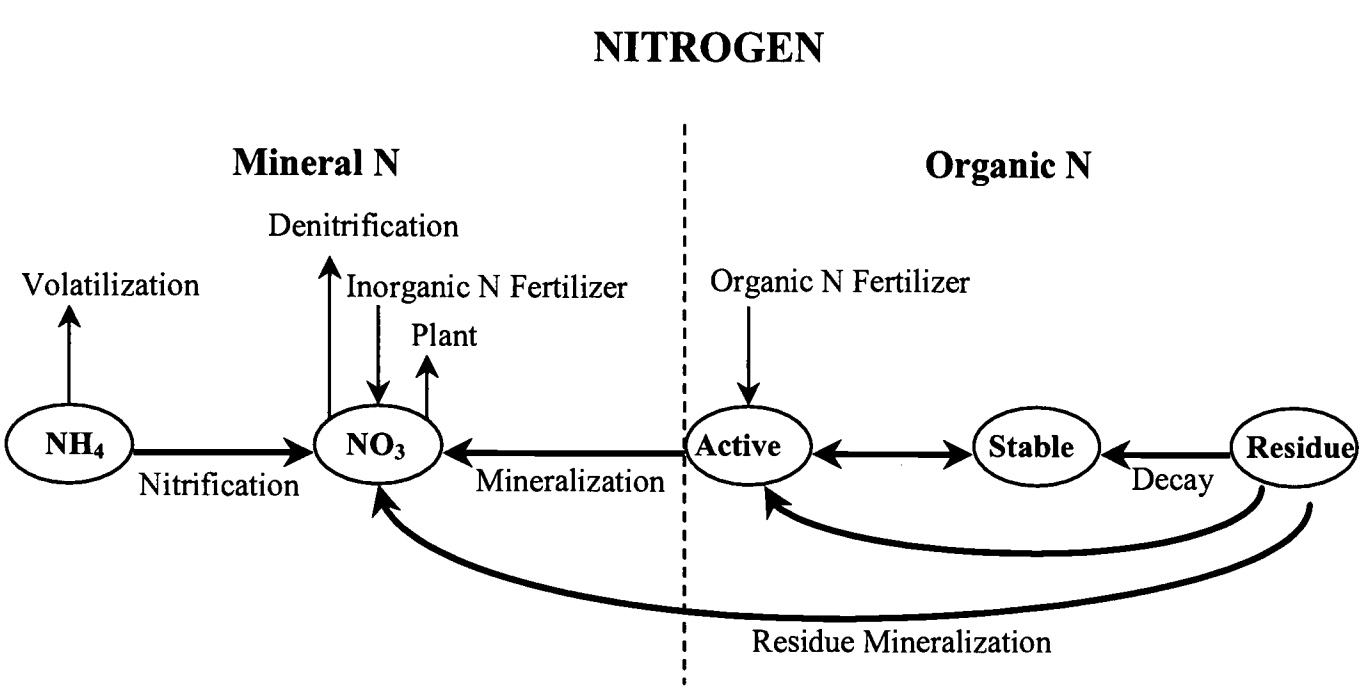


Figure 1. Nitrogen Processes Modeled in SWAT (USDA-ARS, 1999).

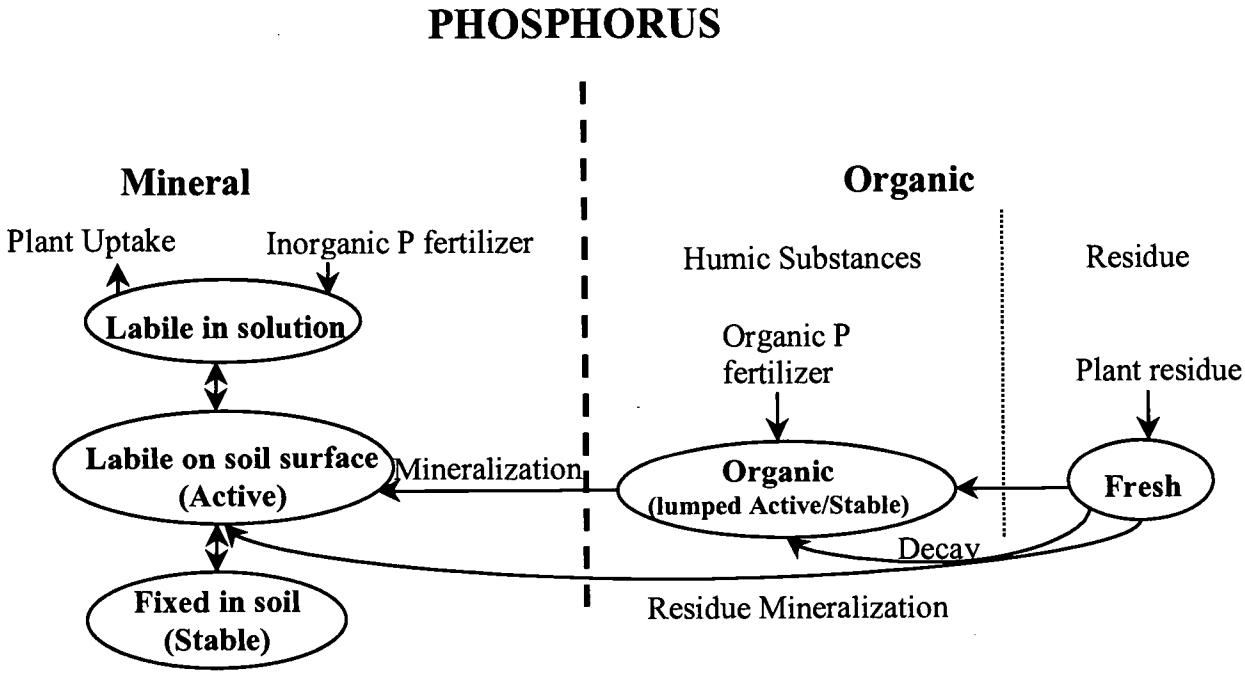


Figure 2. Phosphorus Processes Modeled in SWAT (USDA-ARS, 1999).

uptake and cycling. The transformation is particularly important during low flow periods because extremely low stream velocities create long travel times. Equations for phosphorus are given below:

$$PC_o = PC_i * \exp^{-a(chl/q)} \quad (2)$$

$$\Delta SP = SP_i - SP_o \quad (3)$$

$$OP_o = OP_i + \Delta SP \quad (4)$$

where, PC_i and PC_o are reach soluble P inflow and outflow concentrations in g/m^3; a is the degradation coefficient; chl is the channel length in km; q is the

flow rate in mm/day; SP_i and SP_o are the inflow and outflow soluble P loads in kg; and OP_i and OP_o are the inflow and outflow organic P loads in kg. Similar equations were developed for nitrogen.

SWAT has been extensively validated across the U.S. for stream flow and sediment yields (Arnold *et al.,* 1999). Limited validation of the SWAT nutrient simulation has been attempted (Engel *et al.,* 1993; Jacobson *et al.,* 1995; Alexander *et al.,* 2000; Saleh *et al.,* 2000). Saleh *et al.* (2000) applied SWAT to subwatersheds in the Bosque River basin upstream of Hico. However, in that project, dairy waste application areas were simulated by a multi-field scale model, Agricultural Policy Environmental eXtender (APEX) and input to SWAT. In this project, dairy management practices were directly input to and simulated by SWAT.

Watershed Description

The SWAT model was applied to the 4277 km^2 Bosque River Watershed that flows into Lake Waco (Figure 3) which is the source of drinking water to the city of Waco, Texas. Landuses in this watershed is mostly range and pasture in the upper portion while

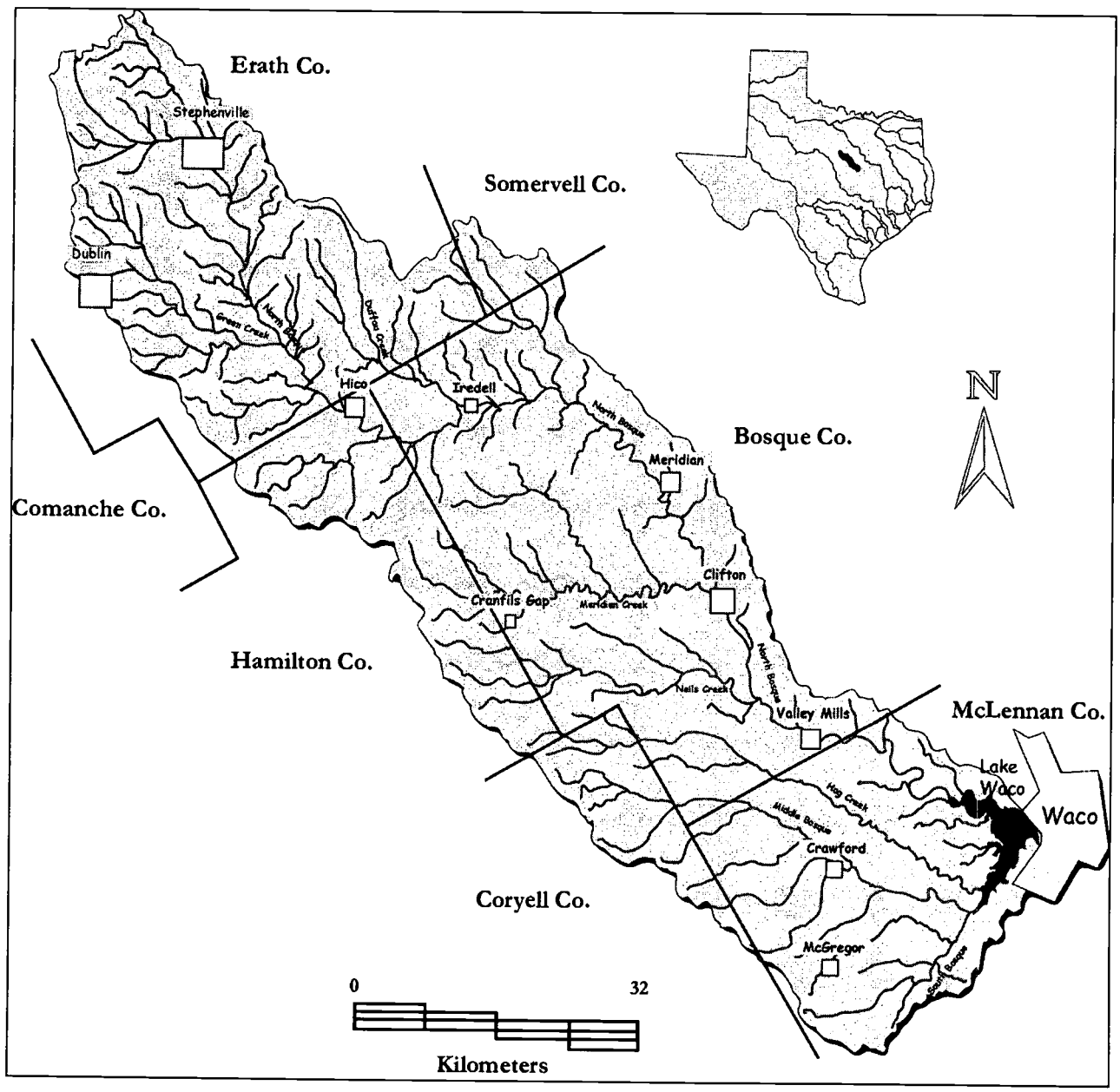


Figure 3. Bosque River Watershed in Texas.

TABLE 1. Percentage of Major Landuses in Bosque River Watershed.

Location	Pasture	Range/ Forest	Row and Non-Row Crops	Urban	Dairy Waste Application Fields
Upstream of Hico	15.4	69.2	6.5	1.7	7.2
Upstream of Valley Mills	13.6	73.0	8.9	1.4	3.1
Entire Watershed	15.0	64.0	17.0	2.0	2.0

cropland is wide spread in the southern portion near Middle Bosque River (Table 1). Major soil series are Windthorst (sandy loam, deep, hydrologic group C), Purves (clay, fine, shallow, hydrologic group D), Denton (silty clay, fine, deep, hydrologic group D), Brackett (clay loamy, gravel, deep, hydrologic group C), Crawford (silty clay, fine, deep, hydrologic group C), Eckrant (clay, fine, shallow, hydrologic group D), and Aledo (clay loam, gravel, shallow, hydrologic group C). The percentages of shallow soils above Hico, above Valley Mills, and in the entire watershed are about 5.5, 22.5 and 28.0, respectively.

There are about 100 dairies with 40,450 cows in this watershed mainly located upstream of Hico. Dairy manure is applied over an area of about 9,450 ha. Application of manure to pasture or cropland may contribute to the nonpoint source pollution. The Texas Institute for Applied Environmental Research (TIAER) has monitored stream runoff, sediment, and nutrients for several areas in the watershed since the early 1990s (McFarland and Hauck, 1995). In the validation process, the model is operated with input parameters set during the calibration process without any change and the results are compared to the remaining observational data. There is a strong positive correlation between elevated levels of phosphorus, the number of cows and the total acreage of manure application fields (McFarland and Hauck, 1997; McFarland and Hauck, 1999). Other sources of pollution include runoff from cropland and urban areas and effluent from WWTPs.

Model Inputs for Bosque River Watershed

A Geographic Resource Analysis Support System-Geographic Information System (GRASS-GIS) interface (Srinivasan and Arnold, 1994) was used to develop SWAT input files for the watershed (Table 2). Initially, the watershed was delineated into subbasins using the digital elevation map. The delineated subbasin map, landuse, soils and waste application field maps were overlaid to identify the manure-application and nonapplication areas in each subbasin. SWAT simulates different landuses in each subbasin.

The following crops were used on the manure/waste application area: summer pasture/bermuda grass (40 percent of the area); summer pasture grass with winter wheat in rotation (30 percent); sorghum

TABLE 2. Model Input Data Sources for Bosque River Watershed.

Data Type	Scale	Source	Data Description/Properties
Topography	1:24,000	USGS	Elevation, overland, and channel slopes, lengths
Soils	1:24,000	USDA-NRCS	Soil physical properties like bulk density, texture, saturated conductivity, etc.
Landuse	1:24,000	USGS	Landuse classifications
Manure Application Field Map	1:24,000	TIAER	Location and area of the waste application fields
Weather	12 stations	NWS	Daily precipitation and temperature
Waste Water Treatment Plant Information	8 plants	TIAER	Daily outflow, sediment, organic and mineral nutrients
Land Management Information	–	TIAER	Fertilizer and manure application rates and timing, tillage, planting, and harvesting dates for different crops

hay (5 percent); and sorghum hay-winter wheat in rotation (25 percent). Four to five hay cuttings per year were simulated. For waste application area, the annual manure application rate was determined based on the number of animals and the annual amount of manure generated per animal (ASAE, 1988). Manure nutrient concentrations were taken from experimental studies (Gassman, 1997).

Nonwaste application pasture was modeled as improved pasture, with typical nutrient application rate and four grass cuttings per year. Corn, winter wheat, and grain sorghum were the major crops on cropland. Urban land inputs had pervious (to represent lawn/garden) and impervious (street sweeping) land management. Other typical management inputs on tillage operations, irrigation, fertilizer application dates and amounts were used wherever applicable.

Water quality data from WWTPs of the eight towns in the watershed were input into the SWAT-GIS interface as point sources (Figure 3).

Evaluation of Model Prediction

Mean, standard deviation, coefficient of determination (R^2), Nash-Suttcliffe simulation efficiency (E_{NS}) (Nash and Suttcliffe, 1970) and sorted efficiency or prediction efficiency (P_E) were used to evaluate model prediction. The R^2 value is an indicator of strength of relationship between the observed and simulated values. Nash-Suttcliffe simulation efficiency (E_{NS}) indicates how well the plot of observed versus simulated value fits the 1:1 line. The prediction efficiency (P_E) indicates the model's ability to describe the probability distribution of the observed results. If the R^2, E_{NS}, and P_E values are less than or very close to zero, the model prediction is considered "unacceptable or poor." If the values are one, then the model prediction is "perfect." However, there are no explicit standards specified for assessing the model prediction using these statistics.

Model Calibration

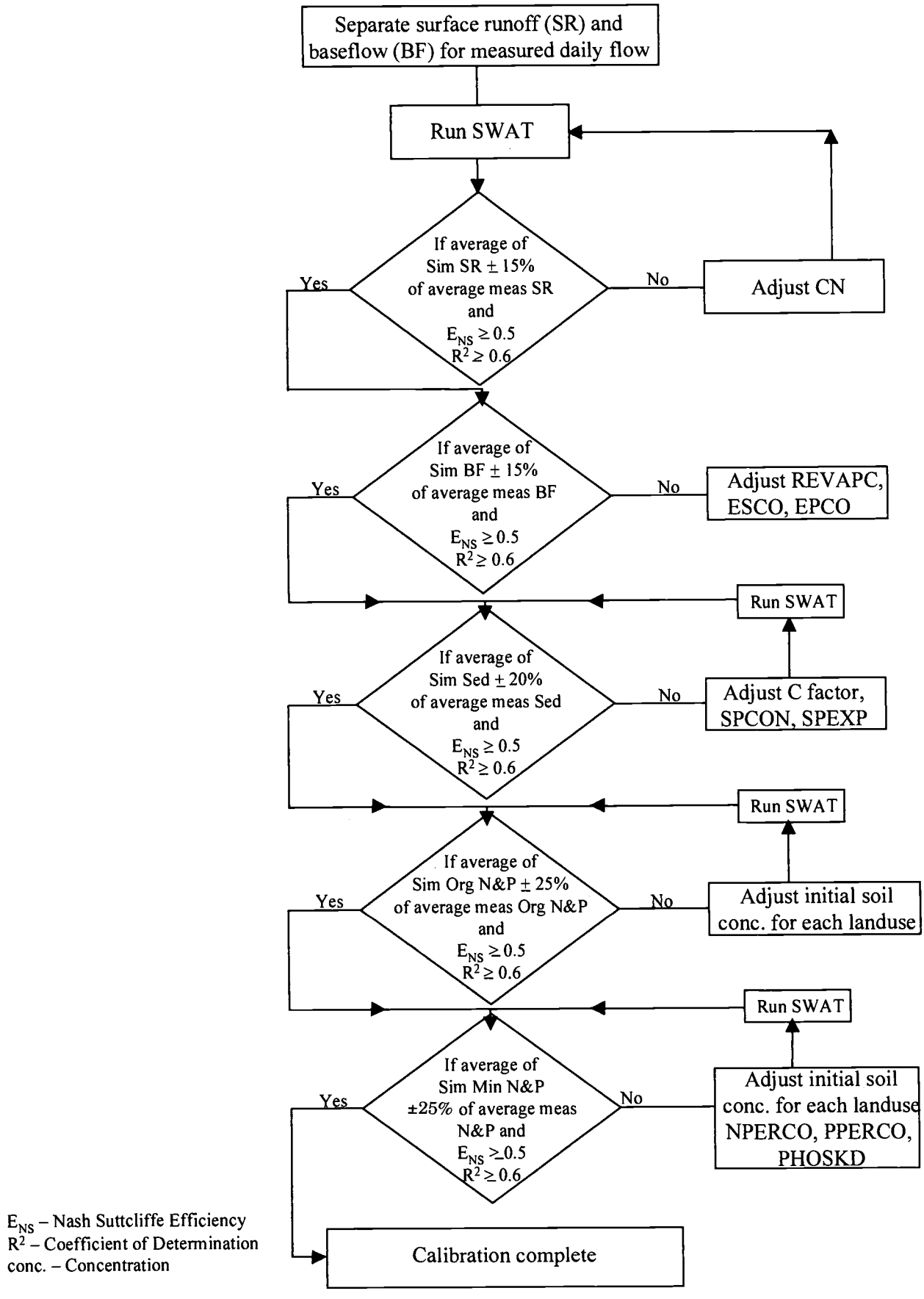
The SWAT model was built with state-of-the-art components with an attempt to simulate the processes physically and realistically. Most of the model inputs are physically based (that is, based on readily available information). It is important to understand that SWAT is not a "parametric model" with a formal optimization procedure (as part of the calibration process) to fit any data. Instead, a few important variables that are not well defined physically such as runoff curve number and Universal Soil Loss Equation's cover and management factor, or C factor, may be adjusted to provide a better fit.

Water quality data from TIAER monitoring stations (McFarland and Hauck, 1997) were used to calibrate and validate SWAT for the Bosque River Watershed. Both long-term (wherever measured data available) and short-term simulation results were compared with measured data at six locations in the watershed. The results of the two most important gaging stations (Hico and Valley Mills on the North Bosque River) are discussed in this paper. Hico is located immediately below the majority of the dairy industry and the largest WWTP (Stephenville). Valleys Mills is the last monitoring station along the North Bosque River near Lake Waco. Watershed areas above Hico and Valley Mills are 926 and 2,997 km^2, respectively.

Calibration Procedure. The procedure for calibrating the SWAT model for flow, sediment and nutrients is shown in Figure 4. Initially, base flow was separated from surface flow for both observed and simulated stream flows using an automated digital filter technique (Nathan and McMahon, 1990; Arnold and Allen, 1999). Calibration parameters for various model outputs were constrained within the ranges shown in Table 3. Model outputs were calibrated to fall within a percentage of average measured values and then monthly regression statistics (R^2 and E_{NS}) were evaluated. If measured and simulated means met the calibration criteria and monthly R^2 and E_{NS} did not, then additional checking was performed to ensure that rainfall variability and plant growing seasons were properly simulated over time. If all parameters were pushed to the limit of their ranges for a model output (i.e., flow or sediment or nutrient) and the calibration criteria were still not met, then calibration was stopped for that output.

Stream flow was the first output calibrated (Figure 4). Surface runoff was calibrated until average measured and simulated surface runoff was within 15 percent and monthly $R^2 > 0.6$ and $E_{NS} > 0.5$. The same criteria were applied to base flow, and surface runoff was continually rechecked as the base flow calibration variables also effect surface runoff. Sediment was calibrated after flow calibration and continued until average measured and simulated sediment loads were within 20 percent. Organic and mineral nitrogen and phosphorus were calibrated to within 25 percent after flow and sediment calibration were completed (Figure 4).

There are numerous potential errors that can occur in the measured input data and data used for calibration, including: (1) spatial variability errors in rainfall, soils and land use; (2) errors in measuring flow;



E_{NS} – Nash Suttcliffe Efficiency
R^2 – Coefficient of Determination
conc. – Concentration

Figure 4. Calibration Procedure for Flow, Sediment, and Nutrients in the SWAT Model.

TABLE 3. Inputs Used in Model Calibration.

Variable Name	Model Processes	Description*	Model Range	Actual Value/ Change Used
CN2	Flow	Curve number	±10%	+ 10%
REVAPC	Flow	Ground water revap coefficient	0.00 to 1.00	0.03
ESCO	Flow	Soil evaporation compensation factor	0.00 to 1.00	0.60
EPCO	Flow	Plant uptake compensation factor	0.00 to 1.00	0.10
C FACTOR	Sediment	Cover or management factor	0.003 to 0.45	Pasture: 0.006 Range: 0.10 Cropland: 0.20
SPCON	Sediment	Linear factor for channel sediment routing	0.0001 to 0.01	0.0008
SPEXP	Sediment	Exponential factor for channel sediment routing	1.0 to 1.5	1.00
SOL_ORGN	Organic N	Initial organic N concentration in the upper soil layer for a particular land use		Manure Area: 5000 ppm Pasture/Range: 850 ppm Cropland: 1100 ppm Urban: 2000 ppm
SOL_ORGP	Organic P	Initial organic P concentration in the upper soil layer for a particular land use		Manure Area: 700 ppm Pasture/Range: 150 ppm Cropland: 200 ppm Urban: 400 ppm
NPERCO	Mineral N	Nitrogen percolation coefficient	0.2 to 0.6	0.5
SOL_MINP	Mineral P	Initial mineral P concentration in the upper soil layer for a particular land use		Manure Area: 250 ppm Pasture/Range: 5 ppm Cropland: 20 ppm Urban: 5 ppm
PPERCO	Mineral P	Phosphorus percolation coefficient	10.0 to 17.5	10
PHOSKD	Mineral P	Phosphorus soil partitioning coefficient	100-175	100
BIOMIX	Sediment, Organic, and Mineral Nutrients	Biological mixing efficient	0.2 to 0.5	0.40
RSDCO	Sediment, Organic, and Mineral Nutrients	Residue decomposition coefficient	0.01 to 0.05	0.05

*Detailed descriptions are available at http://www.brc.tamus.edu/swat/manual (USDA-ARS, 1999).

and (3) errors caused by sampling strategies. Winter (1981) suggests errors in annual estimates of precipitation, stream flow, and evaporation ranged from 2 to 15 percent whereas monthly rates could range from 2 to 30 percent. Errors in sampling strategies can also be significant. Walling and Webb (1988) determined that using continuous turbidity and daily flow data resulted in errors of 23 to 83 percent when calculating annual sediment loads. Robertson and Roerish (1999) found median absolute errors in annual phosphorus loads up to 30 percent depending on sampling strategies. The calibration criteria for this study evolved based on these potential errors shown in literature.

Flow. Stream flows from the United States Geological Survey's (USGS) stations, and SWAT simulation were calibrated (Figure 4) for the period from 1960 through 1997 at Hico and Valley Mills. For flow calibration, the runoff curve numbers (CN2) were adjusted within 10 percent from the tabulated curve numbers (Mockus, 1969) to reflect conservation tillage practices and soil residue cover conditions of the watershed (Table 3). Other flow related model parameters such as re-evaporation coefficient for ground water [REVAPC represents the water that moves from the shallow aquifer back to the soil profile/root zone and plant uptake from deep roots (Arnold *et al.*, 1993)], soil evaporation compensation factor (ESCO), and plant evaporation compensation factor (EPCO) were adjusted from SWAT initial estimates to match the simulated and observed flows (Table 3). However, long-term calibration for sediment and nutrients

could not be done, as observed data were not available.

The model was then run from 1990 through 1998 for calibrating sediment and nutrients as per availability of the monitored data. Calibration of sediment and nutrient loads (kg/ha) were conducted for Hico from 1993 through 1997 and for Valley Mills from 1996 through 1997 on a monthly basis. The simulation was started from 1990 to reduce errors in initial estimates of state variables such as soil water content and surface residue.

Sediment. The cover, or C factor, of the Universal Soil Loss Equation for range and pasture was adjusted to match observed and simulated sediment loads (Figure 4). The C factor was adjusted (Table 3) to represent the surface cover better in the range and pasture lands. Channel sediment routing variables such as the linear factor for calculating the maximum amount of sediment reentrained during channel sediment routing (SPCON) and the exponential factor for calculating the sediment reentrained in the channel sediment routing (SPEXP) were also adjusted (Table 3) during the sediment calibration. These two variables were adjusted to represent the cohesive nature of the channels in this watershed (Allen *et al.,* 1999).

Organic Nutrients. Initial concentrations of organic nitrogen and phosphorus in the soil upper layers (SOL_ORGN and SOL_ORGP) for different landuses are available in the soil database table (USDA-ARS, 1999). However, these values were refined/modified to suit each landuse condition in this watershed (Table 3 and Figure 4).

Mineral Nutrients. SWAT estimates the initial concentration for mineral N (Min N) based on the soil properties at individual subbasins. Therefore, no adjustments were made to initial concentration of min N. Nitrogen percolation coefficient (NPERCO) was adjusted from initial value of SWAT to match this watershed condition (Table 3 and Figure 4). Initial concentration for mineral P (min P) in the soil upper layer (SOL_MINP) for different landuse was set at appropriate levels based on available literature (Gassman, 1997; A. N. Sharpley, USDA-ARS, Durant, Oklahoma, and L. M. Hauck, TIAER, Stephenville, Texas, personal communication, 1998). Other min P related coefficients such as phosphorus percolation coefficient (PPERCO) and phosphorus soil partitioning coefficient (PHOSKD) were initialized at acceptable levels (Table 3 and Figure 4) to suit the conditions of the watershed (L. M. Hauck, TIAER, Stephenville, Texas, personal communication, 1998). The residue decomposition coefficient (RSDCO) and biological mixing efficiency (BIOMIX) were also adjusted (Table 3). The initial values of most of these variables are already set at default values in the SWAT model. They were refined during the calibration to suit the Bosque River Watershed conditions.

Model Validation

In the validation process, the model is operated with input parameters set during the calibration process without any change and the results are compared to the remaining observational data to evaluate the model prediction. Measurements for January through December 1998 were used to validate the model for Hico and Valley Mills. The same statistical measures were used to assess the model prediction.

Best Management Practices

The calibrated model was used to study the long-term effects of various BMPs related to dairy manure management and municipal wastewater treatment plant loads in this watershed. Among several scenarios studied, four scenarios are discussed in this paper. Detailed description of the BMPs can be found in Santhi *et al.* (2000). The existing condition scenario simulates the watershed under existing conditions such as present dairy herd size, present waste application fields (WAF) areas, average manure application rate (13 t/ha/yr), present discharge volumes from WWTPs with current median concentrations for nutrients, and present urban and cropland areas (Table 4). The future condition scenario reflects the projected conditions of the watershed in year 2020 such as projected dairy herd size (67,000), manure application in WAFs at the crop nitrogen requirement rate (N rate at 46 t/ha/yr), WAF area calculated at N rate requirement, maximum permitted discharge volumes from WWTPs using nutrient concentrations defined by current median values, urban area increased by 30 percent to reflect the projected population growth in 2020, and cropland area at current levels (due to no increase in cropland over last two decades) (Table 4). Three additional WWTPs with 1 mg/l concentration of total P were input into the model as point sources along the North Bosque River to account for possible industrial future growth outside existing communities.

Several management practices on dairy manure and WWTP effluents were simulated to study the impact in reducing the min P loadings. Dairy management practices such as hauling of the solid manure from watershed, application of manure at crop P requirement rate (P rate) at 6.3 t/ha/yr (as N rate allows excess application of P than crop required),

TABLE 4. Assumptions of BMP Scenarios.

Scenario	WWTP Flow Period	WWTP P Limit	Dairy Manure Application Rate	Reduced P in Diet	Manure Haul Off
Existing	1997-1998 (actual)	Median Concentration	Btw N&P Rate	No	No
Future	2020 (permitted)	Median Concentration	N Rate	No	No
Scenario E	1997-1998	All WWTPs at Median Concentration and Stephenville WWTP – 1 mg/l	P Rate	Yes	Yes
Scenario F	2020	All WWTPs with Loads Equal to Scenario E and Stephenville WWTP – With load equal to 1 mg/l of future	P Rate	Yes	Yes

and reduction of the dairy diet P to 0.4 percent (results in reducing the dairy manure P content by 29 percent as suggested by Keplinger, 1999) were imposed. The concentrations of total P in WWTP effluents were reduced to 1 mg/l.

Scenario E was a modification of the existing condition scenario with additional conditions imposed on manure application rate (P rate), hauling off 38 percent of the manure, P diet reduction in animal feed, and 1 mg/l limits of P in WWTPs (Table 4). Scenario F was a modification over the future scenario with manure applied at P rate, hauling off 38 percent of the manure, P diet reduction, and 1 mg/l P limits on all WWTPs.

RESULTS AND DISCUSSION

Model Calibration

Flow. Measured and simulated annual flows at Hico and Valley Mills matched well (Figures 5a and 5b). Monthly simulated and observed flows during the nutrient calibration at the two locations matched well (Figures 6a and 7a). Means and standard deviations of the observed and simulated flows for long-term and short-term at Hico and Valley Mills were within a difference of 10 percent (Tables 5 and 6). Further agreement between observed and simulated flows at Hico and Valley Mills are shown by the coefficient of determinations greater than 0.6, E_{NS} and P_E values greater than 0.72 (Tables 5 and 6). The estimated proportions of base flow from the observed flows at Hico and Valley Mills were 30 percent and 34 percent from the filter technique. They were 28 percent and 27 percent for the same locations for SWAT simulated flows. These results for surface runoff and base flow for observed and simulated flows reveal that hydrologic processes in SWAT are modeled realistically and the concentrations at all flow regimes are realistic.

Sediment. The temporal variations of sediment loading at Hico and Valley Mills are represented in Figures 6b ad 7b. There is a significant R^2 relationship between observed and simulated sediments both at Hico and Valley Mills ($R^2 \geq 0.81$). The values of E_{NS} for Hico and Valley Mills above 0.69 indicate that the simulated sediment is closer to the observed sediment. The P_E values at Hico and Valley Mills indicate that model explained the probability distribution of the observed sediments well (Tables 5 and 6).

Organic Nutrients. Monthly loadings of organic nitrogen and phosphorus (Org N and org P) for Hico and Valley Mills are shown in Figures 6c, 6d, 7c and 7d. Mean and standard deviation for observed and simulated org N are within 10 percent of difference at Hico (Table 5). The R^2 value indicated that observed and simulated values were closer and E_{NS} indicated that the observed versus simulated plot was close to 1:1. There were under prediction of loads during a few months in early 1993 and middle of 1997 (Figure 6c). At Valley Mills, simulated org N was much closer to observed org N (Table 6). At Hico and Valley Mills, the values of simulated and observed org P were closer (Tables 5 and 6). The deviations of the simulated values were closer to their mean compared to the observed values.

Mineral Nutrients. The temporal patterns of observed and simulated min N and P for Hico (Figures 6e and 6f) and statistics indicated that predictions of Min N and P at Hico corresponded well with the observed values (Table 5). However, the model overpredicted the min N at Valley Mills during

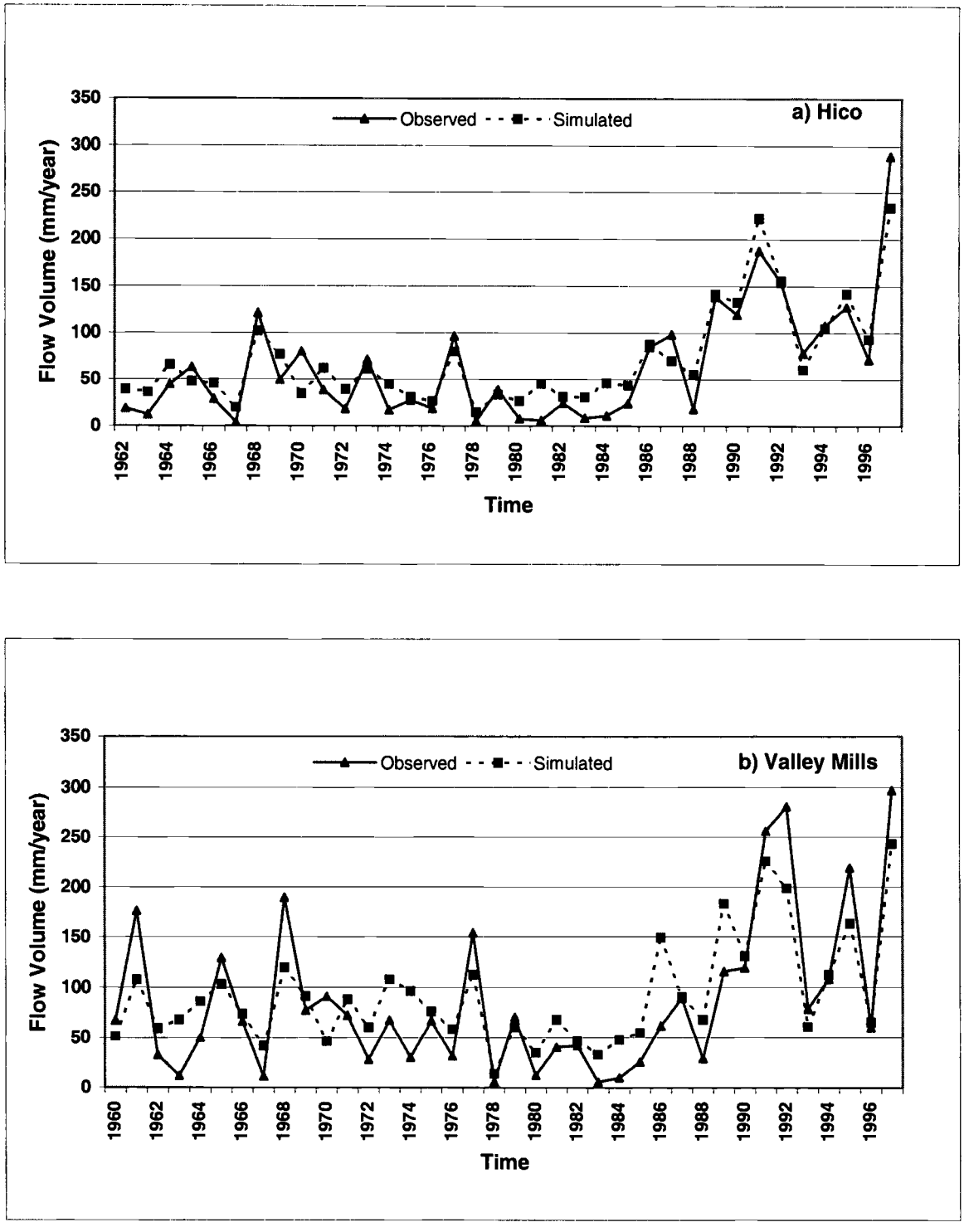


Figure 5. Observed and Simulated Annual Flows at (a) Hico and (b) Valley Mills.

February 1997 (Figure 7e) and as a result the E_{NS} and prediction efficiency showed poor correspondence of observed versus simulated values, even though the R^2 value of 0.72 (Table 6) indicated the strong linear relationship between the observed and simulated loadings. The trends for min P were relatively closer to the observed values at Valley Mills (Figure 7f) and statistics indicated that the prediction of min P was reasonable (Table 6).

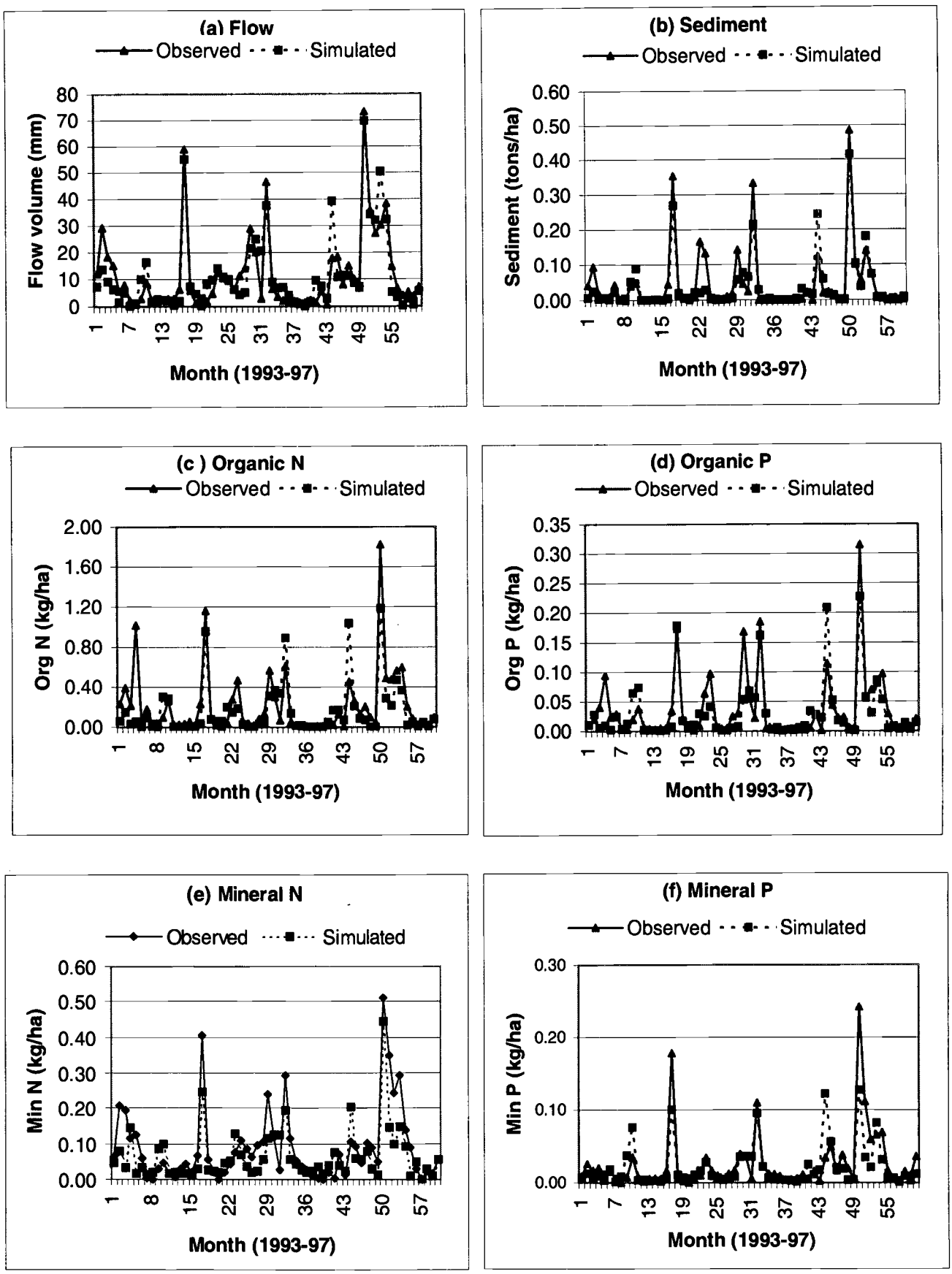


Figure 6. Observed and Simulated Monthly Flow and Sediment and Nutrient Loadings at Hico During Calibration Period.

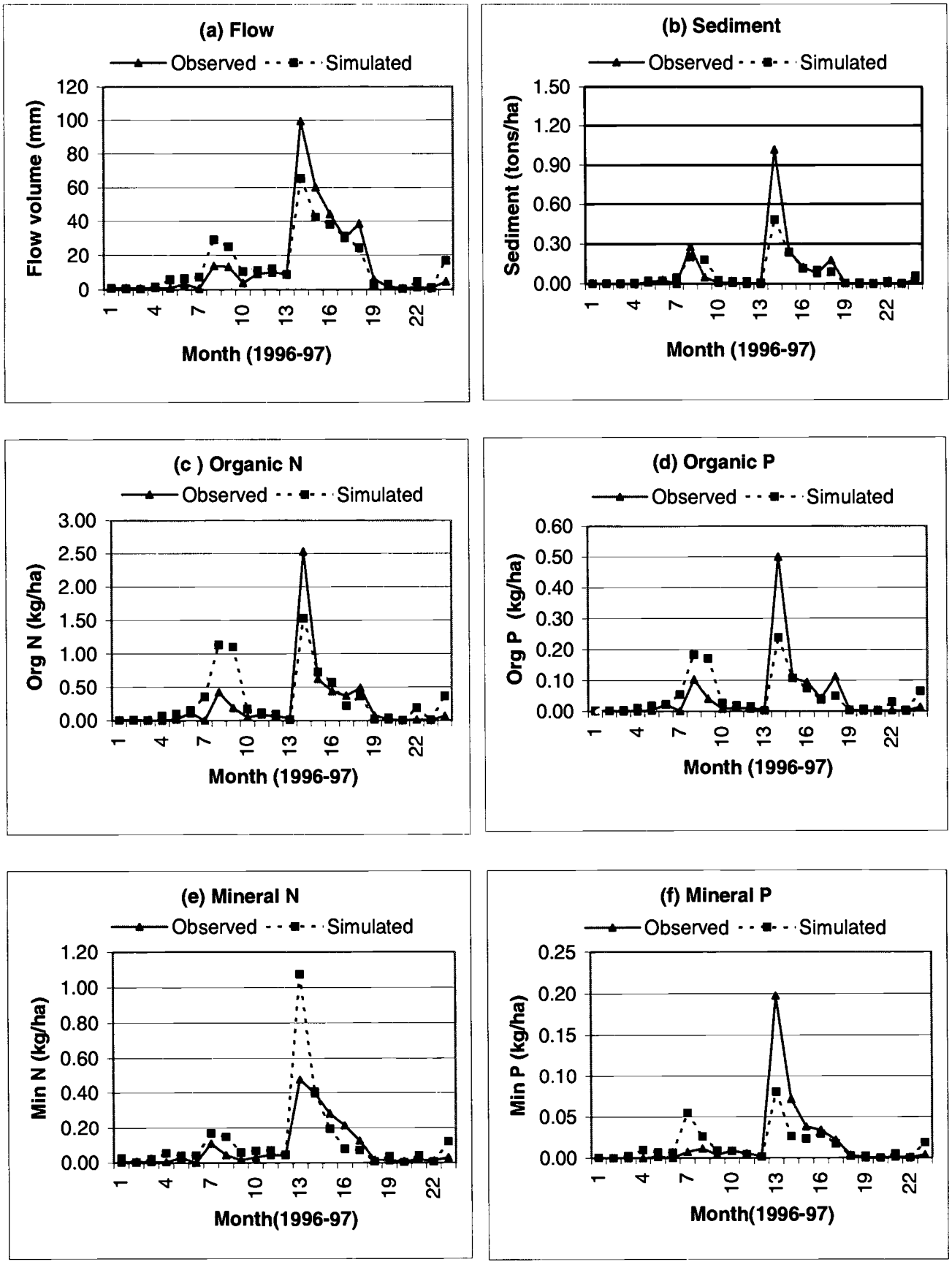


Figure 7. Observed and Simulated Monthly Flow and Sediment and Nutrient Loadings at Valley Mills During Calibration Period.

TABLE 5. Monthly Calibration Results at Hico for the Period 1993 to 1997.

Variable (units)	Mean		Standard Deviation		R^2	E_{NS}	P_E
	Observed	Simulated	Observed	Simulated			
Flow Volume (mm)*	64.460	72.090	62.280	52.970	0.88	0.86	0.92
Flow Volume (mm)	12.110	11.790	15.060	14.820	0.80	0.79	0.99
Sediment (t/ha)	0.045	0.038	0.092	0.077	0.81	0.80	0.94
Organic N (kg/ha)	0.213	0.161	0.322	0.260	0.61	0.58	0.87
Organic P (kg/ha)	0.036	0.031	0.057	0.049	0.71	0.70	0.93
Mineral N (kg/ha)	0.090	0.065	0.105	0.073	0.64	0.59	0.82
Mineral P (kg/ha)	0.026	0.021	0.042	0.030	0.60	0.59	0.83

*Annual flow between 1962 and 1997.

TABLE 6. Monthly Calibration Results at Valley Mills for the Period 1993 to 1997.

Variable (units)	Mean		Standard Deviation		R^2	E_{NS}	P_E
	Observed	Simulated	Observed	Simulated			
Flow Volume (mm)*	86.500	92.310	77.050	53.230	0.66	0.72	0.89
Flow Volume (mm)	15.220	14.800	25.340	17.420	0.89	0.83	0.85
Sediment (t/ha)	0.086	0.069	0.214	0.112	0.87	0.69	0.72
Organic N (kg/ha)	0.236	0.308	0.522	0.418	0.60	0.57	0.70
Organic P (kg/ha)	0.045	0.048	0.104	0.065	0.61	0.59	0.67
Mineral N (kg/ha)	0.081	0.117	0.130	0.222	0.72	-0.08	0.03
Mineral P (kg/ha)	0.017	0.014	0.042	0.019	0.66	0.53	0.64

*Annual flow between 1960 and 1997.

Model Validation

Flow. Observed and simulated flows at Hico matched well (Figure 8a and Table 7). The model underpredicted the flow in the month of March 1998 and slightly overpredicted in late 1998 at Valley Mills (Figure 9a). The difference might be due to the spatial variability of precipitation. However, the prediction statistics were high at both locations (Tables 7 and 8).

Sediment. Observed and simulated sediment loading at Hico matched well except for March 1998 when the flow was also underpredicted by the model (Figure 8b). Again, statistics show prediction at Hico was satisfactory (Table 7). Predicted sediment was very low for March 1998 at Valley Mills (Figure 9b) and statistical parameters (Table 8) show poor agreement between observed and simulated results.

Organic Nutrients. The time series plots for organic N and P at Hico and Valley Mills (Figures 8c, 8d, 9c, and 9d) show model underprediction in March 1998. Being sediment bound nutrients, they follow the trends of sediment. Observed and simulated loading for both nutrients at Hico corresponded reasonably well (Table 7), while results indicate that the model underpredicted these nutrients at Valley Mills (Table 8).

Mineral Nutrients. Observed and simulated min N and P at Hico and Valley Mills showed similar trends (Figures 8e, 8f, 9e, and 9f). Predicted and observed min N and P at Hico and Valley Mills matched fairly well except for a slight overprediction of min P in early 1998 at Hico and at the end of 1998 at both locations. Statistics show simulated and observed min N and P at both locations were closer (Tables 7 and 8).

BMP Analysis

Min P loadings are displayed as probability exceedance plots to analyze the effectiveness of BMPs. In these exceedance plots, annual min P loadings (y-axis) for the simulation period (1960 through 1998) were ordered and plotted with their associated exceedance probability values (x-axis) for Hico and

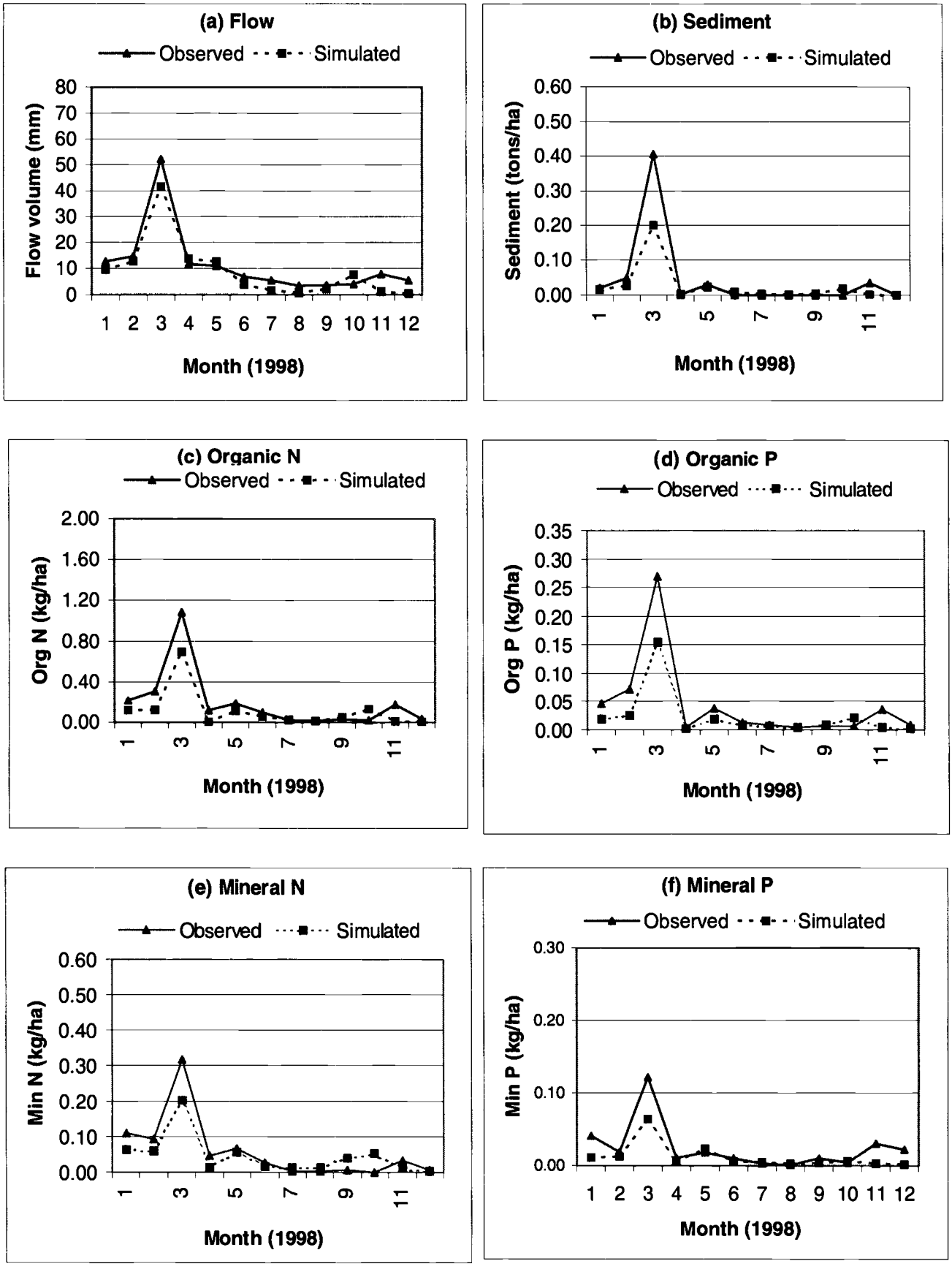


Figure 8. Observed and Simulated Monthly Flow and Sediment and Nutrient Loadings at Hico During Validation Period.

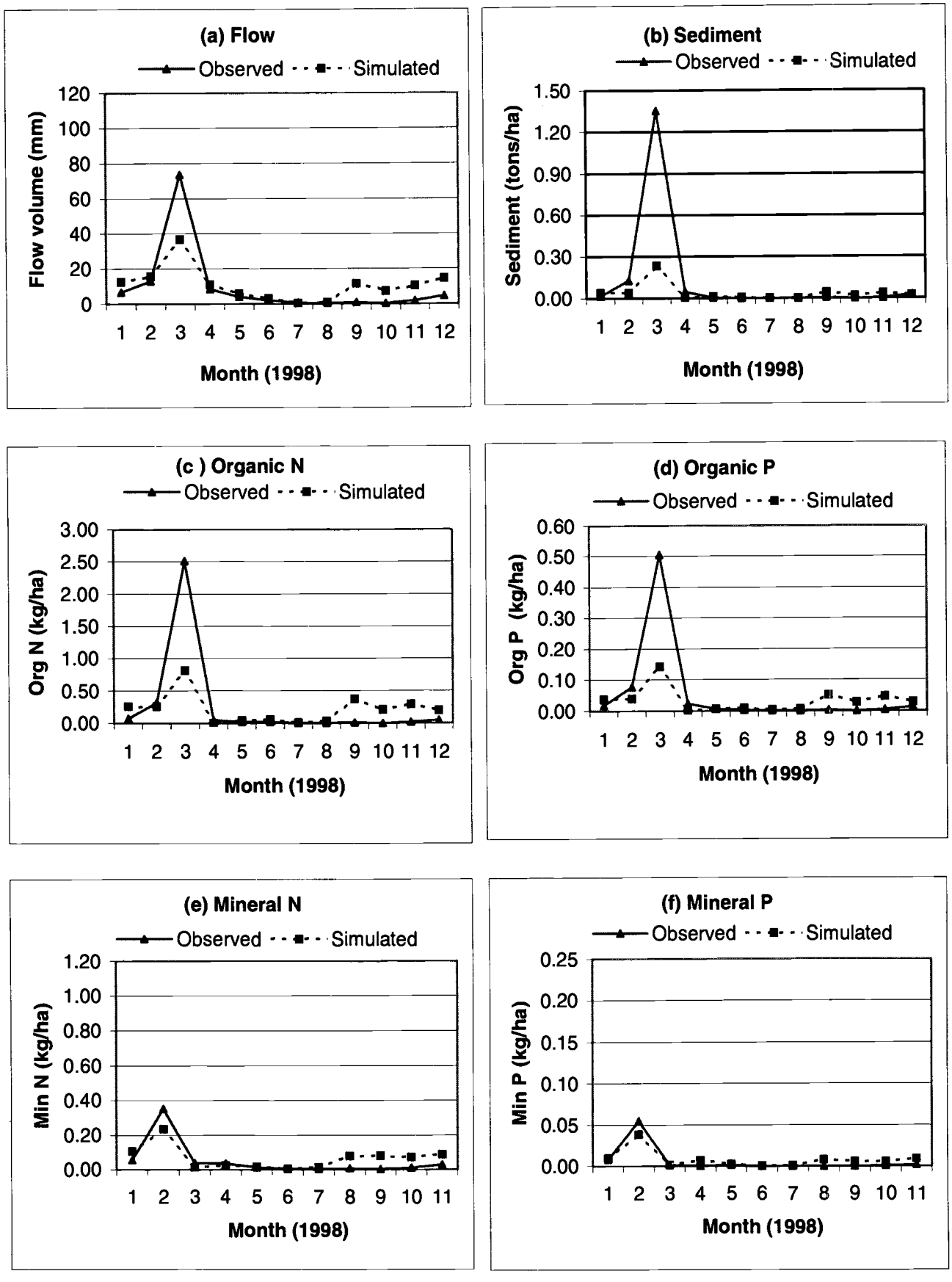


Figure 9. Observed and Simulated Monthly Flow and Sediment and Nutrient Loadings at Valley Mills During Validation Period.

TABLE 7. Monthly Validation Results at Hico for the Period 1998.

Variable (units)	Mean		Standard Deviation		R^2	E_{NS}	P_E
	Observed	Simulated	Observed	Simulated			
Flow Volume (mm)	11.580	9.000	13.120	11.290	0.92	0.87	0.91
Sediment (t/ha)	0.045	0.025	0.114	0.056	0.98	0.70	0.70
Organic N (kg/ha)	0.194	0.114	0.296	0.191	0.92	0.73	0.79
Organic P (kg/ha)	0.043	0.023	0.074	0.042	0.95	0.72	0.73
Mineral N (kg/ha)	0.060	0.046	0.089	0.054	0.89	0.75	0.81
Mineral P (kg/ha)	0.024	0.012	0.033	0.017	0.83	0.53	0.62

TABLE 8. Monthly Validation Results at Valley Mills for the Period 1998.

Variable (units)	Mean		Standard Deviation		R^2	E_{NS}	P_E
	Observed	Simulated	Observed	Simulated			
Flow Volume (mm)	9.760	10.980	20.150	9.470	0.80	0.62	0.63
Sediment (t/ha)	0.132	0.039	0.386	0.064	0.95	0.23	0.23
Organic N (kg/ha)	0.257	0.211	0.715	0.224	0.71	0.43	0.44
Organic P (kg/ha)	0.055	0.034	0.144	0.039	0.80	0.39	0.41
Mineral N (kg/ha)	0.050	0.068	0.097	0.063	0.72	0.64	0.73
Mineral P (kg/ha)	0.006	0.008	0.016	0.010	0.93	0.81	0.83

Valley Mills (Figure 10). These plots provide information on the probability of achieving a particular load of min P through a BMP at a particular location. Min P loading curves for the various scenarios varied from 10,000 kg to 40,000 kg at 10 percent probability at Hico, whereas it varied from 20,000 kg to 80,000 kg at Valley Mills. These curves showed loadings within 10,000 kg at Hico at 90 percent probability and they showed loadings within 20,000 kg at Valley mills for the same probability. In general, the loading curves were wider at lower probabilities and they become closer as they reach higher probabilities. The min P loadings were increased by about 27 percent at Hico and 29 percent at Valley Mills in the future condition scenario as compared to the existing condition scenario. These increases were predominantly caused by projected conditions for dairy and WWTPs in the future scenario (Table 4). Scenario E showed reduction in min P loadings of about 67 percent at Hico and 57 percent at Valley Mills from the future scenario. Scenario F showed reduction in min P loadings of about 54 percent at Hico and 48 percent at Valley Mills from the future scenario. Scenario E indicated that at existing conditions implementation of the BMPs (Table 4) would come closer in achieving the desired water quality goals. However, with year 2020 growth (future) conditions, more stringent controls are required to meet the water quality goals.

CONCLUSIONS

The objective of this study was to calibrate and validate the SWAT model for flow, sediment, and nutrients for a watershed where water quality problems exist that involve dairy manure application fields, wastewater treatment plants, croplands, and urban areas. Monthly simulated flow, sediment, and nutrient (organic and mineral) loadings were compared with observed values at Hico and Valley Mills gauging stations for the calibration and validation period.

In most instances, simulated flow, sediment, and nutrients were closer to the measured values during the calibration period. Model validation was done for one year, 1998. In general, simulated flow and nutrients were closer to the measured values during the validation except for some underprediction of simulated sediment and organic nutrients in March 1998 at Valley Mills. These underpredictions caused significant degradation in model prediction statistics in validation. SWAT predictions were acceptable, especially given the approximations and spatial variability involved in simulating a large complex system or watershed.

The calibrated model was used to study the effects of various BMPs on nutrients (Santhi *et al.,* 2000). Scenario E, a scenario with added BMP conditions over the existing scenario, showed higher percentage reductions in min P loadings. SWAT is integrated into

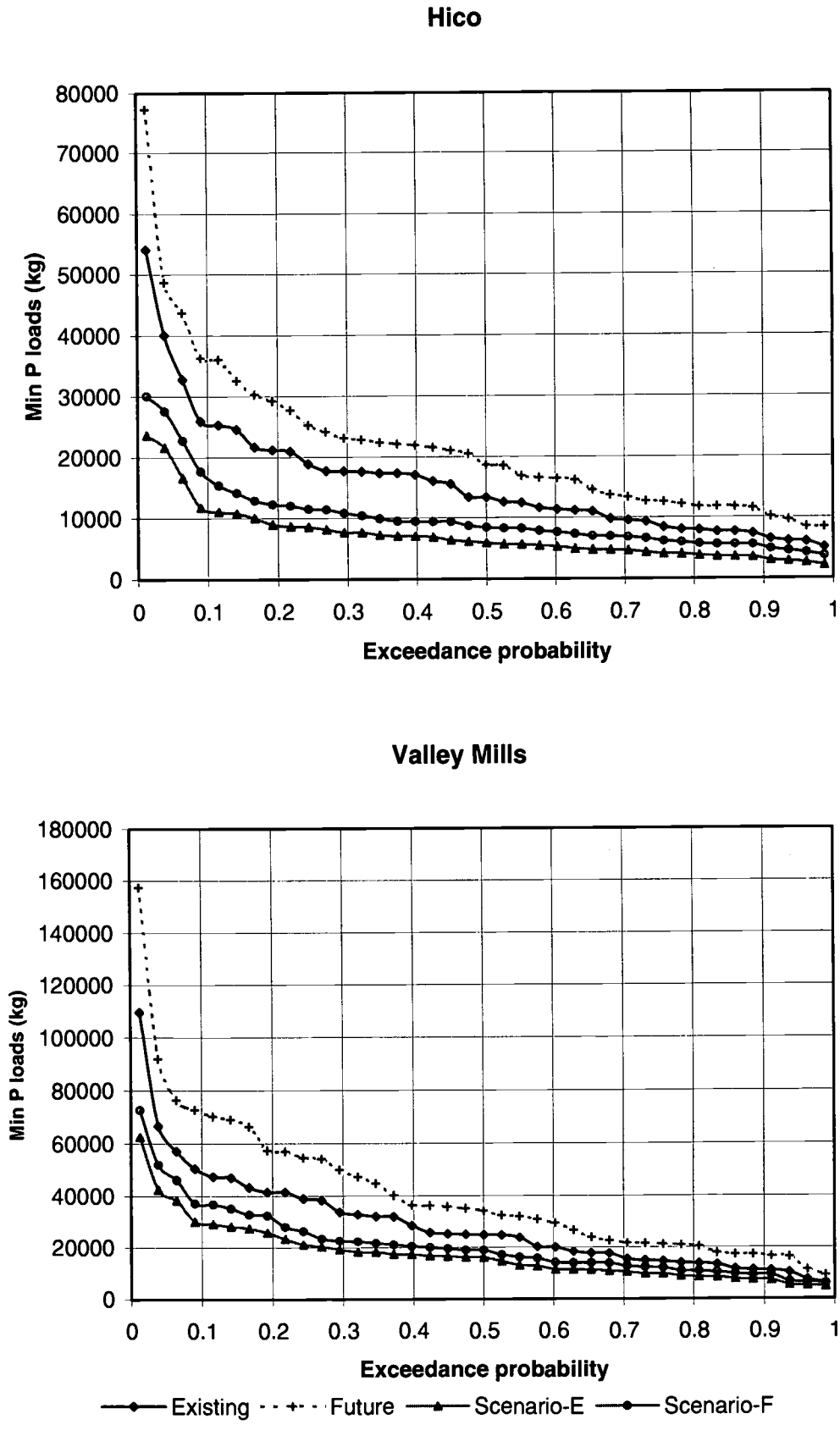


Figure 10. Exceedance Probability of Mineral P Loadings for BMP Scenarios at Hico and Valley Mills.

the USEPA's watershed modeling framework, called BASINS and is expected to be used by many state and federal agencies. The SWAT calibration and validation procedures presented in this paper will be useful to researchers and engineers involved in studying water quality problems.

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Information to Run SWAT Model

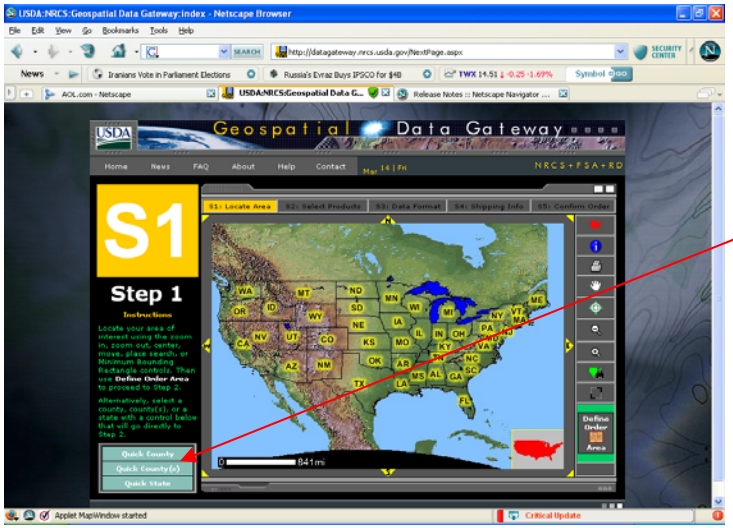
Type	Information	File	Note
Basic Model Info	Model Objectives	-	Have overall objectives of modeling (e.g. nitrogen discharge study)
	Model scale	-	Decide Spatial and temporal scale (How large area, what is the term e.g. daily, monthly, or yearly)
	Modeling period	-	Decide from when to when for model
	Watershed size	-	SWAT also provide watershed size after delineation
GIS data	DEM	GRID	Required. Usually 10m to 30m, sometimes coarser resolution (e.g. USGS DEM or NED)
	Landuse	GRID, .shp	Required.
	Soil	.shp	Required. STATSGO or SSURGO
	Channel network	.shp	Useful to compare with SWAT delineation
Observation Location	Weather station	.shp	Required. Weather station location
	Flow gage station	.shp	Needed for model calibration. Flow gage station location (e.g. USGS gage station)
	Sampling points	.shp	If any.
	Point sources	.shp	Point sources, if any, in watershed. Either existing one or can be manually input.
	Other flow input	.shp	Flow input from outside of watershed, if any
Weather	Precipitation	.pcp	Required. Daily precipitation
	Min. Temperature	.tmp	Required. Daily temperature
	Max Temperature	.tmp	Required. Daily temperature
	Other weather info	.wgn	Not required. Simulated solar energy, wind velocity etc can be used.
Landuse general	Landuse (in HRU) parameters	.hru	SWAT generates default value of all parameters depending on the types of landuse. For example, Initial residue cover, Manning's n for overland flow, Sediment concentration in lateral flow, Enrichment ratio for sediment and nutrients, Pothole storage, etc. Values can be adjusted as necessary.
Management	Management (in HRU) parameters	.mgt	SWAT generates default value of all parameters depending on the types of management. For example, Initial LAI, Initial biomass, Curve number, USLE P, Filter strip width, Irrigation amount, etc. Values can be adjusted as necessary. If tile is simulated, Time to drain soil to field capacity and Drain tile lag time are needed.
	Management schedule	.mgt	Management schedule including plant, harvest, fertilizer and pesticide application, and tillage operation can be input in SWAT, if needed. Auto application can also be established. Information needed includes operation dates, fertilizer amount, tillage depth etc.

SWAT default data	Crop	crop.dat	SWAT offers default value of all parameters for each crop type. For example, LAI, Heat unit, Optimum and minimum temperature, Harvest index, Intercepted PAR, Radiation efficiency, USLE C, Biomass energy ratio, Plant decomposition rate, and etc. However, values can be adjusted as necessary.
	Tillage	till.dat	SWAT offers default value of all parameters for each tillage type. For example, Mixing efficiency and Tillage depth. However, values can be adjusted as necessary.
	Pesticide	pest.dat	SWAT offers default value of all parameters for pesticide. For example, Name, Absorption rate, Wash off, Degradation, Solubility, etc. However, values can be adjusted as necessary.
	Fertilizer	fert.dat	SWAT offers default value of all parameters for fertilizer. For example, Name, Fraction of each nutrient and bacteria. However, values can be adjusted as necessary.
	Urban	urban.dat	SWAT offers default value of all parameters for urban. For example, Fraction of impervious land, Maximum amount of solid built-up in impervious area, Concentration of each nutrient, Curve number for impervious land, etc. However, values can be adjusted as necessary.
Soil	Soil properties	.sol	Usually soil properties are used as default from soil data. However, if necessary, properties can be adjusted such as hydraulic conductivity and USLE K, etc
	Chemical properties	.chm	Optional. For example, initial nutrients and pesticide in soil
Ground Water	Ground water properties	.gw	SWAT offers default value. If necessary, parameter value can be adjusted for Depth of aquifers, Ground water delay time, recharge, and soluble phosphorus, etc
Channel	Channel properties	.rte	SWAT generates channel properties based on DEM and some default value. However, if necessary, properties such as Manning's n, channel erodibility, hydraulic conductivity, channel cover factor, and so on can be adjusted.
Pond	Pond information	.pnd	If pond is included in simulation, some parameters are necessary from user input (usually physical properties) and most of parameter values are offered as default. Parameters are Fraction of subbasin area that draining into the pond(s), Surface area, Volume of water, Initial volume of water, Initial sediment concentration, hydraulic conductivity at the bottom, nutrients settling rate, etc.
Water quality	Watershed-wide water quality	.wwq	SWAT offers default value for all parameters. It can be specified here for watershed wide parameters such as uptake of nutrients by algae and relationship between nutrients, oxygen, and algae.
	Sub-watershed water quality	.swq	SWAT offers default value for all parameters. It can be adjusted for each sub-basin separately for decay and settling of nutrients, bacteria, algae relationship.
	Reservoir	.res	Similar to pond information, some physical properties are necessary for user to input.
	Lake	.lwq	Similar to pond information, some physical properties are necessary for user to input.
Point source	Point source discharge	.dat	Point source including flow, sediment, and nutrients can be input as hourly, daily, monthly, yearly discharge.

SSURGO Processing for ArcSWAT (Geospatial Gateway website)

Go to following website address:
http://datagateway.nrcs.usda.gov/Gatewayhome.html

Get Data

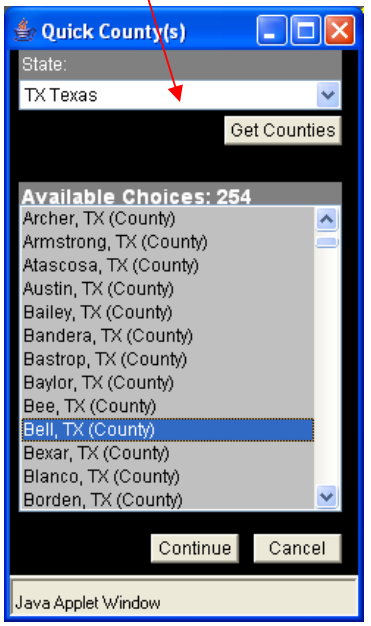


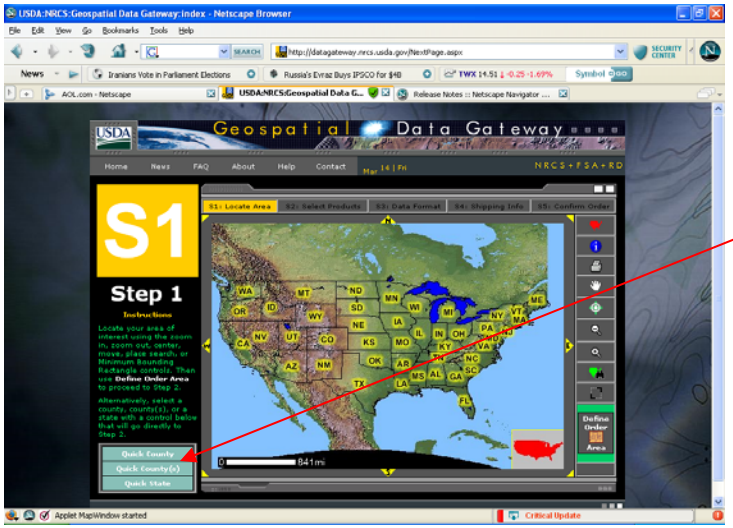
Quick Counties

SSURGO Processing for ArcSWAT (Geospatial Gateway website)

1. Get Data

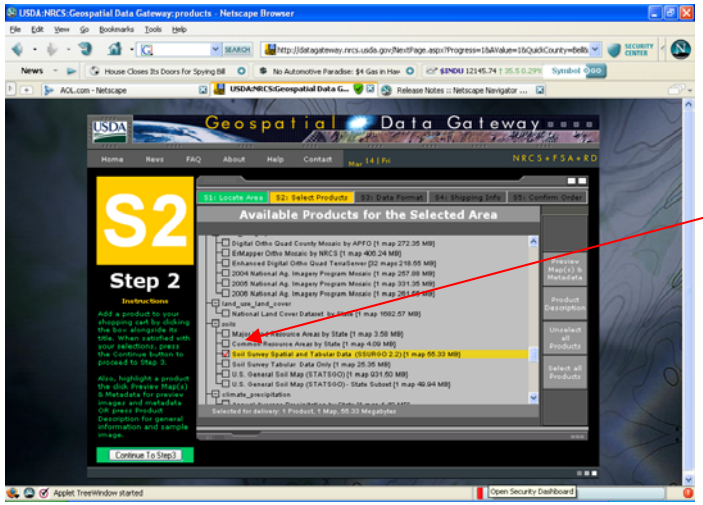
3. Choose state
Get Counties
Choose county
Continue



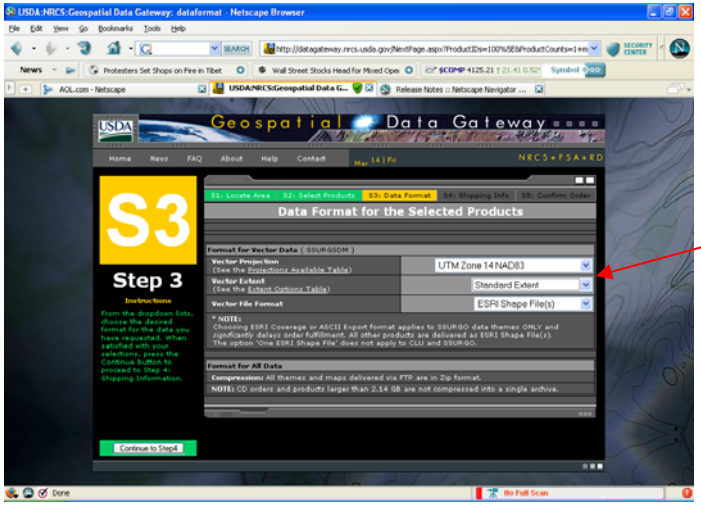


2. Quick Counties

SSURGO Processing for ArcSWAT (Geospatial Gateway website)

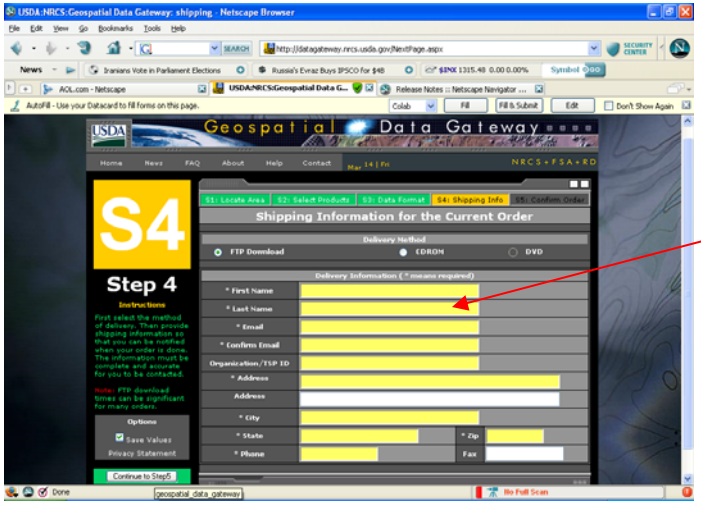


Check Soil Survey Spatial and Tabular Data
SSURGO 2.2
Continue to Step 3

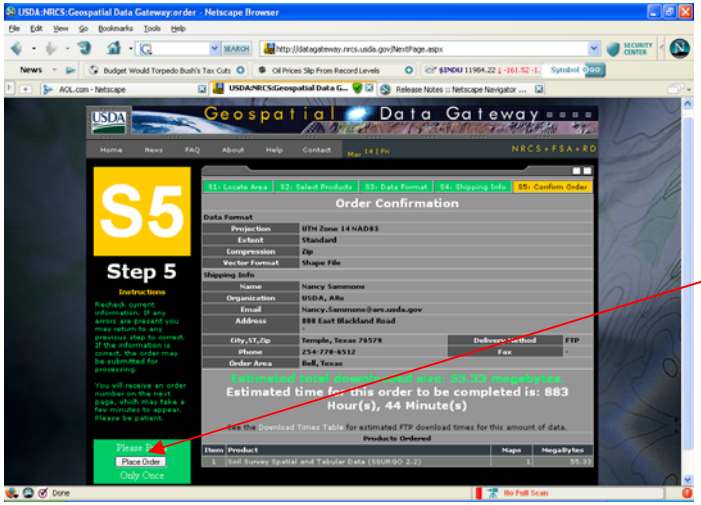


Vector projection – UTM Zone NAD83
Standard Extent
ESRI Shape Files
Continue to Step 4

SSURGO Processing for ArcSWAT (Geospatial Gateway website)



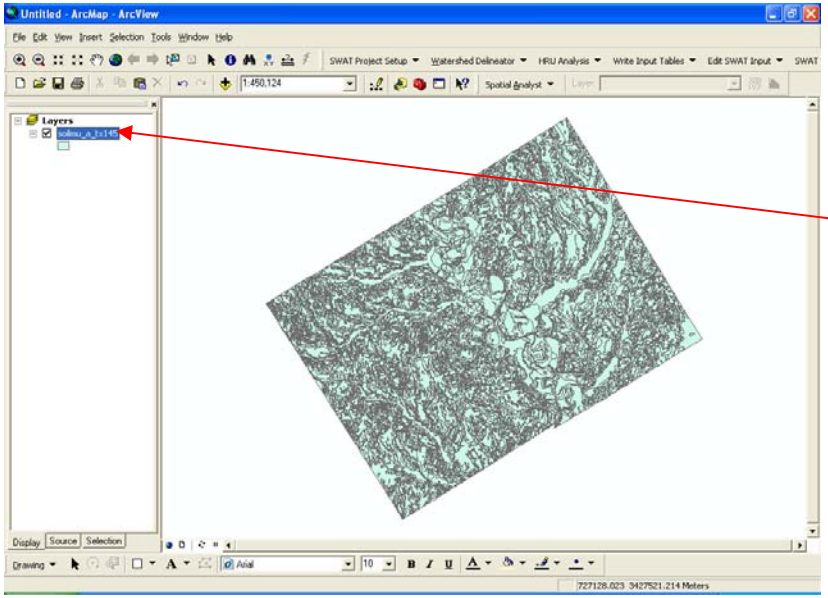
Fill out form to order file(s)
Continue to Step 5



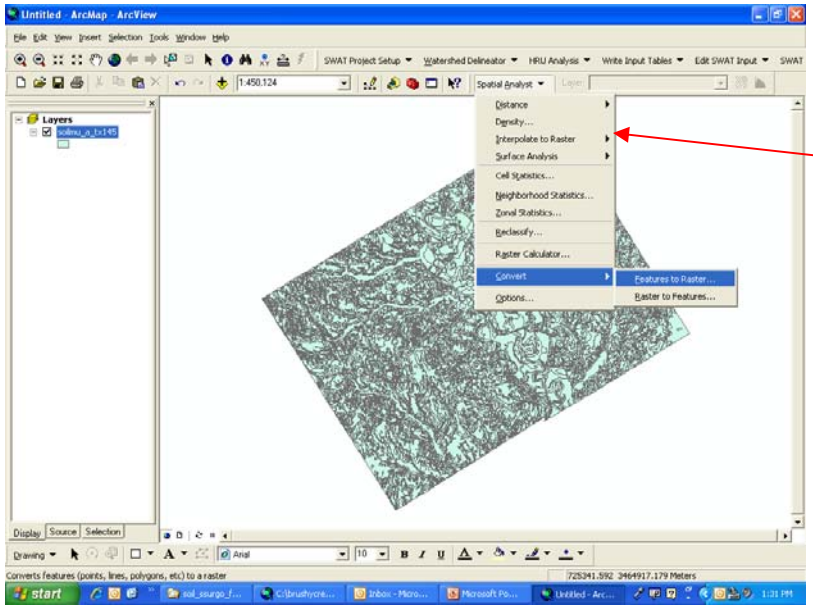
Click on Place Order

You will receive an email from Geospatial Gateway with links to the files you ordered.

SSURGO Processing for ArcSWAT (Geospatial Gateway website)
Preparing files for ArcSWAT interface

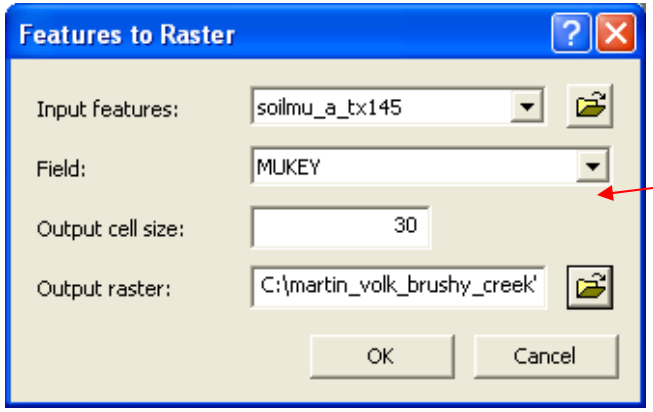


Open ArcMap and add ‘soilmu_a_*.shp’ in ‘spatial’ directory



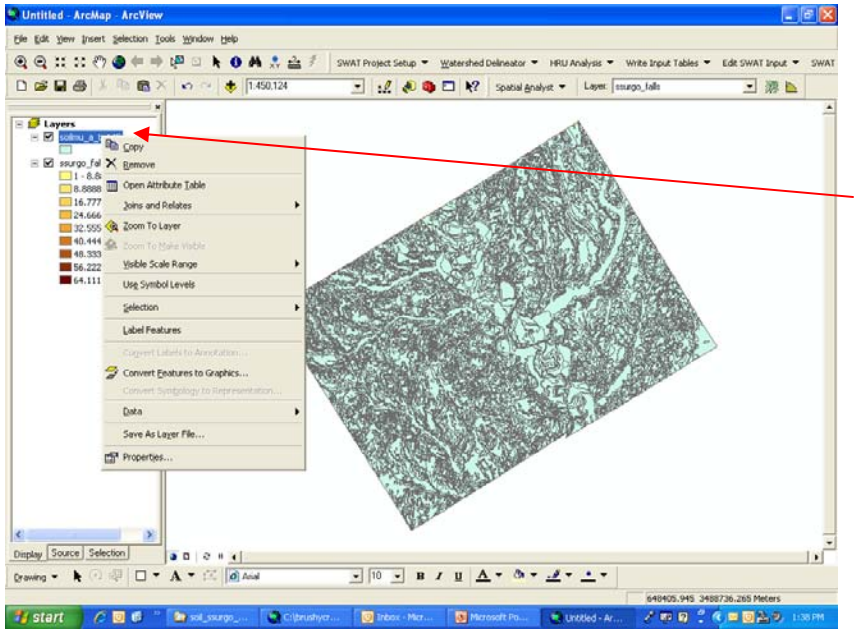
Click on Spatial Analyst/Convert/ Features to Raster

SSURGO Processing for ArcSWAT (Geospatial Gateway website)



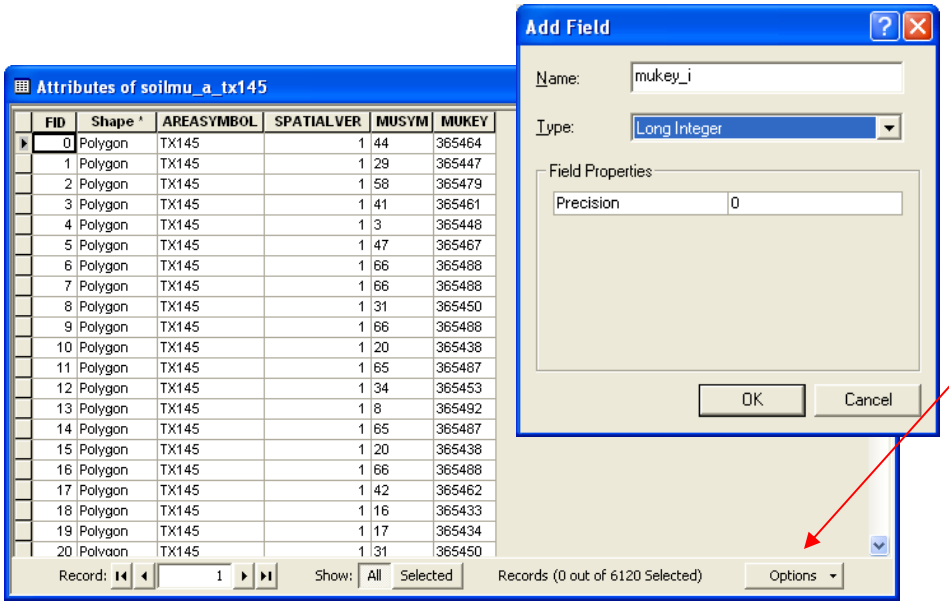
Input features: soilmu_a file
Field: MUKEY
Output cell size: 30
Output raster: newfilename

OK – (this process may take a few minutes)

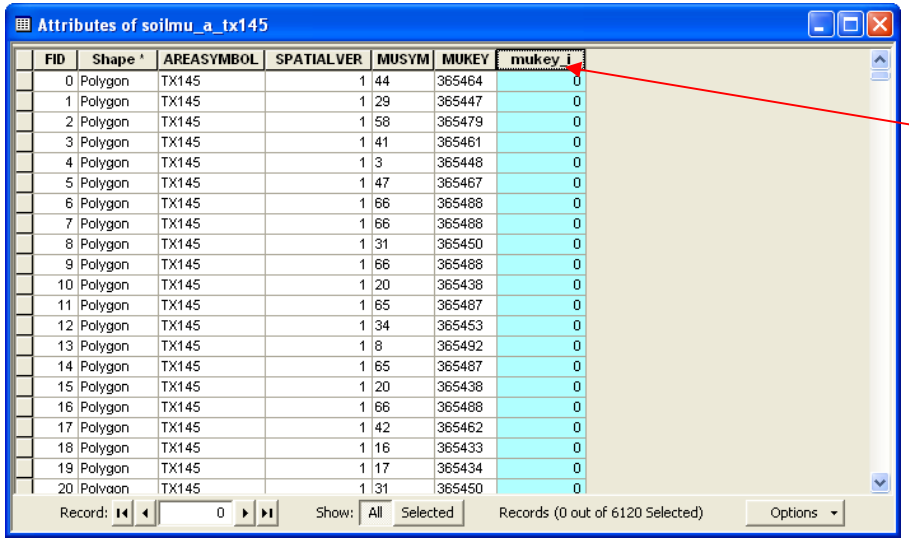


Right-mouse click on shapefile
Open Attribute table

SSURGO Processing for ArcSWAT (Geospatial Gateway website)

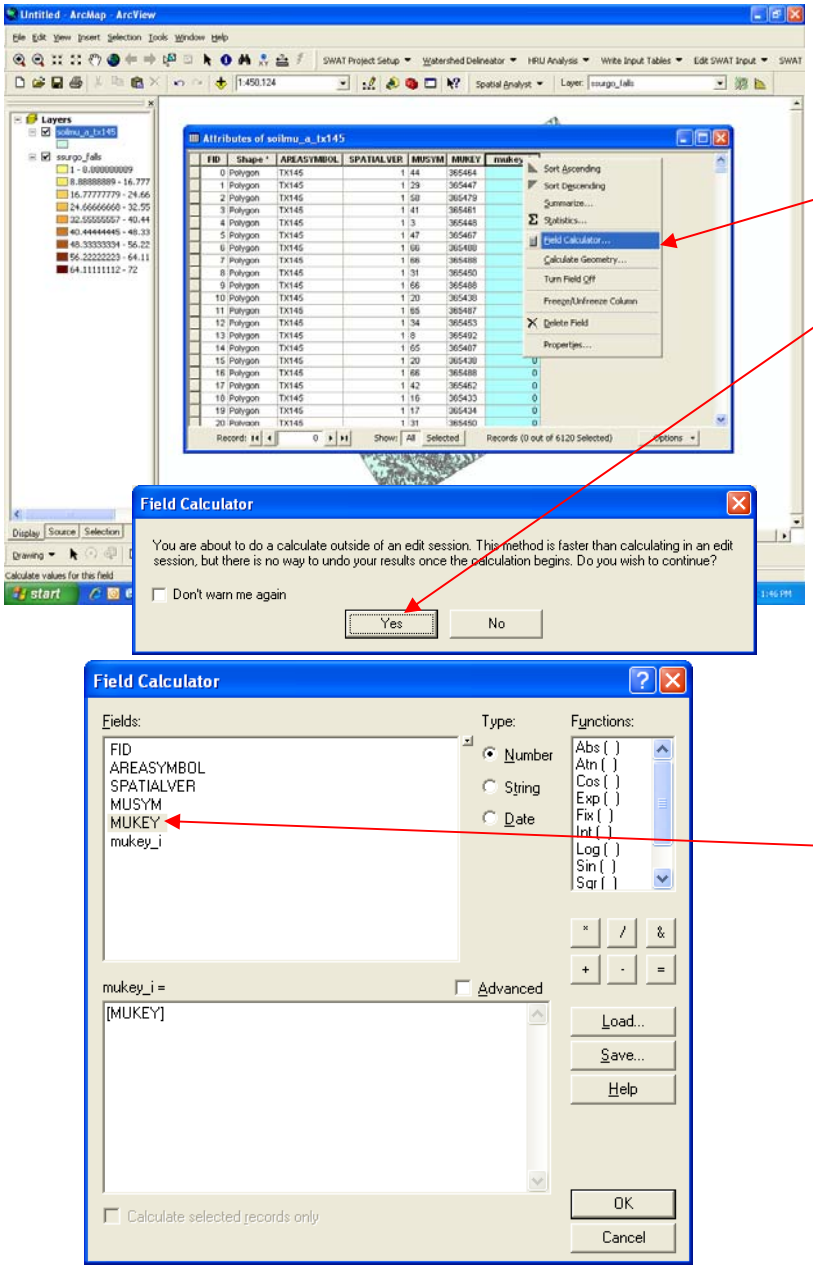


Click on ‘Options’/Add field
Name: mukey_i
Type: Long integer
Ok



Right-mouse click on new column

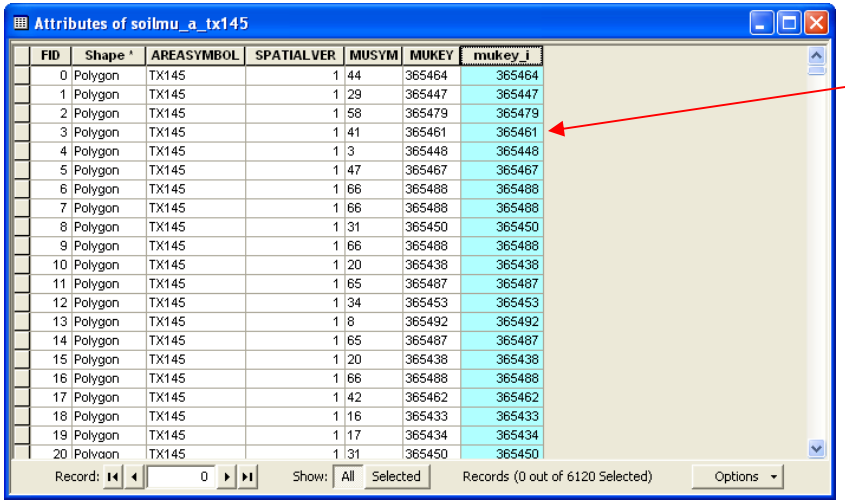
SSURGO Processing for ArcSWAT (Geospatial Gateway website)



Click on Field Calculator
Click yes on next window

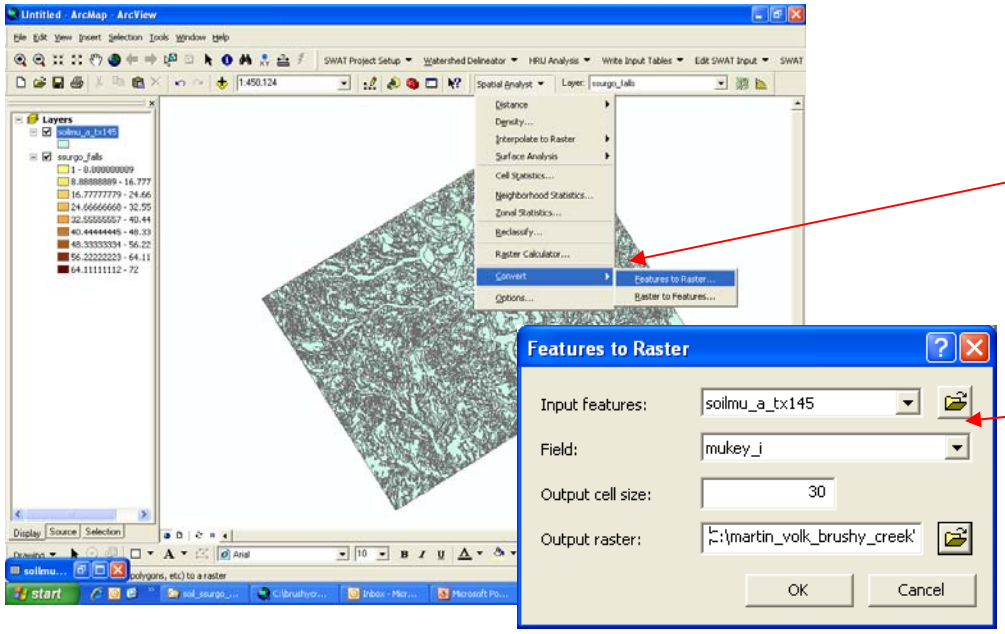
Double click on “MUKEY”
Ensure type is “Number”
Click OK

SSURGO Processing for ArcSWAT (Geospatial Gateway website)



After calculations, a new column is added to table that is right-justified

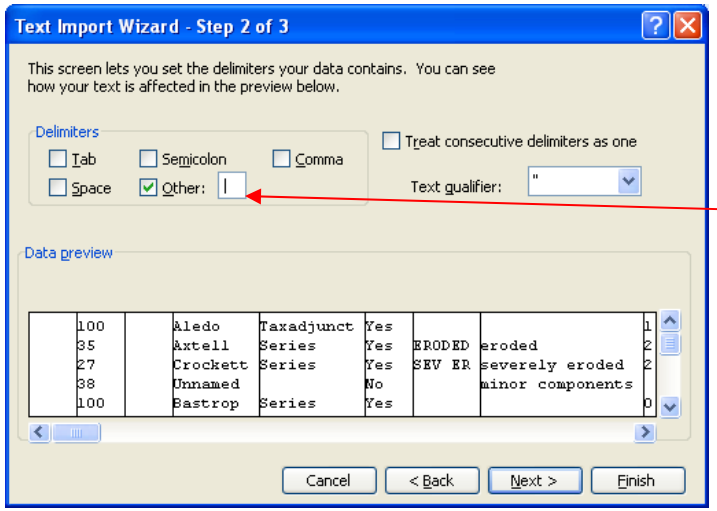
Minimize this window



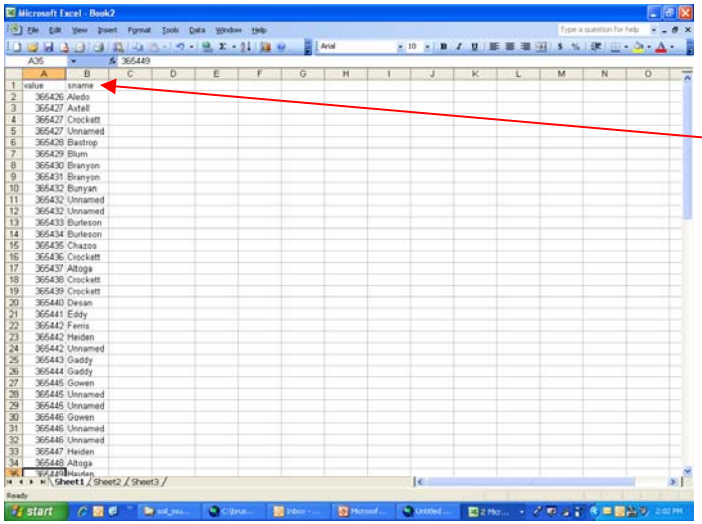
Go to Spatial Analyst/Convert/ Features to Raster

Input features: soilmu_a
Field: mukey_i
Output cell size: 30
Output raster: newfilename
Click Ok

SSURGO Processing for ArcSWAT (Geospatial Gateway website)

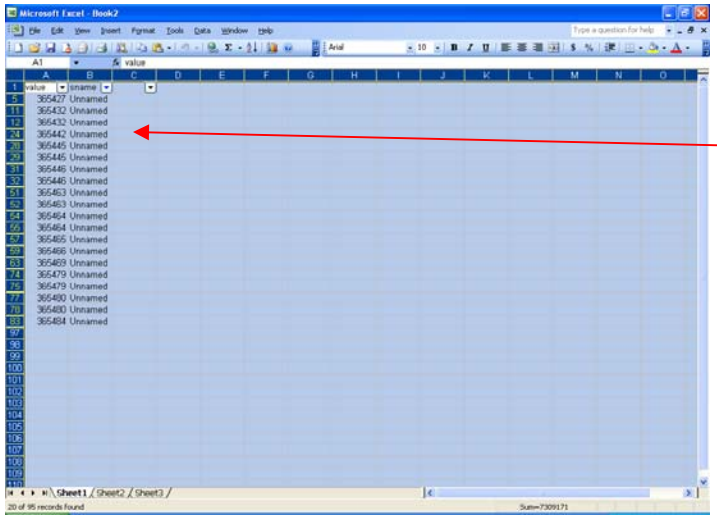


To Create lookup table file -
Open comp.txt (in tabular directory) in Excel (as "|" delimited file)

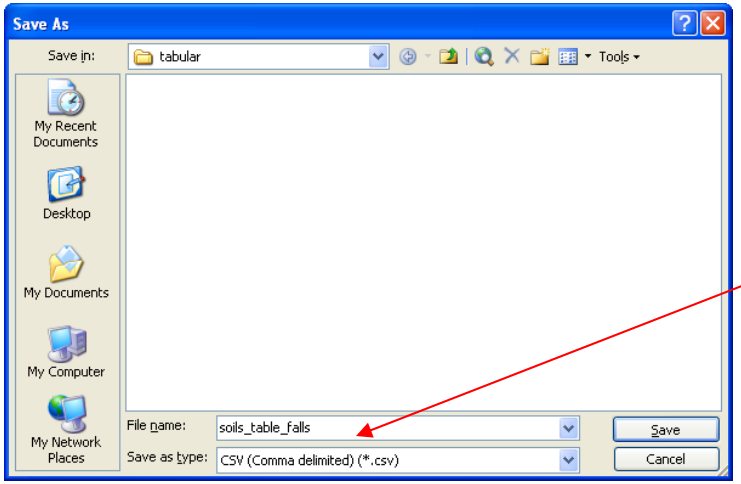


Copy Column D and DD to new workbook
DD – First column (add value header)
D – Second column (add name header)

SSURGO Processing for ArcSWAT (Geospatial Gateway website)



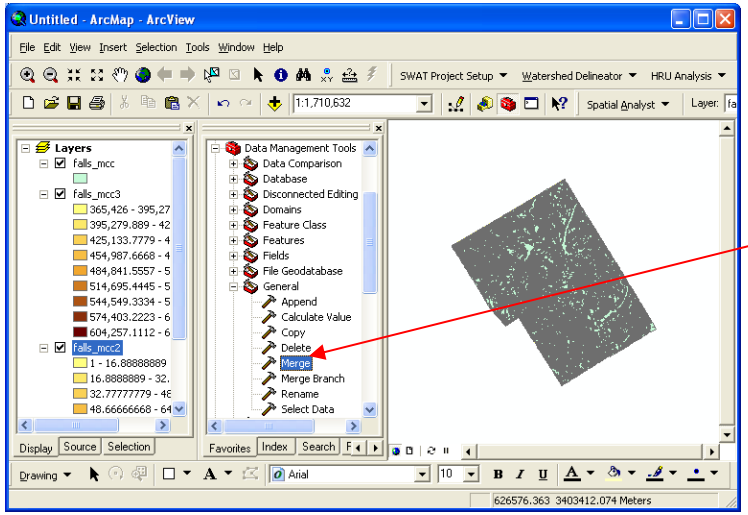
Autofilter the ‘Unnamed’ soils and delete



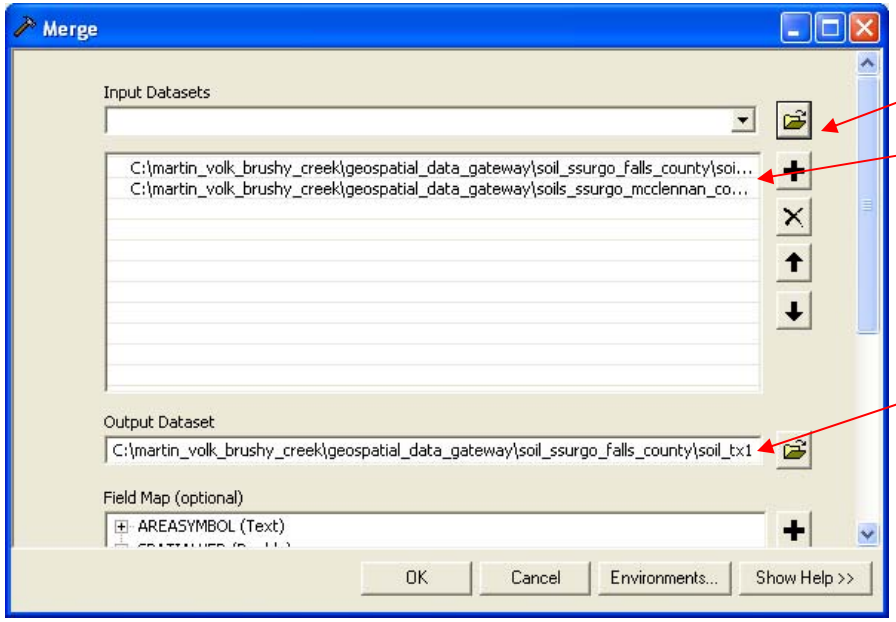
Save file as *.csv type

Browse in Windows Explorer and rename *.csv to *.txt extension.

If two or more counties need to be merged



Open ArcMAP/ArcToolBox
Click on Data Management Tools
General/Merge



Use the browser and add the two (or more) counties that you need merged.

Input the name of the newly merged file
Click OK.

You also need to merge the tables.

MERGING TWO OR MORE TABLES:
Combine the comp.txt files for both counties in Excel. Delete the unnamed Soils. Add headings, save as *.csv file. Rename the .csv to .txt.
(See Pages 10-11)

You must load the states SSURGO soils (get from Srini) into the SWAT2005.mdb file before using in ArcSWAT. To do this, see the following document:
C:\mydocuments\arcswat_instructions\arcswat_ssugo_import.ppt

MODEL EVALUATION GUIDELINES FOR SYSTEMATIC QUANTIFICATION OF ACCURACY IN WATERSHED SIMULATIONS

D. N. Moriasi, J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, T. L. Veith

ABSTRACT. *Watershed models are powerful tools for simulating the effect of watershed processes and management on soil and water resources. However, no comprehensive guidance is available to facilitate model evaluation in terms of the accuracy of simulated data compared to measured flow and constituent values. Thus, the objectives of this research were to: (1) determine recommended model evaluation techniques (statistical and graphical), (2) review reported ranges of values and corresponding performance ratings for the recommended statistics, and (3) establish guidelines for model evaluation based on the review results and project-specific considerations; all of these objectives focus on simulation of streamflow and transport of sediment and nutrients. These objectives were achieved with a thorough review of relevant literature on model application and recommended model evaluation methods. Based on this analysis, we recommend that three quantitative statistics, Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR), in addition to the graphical techniques, be used in model evaluation. The following model evaluation performance ratings were established for each recommended statistic. In general, model simulation can be judged as satisfactory if NSE > 0.50 and RSR ≤ 0.70, and if PBIAS ± 25% for streamflow, PBIAS ± 55% for sediment, and PBIAS ± 70% for N and P. For PBIAS, constituent-specific performance ratings were determined based on uncertainty of measured data. Additional considerations related to model evaluation guidelines are also discussed. These considerations include: single-event simulation, quality and quantity of measured data, model calibration procedure, evaluation time step, and project scope and magnitude. A case study illustrating the application of the model evaluation guidelines is also provided.*

Keywords. *Accuracy, Model calibration and validation, Simulation, Watershed model.*

Computer-based watershed models can save time and money because of their ability to perform long-term simulation of the effects of watershed processes and management activities on water quality, water quantity, and soil quality. These models also facilitate the simulation of various conservation program effects and aid policy design to mitigate water and soil quality degradation by determining suitable conservation programs for particular watersheds and agronomic settings. In order to use model outputs for tasks ranging from regulation to research, models should be scientifically sound, robust, and defensible (U.S. EPA, 2002).

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Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs (parameters). It is a necessary process to identify key parameters and parameter precision required for calibration (Ma et al., 2000). Model calibration is the process of estimating model parameters by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions. Model validation involves running a model using input parameters measured or determined during the calibration process. According to Refsgaard (1997), model validation is the process of demonstrating that a given site-specific model is capable of making "sufficiently accurate" simulations, although "sufficiently accurate" can vary based on project goals. According to the U.S. EPA (2002), the process used to accept, reject, or qualify model results should be established and documented before beginning model evaluation. Although ASCE (1993) emphasized the need to clearly define model evaluation criteria, no commonly accepted guidance has been established, but specific statistics and performance ratings for their use have been developed and used for model evaluation (Donigian et al., 1983; Ramanarayanan et al., 1997; Gupta et al., 1999; Motovilov et al., 1999; Saleh et al., 2000; Santhi et al., 2001; Singh et al., 2004; Bracmort et al., 2006; Van Liew et al., 2007). However, these performance ratings are model and project specific. Standardized guidelines are needed to establish a common system for judging model performance and comparing various models (ASCE, 1993). Once established, these guidelines will assist modelers in preparing and reviewing quality assurance project plans for modeling (U.S. EPA, 2002) and will increase accountability and public acceptance of models to support

scientific research and to guide policy, regulatory, and management decision-making.

A number of publications have addressed model evaluation statistics (Willmott, 1981; ASCE, 1993; Legates and McCabe, 1999), but they do not include recently developed statistics (e.g., Wang and Melesse, 2005; Parker et al., 2006). More importantly, none of the previous publications provide guidance on acceptable ranges of values for each statistic. Borah and Bera (2004) present an excellent review of values for various statistics used in hydrologic and nonpoint-source model applications, but more elaborate analysis is needed to aid modelers in determining performance ratings for these statistics.

In most watershed modeling projects, model output is compared to corresponding measured data with the assumption that all error variance is contained within the predicted values and that observed values are error free. In discussions of model evaluation statistics, Willmott (1981) and ASCE (1993) do recognize that measured data are not error free, but measurement error is not considered in their recommendations perhaps because of the relative lack of data on measurement uncertainty. However, uncertainty estimates for measured streamflow and water quality data have recently become available (Harmel et al., 2006) and should be considered when calibrating, validating, and evaluating watershed models because of differences in inherent uncertainty between measured flow, sediment, and nutrient data.

The importance of standardized guidelines for model evaluation is illustrated by the Conservation Effects Assessment Project Watershed Assessment Study (CEAP-WAS, 2005). The CEAP-WAS seeks to quantify the environmental benefits of conservation practices supported by USDA in the 2002 Farm Bill, also known as the Farm Security and Rural Investment Act. One of the CEAP-WAS goals is to formulate guidelines for calibration, validation, and application of models used in CEAP to simulate environmental effects of conservation practices. Thus, based on the need for standardized model evaluation guidelines to support watershed modeling in CEAP-WAS and other projects, the objectives for the present research were to: (1) determine recommended model evaluation techniques (statistical and graphical), (2) review reported ranges of values and corresponding performance ratings for the recommended statistics, and (3) establish guidelines for model evaluation based on the review results and project-specific considerations. In addition, a case study illustrating the application of the model evaluation guidelines was provided. This research focuses on watershed model evaluation guidelines for streamflow, sediments, and nutrients. Throughout this article, "model evaluation" refers to the applicable steps of sensitivity analysis, calibration, validation, uncertainty analysis, and application.

METHODS

MODEL EVALUATION TECHNIQUES

To determine recommended techniques for watershed model evaluation, an extensive review was conducted on published literature related to calibration, validation, and application of watershed models. Specifically, the information compiled focused on the strengths and weaknesses of each statistical and graphical technique and on recommendations for their application. The recommended model evaluation statistics were selected based on the following factors: (1) robustness in terms of applicability to various constituents, models, and climatic conditions; (2) commonly used, accepted, and recommended in published literature; and (3) identified strengths in model evaluation. The trade-off between long-term bias and residual variance was also considered, as recommended by Boyle et al. (2000). Bias measures the average tendency of the simulated constituent values to be larger or smaller than the measured data. Residual variance is the difference between the measured and simulated values, often estimated by the residual mean square or root mean square error (RMSE). According to Boyle et al. (2000), optimizing RMSE during model calibration may give small error variance but at the expense of significant model bias. The compilation of recommended statistics was also constrained by the recommendation of Legates and McCabe (1999) to include at least one dimensionless statistic and one absolute error index statistic with additional information such as the standard deviation of measured data, and to include at least one graphical technique as well.

REPORTED VALUE RANGES AND PERFORMANCE RATINGS FOR RECOMMENDED STATISTICS

Additional literature review was conducted to determine published ranges of values and performance ratings for recommended model evaluation statistics. Reported daily and monthly values during the calibration and validation periods for streamflow, sediment, and nutrients are recorded along with the model used for evaluation in tables A-1 through A-9 in the Appendix. All the reported data were analyzed and compiled into a summary of daily and monthly value ranges for different constituents during calibration and validation (table 1). The summary values in table 1 include the sample size of the reported values (n) and the minimum, maximum, and median of the values reported for streamflow, surface runoff, sediment, organic, mineral and total nitrogen, and organic, mineral, and total phosphorus.

MODEL EVALUATION GUIDELINES

General model evaluation guidelines that consider the recommended model evaluation statistics with corresponding performance ratings and appropriate graphical analyses were then established. A calibration procedure chart for flow, sediment, and nutrients, similar to the one proposed by Santhi et al. (2001), is included to assist in application of the model evaluation guidelines to manual model calibration. It is noted, however, that these guidelines should be adjusted by the modeler based on additional considerations such as: single-event simulation, quality and quantity of measured data, model calibration procedure, evaluation time step, and project scope and magnitude. Additionally, a brief discussion of the implications of unmet performance ratings is provided.

RESULTS AND DISCUSSION

MODEL EVALUATION TECHNIQUES

Both statistical and graphical model evaluation techniques were reviewed. The quantitative statistics were divided into three major categories: standard regression, dimensionless, and error index. Standard regression statistics determine the strength of the linear relationship between simulated and measured data. Dimensionless techniques provide

a relative model evaluation assessment, and error indices quantify the deviation in the units of the data of interest (Legates and McCabe, 1999). A brief discussion of numerous model evaluation statistics (both recommended statistics and statistics not selected for recommendation) appears subsequently; however, the relevant calculations are provided only for the recommended statistics.

Several graphical techniques are also described briefly because graphical techniques provide a visual comparison of simulated and measured constituent data and a first overview of model performance (ASCE, 1993) and are essential to appropriate model evaluation (Legates and McCabe, 1999). Based on recommendations by ASCE (1993) and Legates and McCabe (1999), we recommend that both graphical techniques and quantitative statistics be used in model evaluation.

Model Evaluation Statistics (Standard Regression)

Slope and *y*-intercept: The slope and *y*-intercept of the best-fit regression line can indicate how well simulated data match measured data. The slope indicates the relative relationship between simulated and measured values. The *y*-intercept indicates the presence of a lag or lead between model predictions and measured data, or that the data sets are not perfectly aligned. A slope of 1 and *y*-intercept of 0 indicate that the model perfectly reproduces the magnitudes of measured data (Willmott, 1981). The slope and *y*-intercept are commonly examined under the assumption that measured and simulated values are linearly related, which implies that all of the error variance is contained in simulated values and that measured data are error free (Willmott, 1981). In reality, measured data are rarely, if ever, error free. Harmel et al. (2006) showed that substantial uncertainty in reported water quality data can result when individual errors from all procedural data collection categories are considered. Therefore, care needs to be taken while using regression statistics for model evaluation.

Pearson's correlation coefficient (r) and coefficient of determination (R^2): Pearson's correlation coefficient (r) and coefficient of determination (R^2) describe the degree of collinearity between simulated and measured data. The correlation coefficient, which ranges from −1 to 1, is an index of the degree of linear relationship between observed and simulated data. If r = 0, no linear relationship exists. If r = 1 or −1, a perfect positive or negative linear relationship exists. Similarly, R^2 describes the proportion of the variance in measured data explained by the model. R^2 ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable (Santhi et al., 2001, Van Liew et al., 2003). Although r and R^2 have been widely used for model evaluation, these statistics are oversensitive to high extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data (Legates and McCabe, 1999).

Model Evaluation Statistics (Dimensionless)

Index of agreement (d): The index of agreement (d) was developed by Willmott (1981) as a standardized measure of the degree of model prediction error and varies between 0 and 1. A computed value of 1 indicates a perfect agreement between the measured and predicted values, and 0 indicates no agreement at all (Willmott, 1981). The index of agreement represents the ratio between the mean square error and the "potential error" (Willmott, 1984). The author defined potential error as the sum of the squared absolute values of the distances from the predicted values to the mean observed value and distances from the observed values to the mean observed value. The index of agreement can detect additive and proportional differences in the observed and simulated means and variances; however, d is overly sensitive to extreme values due to the squared differences (Legates and McCabe, 1999). Legates and McCabe (1999) suggested a modified index of agreement (d1) that is less sensitive to high extreme values because errors and differences are given appropriate weighting by using the absolute value of the difference instead of using the squared differences. Although d1 has been proposed as an improved statistic, its limited use in the literature has not provided extensive information on value ranges.

Nash-Sutcliffe efficiency (NSE): The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as shown in equation 1:

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean}\right)^2} \right] \quad (1)$$

where Y_i^{obs} is the ith observation for the constituent being evaluated, Y_i^{sim} is the ith simulated value for the constituent being evaluated, Y^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations.

NSE ranges between $-\infty$ and 1.0 (1 inclusive), with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values $\leq$0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance.

NSE was recommended for two major reasons: (1) it is recommended for use by ASCE (1993) and Legates and McCabe (1999), and (2) it is very commonly used, which provides extensive information on reported values. Sevat and Dezetter (1991) also found NSE to be the best objective function for reflecting the overall fit of a hydrograph. Legates and McCabe (1999) suggested a modified NSE that is less sensitive to high extreme values due to the squared differences, but that modified version was not selected because of its limited use and resulting relative lack of reported values.

Persistence model efficiency (PME): Persistence model efficiency (PME) is a normalized model evaluation statistic that quantifies the relative magnitude of the residual variance ("noise") to the variance of the errors obtained by the use of a simple persistence model (Gupta et al., 1999). PME ranges from 0 to 1, with PME = 1 being the optimal value. PME values should be larger than 0.0 to indicate "minimally acceptable" model performance (Gupta et al., 1999). The power of PME is derived from its comparison of model performance with a simple persistence forecast model. According to Gupta et al. (1999), PME is capable of clearly indicating poor model

performance, but it has been used only occasionally in the literature, so a range of reported values is not available.

Prediction efficiency (P_e): Prediction efficiency (P_e), as explained by Santhi et al. (2001), is the coefficient of determination (R^2) calculated by regressing the rank (descending) of observed versus simulated constituent values for a given time step. P_e determines how well the probability distributions of simulated and observed data fit each other. However, it has not been used frequently enough to provide extensive information on ranges of values. In addition, it may not account for seasonal bias.

Performance virtue statistic (PV_k): The performance virtue statistic (PV_k) is the weighted average of the Nash-Sutcliffe coefficients, deviations of volume, and error functions across all flow gauging stations within the watershed of interest (Wang and Melesse, 2005). PV_k was developed to assess if watershed models can satisfactorily predict all aspects (profile, volume, and peak) of observed flow hydrographs for watersheds with more than one gauging station (Wang and Melesse, 2005). PV_k can range from $-\infty$ to 1.0, with a PV_k value of 1.0 indicating that the model exactly simulates all three aspects of observed flow for all gauging stations within the watershed. A negative PV_k value indicates that the average of observed streamflow values is better than simulated streamflows (Wang and Melesse, 2005). PV_k was developed for use in snow-fed watersheds; therefore, it may be necessary to make adjustments to this statistic for rain-fed watersheds. PV_k was not selected for recommendation because it was developed for streamflow only. In addition, PV_k was only recently developed; thus, extensive information on value ranges is not available.

Logarithmic transformation variable (e): The logarithmic transformation variable (e) is the logarithm of the predicted/observed data ratio (E) that was developed to address the sensitivity of the watershed-scale pesticide model error index (E) to the estimated pesticide application rates (Parker et al., 2006). The value of e is centered on zero, is symmetrical in under- or overprediction, and is approximately normally distributed (Parker et al., 2006). If the simulated and measured data are in complete agreement, then e = 0 and E = 1.0. Values of e < 0 are indicative of underprediction; values > 0 are indicative of overprediction. Although e has great potential as an improved statistical technique for assessing model accuracy, it was not selected because of its recent development and limited testing and application.

Model Evaluation Statistics (Error Index)

MAE, MSE, and RMSE: Several error indices are commonly used in model evaluation. These include mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE). These indices are valuable because they indicate error in the units (or squared units) of the constituent of interest, which aids in analysis of the results. RMSE, MAE, and MSE values of 0 indicate a perfect fit. Singh et al. (2004) state that RMSE and MAE values less than half the standard deviation of the measured data may be considered low and that either is appropriate for model evaluation. A standardized version of the RMSE was selected for recommendation and is described later in this section.

Percent bias (PBIAS): Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999). PBIAS is calculated with equation 2:

$$\text{PBIAS} = \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right) * (100)}{\sum_{i=1}^{n} \left(Y_i^{obs}\right)} \right] \quad (2)$$

where PBIAS is the deviation of data being evaluated, expressed as a percentage.

Percent streamflow volume error (PVE; Singh et al., 2004), prediction error (PE; Fernandez et al., 2005), and percent deviation of streamflow volume (D_v) are calculated in a similar manner as PBIAS. The deviation term (D_v) is used to evaluate the accumulation of differences in streamflow volume between simulated and measured data for a particular period of analysis.

PBIAS was selected for recommendation for several reasons: (1) D_v was recommended by ASCE (1993), (2) D_v is commonly used to quantify water balance errors and its use can easily be extended to load errors, and (3) PBIAS has the ability to clearly indicate poor model performance (Gupta et al., 1999). PBIAS values for streamflow tend to vary more, among different autocalibration methods, during dry years than during wet years (Gupta et al., 1999). This fact should be considered when attempting to do a split-sample evaluation, one for calibration and one for validation.

RMSE-observations standard deviation ratio (RSR): RMSE is one of the commonly used error index statistics (Chu and Shirmohammadi, 2004; Singh et al., 2004; Vasquez-Amábile and Engel, 2005). Although it is commonly accepted that the lower the RMSE the better the model performance, only Singh et al. (2004) have published a guideline to qualify what is considered a low RMSE based on the observations standard deviation. Based on the recommendation by Singh et al. (2004), a model evaluation statistic, named the RMSE-observations standard deviation ratio (RSR), was developed. RSR standardizes RMSE using the observations standard deviation, and it combines both an error index and the additional information recommended by Legates and McCabe (1999). RSR is calculated as the ratio of the RMSE and standard deviation of measured data, as shown in equation 3:

$$\text{RSR} = \frac{\text{RMSE}}{\text{STDEV}_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean}\right)^2}\right]} \quad (3)$$

RSR incorporates the benefits of error index statistics and includes a scaling/normalization factor, so that the resulting statistic and reported values can apply to various constituents. RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. The lower RSR, the lower the RMSE, and the better the model simulation performance.

Daily root-mean square (DRMS): The daily root-mean square (DRMS), which is a specific application of the RMSE, computes the standard deviation of the model prediction error (difference between measured and simulated values). The smaller the DRMS value, the better the model performance (Gupta et al., 1999). Gupta et al. (1999) determined that DRMS increased with wetness of the year, indicating that the forecast error variance is larger for higher flows. According to Gupta et al. (1999), DRMS had limited ability to clearly indicate poor model performance.

Graphical Techniques

Graphical techniques provide a visual comparison of simulated and measured constituent data and a first overview of model performance (ASCE, 1993). According to Legates and McCabe (1999), graphical techniques are essential to appropriate model evaluation. Two commonly used graphical techniques, hydrographs and percent exceedance probability curves, are especially valuable. Other graphical techniques, such as bar graphs and box plots, can also be used to examine seasonal variations and data distributions.

A hydrograph is a time series plot of predicted and measured flow throughout the calibration and validation periods. Hydrographs help identify model bias (ASCE, 1993) and can identify differences in timing and magnitude of peak flows and the shape of recession curves.

Percent exceedance probability curves, which often are daily flow duration curves, can illustrate how well the model reproduces the frequency of measured daily flows throughout the calibration and validation periods (Van Liew et al., 2007). General agreement between observed and simulated frequencies for the desired constituent indicates adequate simulation over the range of the conditions examined (Singh et al., 2004).

Table 1. Summary statistics from the literature review of reported NSE and PBIAS values.[a]

		Calibration				Validation			
		NSE		PBIAS		NSE		PBIAS	
Constituent	Statistic	Daily	Monthly	Daily	Monthly	Daily	Monthly	Daily	Monthly
Streamflow	*n*	92	33	72	0	128	70	82	0
	Minimum	-0.23	0.14	-91.70	na	-1.81	-3.35	-155.60	na
	Maximum	0.95	0.91	26.50	na	0.89	0.93	47.18	na
	Median	0.89	0.79	-1.30	na	0.67	0.63	-1.90	na
Surface runoff	*n*	0	2	0	0	0	2	0	0
	Minimum	na	0.35	na	na	na	0.63	na	na
	Maximum	na	0.62	na	na	na	0.77	na	na
	Median	na	0.49	na	na	na	0.70	na	na
Sediment	*n*	2	6	0	0	2	6	0	0
	Minimum	-2.50	0.49	na	na	-3.51	-2.46	na	na
	Maximum	0.11	0.86	na	na	0.23	0.88	na	na
	Median	-1.20	0.76	na	na	-1.64	0.64	na	na
Organic nitrogen (organic N)	*n*	0	2	0	0	0	2	0	0
	Minimum	na	0.57	na	na	na	0.43	na	na
	Maximum	na	0.58	na	na	na	0.73	na	na
	Median	na	0.58	na	na	na	0.58	na	na
Mineral nitrogen (NO_3-N)	*n*	0	2	0	0	0	2	0	0
	Minimum	na	-0.08	na	na	na	0.64	na	na
	Maximum	na	0.59	na	na	na	0.75	na	na
	Median	na	0.26	na	na	na	0.70	na	na
Total nitrogen (organic N + NO_3-N)	*n*	0	0	0	0	1	6	0	0
	Minimum	na	na	na	na	0.19	0.10	na	na
	Maximum	na	na	na	na	0.19	0.85	na	na
	Median	na	na	na	na	0.19	0.76	na	na
Organic phosphorus (organic P)	*n*	0	2	0	0	0	2	0	0
	Minimum	na	0.59	na	na	na	0.39	na	na
	Maximum	na	0.70	na	na	na	0.72	na	na
	Median	na	0.65	na	na	na	0.56	na	na
Mineral phosphorus (PO_4-P)	*n*	0	3	0	0	0	3	0	0
	Minimum	na	0.53	na	na	na	0.51	na	na
	Maximum	na	0.78	na	na	na	0.81	na	na
	Median	na	0.59	na	na	na	0.53	na	na
Total phosphorus (organic P + PO_4-P)	*n*	0	1	0	0	0	1	0	0
	Minimum	na	0.51	na	na	na	0.37	na	na
	Maximum	na	0.51	na	na	na	0.37	na	na
	Median	na	0.51	na	na	na	0.37	na	na

[a] *n* = number of reported values for the studies reviewed (sample size), NSE = Nash-Sutcliffe efficiency, PBIAS = percent bias, and na = not available (used when *n* = 0).

Reported Ranges of Values for Recommended Statistics

A review of published literature produced ranges of daily and monthly NSE and PBIAS values for both model calibration and validation for surface runoff, streamflow, and selected constituents, including: sediment, organic nitrogen, mineral nitrogen, total nitrogen, organic phosphorus, and mineral phosphorus (tables A-1 through A-9). A few weekly values reported by Narasimhan et al. (2005) are also included to indicate ranges of values for a weekly time step. It is important to note that calibration and validation were performed for different time periods; thus, the reported values reflect this difference. A summary of reported values for each constituent appears in table 1. Median values instead of means are included because medians are less sensitive to extreme values and are better indicators for highly skewed distributions.

Most of the reviewed studies performed model calibration and validation based on streamflow (table 1). This is attributed to the relative abundance of measured long-term streamflow data compared to sediment or nutrient data. Based on the summary information for streamflow calibration and validation, daily NSE values tended to be higher than monthly values, which contradicts findings from some individual studies (e.g., Fernandez et al., 2005; Singh et al., 2005; Van Liew et al., 2007). This anomaly is potentially due to the increased sample sizes (n) for daily data. As expected, NSE and PBIAS values for streamflow were better for the calibration periods than the validation periods.

Reported Performance Ratings for Recommended Statistics

A review of published literature resulted in the performance ratings for NSE and PBIAS shown in tables 2 and 3. Because RSR was developed in this research, similar reported performance ratings are not available. Therefore, RSR ratings were based on Singh et al. (2004) recommendations that RMSE values less than half the standard deviation of measured data can be considered low. In this study, we used the recommended less than 0.5 RSR value as the most stringent ("very good") rating and suggested two less stringent ratings of 10% and 20% greater than this value for the "good" and "satisfactory" ratings, respectively.

Model Evaluation Guidelines Based on Performance Ratings

General model evaluation guidelines, for a monthly time step, were developed based on performance ratings for the recommended statistics and on project-specific considerations. As stated previously, graphical techniques, especially hydrographs and percent exceedance probability curves, provide visual model evaluation overviews. Utilizing these important techniques should typically be the first step in model evaluation. A general visual agreement between observed and simulated constituent data indicates adequate calibration and validation over the range of the constituent being simulated (Singh et al., 2004).

Table 2. Reported performance ratings for NSE.

Model	Value	Performance Rating	Modeling Phase	Reference
HSPF	>0.80	Satisfactory	Calibration and validation	Donigian et al. (1983)
APEX	>0.40	Satisfactory	Calibration and validation (daily)	Ramanarayanan et al. (1997)
SAC-SMA	<0.70	Poor	Autocalibration	Gupta et al. (1999)
SAC-SMA	>0.80	Efficient	Autocalibration	Gupta et al. (1999)
DHM	>0.75	Good	Calibration and validation	Motovilov et al. (1999)[a]
DHM	0.36 to 0.75	Satisfactory	Calibration and validation	Motovilov et al. (1999)[a]
DHM	<0.36	Unsatisfactory	Calibration and validation	Motovilov et al. (1999)[a]
SWAT	>0.65	Very good	Calibration and validation	Saleh et al. (2000)
SWAT	0.54 to 0.65	Adequate	Calibration and validation	Saleh et al. (2000)
SWAT	>0.50	Satisfactory	Calibration and validation	Santhi et al. (2001); adapted by Bracmort et al. (2006)
SWAT and HSPF	>0.65	Satisfactory	Calibration and validation	Singh et al. (2004); adapted by Narasimhan et al. (2005)

[a] Adapted by Van Liew et al. (2003) and Fernandez et al. (2005).

Table 3. Reported performance ratings for PBIAS.

Model	Value	Performance Rating	Modeling Phase	Reference
HSPF	< 10%	Very good	Calibration and validation	Donigian et al. (1983)[a]
HSPF	10% to 15%	Good	Calibration and validation	Donigian et al. (1983)[a]
HSPF	15% to 25%	Fair	Calibration and validation	Donigian et al. (1983)[a]
SWAT	<15%	Satisfactory	Flow calibration	Santhi et al. (2001)
SWAT	<20%	Satisfactory	For sediment after flow calibration	Santhi et al. (2001)
SWAT	<25%	Satisfactory	For nitrogen after flow and sediment calibration	Santhi et al. (2001)
SWAT	20%	Satisfactory	Calibration and validation	Bracmort et al. (2006)
SWAT	<10%	Very good	Calibration and validation	Van Liew et al. (2007)
SWAT	<10% to <15%	Good	Calibration and validation	Van Liew et al. (2007)
SWAT	<15% to <25%	Satisfactory	Calibration and validation	Van Liew et al. (2007)
SWAT	>25%	Unsatisfactory	Calibration and validation	Van Liew et al. (2007)

[a] Adapted by Van Liew et al. (2003) and Singh et al. (2004).

Table 4. General performance ratings for recommended statistics for a monthly time step.

Performance Rating	RSR	NSE	PBIAS (%)		
			Streamflow	Sediment	N, P
Very good	0.00 ≤ RSR ≤ 0.50	0.75 < NSE ≤ 1.00	PBIAS < ±10	PBIAS < ±15	PBIAS< ±25
Good	0.50 < RSR ≤ 0.60	0.65 < NSE ≤ 0.75	±10 ≤ PBIAS < ±15	±15 ≤ PBIAS < ±30	±25 ≤ PBIAS < ±40
Satisfactory	0.60 < RSR ≤ 0.70	0.50 < NSE ≤ 0.65	±15 ≤ PBIAS < ±25	±30 ≤ PBIAS < ±55	±40 ≤ PBIAS < ±70
Unsatisfactory	RSR > 0.70	NSE ≤ 0.50	PBIAS ≥ ±25	PBIAS ≥ ±55	PBIAS ≥ ±70

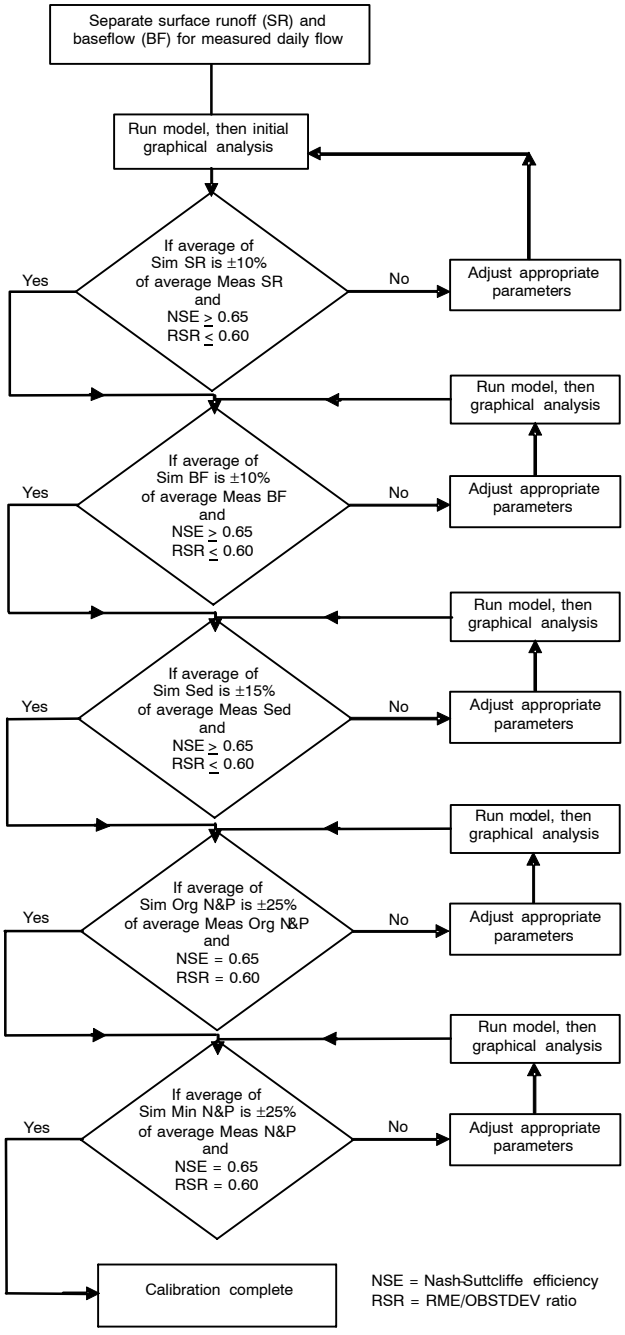

Figure 1. General calibration procedure for flow, sediment, and nutrients in the watershed models (based on calibration chart for SWAT from Santhi et al., 2001).

The next step should be to calculate values for NSE, PBIAS, and RSR. With these values, model performance can be judged based on general performance ratings (table 4). The reported performance ratings and corresponding values developed for individual studies, in addition to the reported ranges of values (table 1), were used to establish general performance ratings, which appear in table 4. As shown in table 4, the performance ratings for RSR and NSE are the same for all constituents, but PBIAS is constituent specific. This difference is due to the recent availability of information (PBIAS) on the uncertainty of measured streamflow and water quality. Harmel et al. (2006) used the root mean square error propagation method of Topping (1972) to calculate the cumulative probable error resulting from four procedural categories (discharge measurement, sample collection, sample preservation and storage, and laboratory analysis) associated with water quality data collection. Under typical scenarios with reasonable quality control attention, typical financial and personnel resources, and typical hydrologic conditions, cumulative probable error ranges (in similar units to PBIAS) were estimated to be 6% to 19% for streamflow, 7% to 53% for sediment, and 8% to 110% for N and P. These results were used to establish constituent-specific performance rating for PBIAS. Constituent-specific ratings for RSR and NSE can be established when similar information becomes available.

Based on table 4, model performance can be evaluated as "satisfactory" if NSE > 0.50 and RSR ≤ 0.70 and, for measured data of typical uncertainty, if PBIAS ± 25% for streamflow, PBIAS ± 55% for sediment, and PBIAS ± 70% for N and P for a monthly time step. These ratings should be adjusted to be more or less strict based on project-specific considerations discussed in the next section.

A general calibration procedure chart (fig. 1) for flow, sediment, and nutrients is included to aid with the manual model calibration process. The recommended values for adequate model calibration are within the "good" and "very good" performance ratings presented in table 4. These limits for adequate manual calibration are stricter than the "satisfactory" rating for general model evaluation because model parameter values are optimized during calibration but not during model validation or application. The importance of and appropriate methods for proper model calibration are discussed in the next section.

Additional Considerations

The model evaluation guidelines presented in the previous section apply to the typical case of continuous, long-term simulation for a monthly time step. However, because of the diversity of modeling applications, these guidelines should be adjusted based on single-event simulation, quality and quantity of measured data, model calibration procedure, evaluation time step, and project scope and magnitude.

Single-Event Simulation

When watershed models are applied on a single-event basis, evaluation guidelines should reflect this specific case. Generally, the objectives of single-event modeling are the determination of peak flow rate and timing, flow volume, and recession curve shape (ASCE, 1993; Van Liew et al., 2003).

Accurate prediction of peak flow rate and time-to-peak is essential for flood estimation and forecasting (Ramírez, 2000). Time-to-peak is affected by drainage network density, slope, channel roughness, and soil infiltration characteristics (Ramírez, 2000), and peak flow rate is typically affected by rainfall intensity and antecedent soil moisture content, among other factors.

One of the recommended (ASCE, 1993) model evaluation statistics for the peak flow rate is a simple percent error in peak flow rates (PEP) computed by dividing the difference between the simulated peak flow rate and measured peak flow rate by the measured peak flow rate and expressing the result as a percentage. Model performance related to time-to-peak can be determined similarly. In addition, for single-event simulation, Boyle et al. (2000) recommended that the hydrograph be divided into three phases (rising limb, falling limb, baseflow) based on differing watershed behavior during rainfall and dry periods. A different performance rating should be applied to each hydrograph phase. If the performance ratings are similar for each phase, then a single performance rating can be applied to the overall hydrograph in subsequent evaluation. Otherwise, a different performance rating should be used to evaluate each hydrograph phase.

Quality and Quantity of Measured Data

Although it is commonly accepted that measured data are inherently uncertain, the uncertainty is rarely considered in model evaluation, perhaps because of the lack of relevant data. Harmel et al. (2006) suggested that the uncertainty of measured data, which varies based on measurement conditions, techniques, and constituent type, must be considered to appropriately evaluate watershed models. In terms of the present guidelines and performance ratings, modeled streamflow may be rated "good" if it is within 10% to 15% of measured streamflow data of typical quality (table 4), for example. In contrast, performance ratings should be stricter when high-quality (low uncertainty) data are available. In this case, PBIAS for modeled streamflow may be required to be <10% to receive a "good" rating. If data collected in worst-case conditions are used for model evaluation, then performance ratings should be relaxed to reflect the extreme uncertainty. It can be argued in this case, however, that highly uncertain data offer little value and should not be used in model evaluation.

Finally, in situations when a complete measured time series does not exist, for instance when only a few grab samples per year are available, the data may not be sufficient for analysis using the recommended statistics. In such situations, comparison of frequency distributions and/or percentiles (e.g., 10th, 25th, 50th, 75th, and 90th) may be more appropriate than the quantitative statistics guidelines.

Model Calibration Procedure

Proper model calibration is important in hydrologic modeling studies to reduce uncertainty in model simulations (Engel et al., 2007). Ideal model calibration involves: (1) using data that includes wet, average, and dry years (Gan et al., 1997), (2) using multiple evaluation techniques (Willmott, 1981; ASCE, 1993; Legates and McCabe, 1999; Boyle et al., 2000), and (3) calibrating all constituents to be evaluated.

The calibration procedure typically involves a sensitivity analysis followed by manual or automatic calibration. The most fundamental sensitivity analysis technique utilizes partial differentiation, whereas the simplest method involves perturbing parameter values one at a time (Hamby, 1994). A detailed review of sensitivity analysis methods is presented by Hamby (1994) and Isukapalli (1999). According to Isukapalli (1999), the choice of a sensitivity method depends on the sensitivity measure employed, the desired accuracy in the estimates of the sensitivity measure, and the computational cost involved. Detailed information on how these factors affect the choice of sensitivity analysis method is given by Isukapalli (1999). After key parameters and their respective required precision have been determined, manual or automatic calibration is done.

Conventionally, calibration is done manually and consists of changing model input parameter values to produce simulated values that are within a certain range of measured data (Balascio et al., 1998). The calibrated model may be used to simulate multiple processes, such as streamflow volumes, peak flows, and/or sediment and nutrient loads. In such cases, two or more model evaluation statistics may be necessary in order to address the different processes (Balascio et al., 1998). However, when the number of parameters used in the manual calibration is large, especially for complex hydrologic models, manual calibration can become labor-intensive (Balascio et al., 1998). In this, case automatic calibration is more appropriate.

Automatic calibration involves computation of the prediction error using an equation (objective function) and an automatic optimization procedure (search algorithm) to search for parameter values that optimize the value of the objective function (Gupta et al., 1999). One of the automatic calibration methods is the shuffled complex evolution global optimization algorithm developed at the University of Arizona (SCE-UA) (Duan et al., 1993) and used by vanGriensven and Bauwens (2003) to develop a multi-objective calibration method for semi-distributed water quality models. Other automatic calibration methods include the multilevel calibration (MLC) semi-automated method (Brazil, 1988), the multi-objective complex evolution algorithm (MOCOM-UA) (Yapo et al., 1998), and parameter estimation by sequential testing (PEST) (Taylor and Creelman, 1967), among others.

Data used to calibrate model simulations have a direct effect on the validation and evaluation results. Ideal calibration should use 3 to 5 years of data that includes average, wet, and dry years so that the data encompass a sufficient range of hydrologic events to activate all model constituent processes during calibration (Gan et al., 1997). However, if this is not possible, then the available data should be separated into two sets, i.e., "above-mean" flows (wet years) and "below-mean" flows (dry years), and then evaluated with stricter performance ratings required for wet years (Gupta et al., 1999). Moreover, if the goal is to test the robustness of the model applications under different environmental conditions, then different datasets can be used during model calibration and validation.

In addition, a good calibration procedure uses multiple statistics, each covering a different aspect of the hydrograph, so that the whole hydrograph is covered. This is important because using a single statistic can lead to undue emphasis on matching one aspect of the hydrograph at the expense of other aspects (Boyle et al., 2000). For manual calibration, each statistic should be tracked while adjusting model parameters (Boyle et al., 2000) to allow for balancing the trade-offs in the ability of the model to simulate various aspects of the hydrograph while recognizing potential errors in the observed data.

Finally, ideal model calibration considers water balance (peak flow, baseflow) and sediment and nutrient transport because calibrating one constituent will not ensure that other constituents are adequately simulated during validation. Even though a complete set of hydrologic and water quality data are rarely available, all available data should be considered. To calibrate water balance, it is recommended to separate baseflow and surface flow (surface runoff) from the total streamflow for both the measured and simulated data using a baseflow filter program. The baseflow filter developed by Arnold et al. (1995) and modified by Arnold and Allen (1999) is available at www.brc.tamus.edu/swat/soft_baseflow .html. Baseflow and recharge data from this procedure have shown good correlation with those produced by SWAT (Arnold et al., 2000). With estimated baseflow data, the baseflow ratio can be computed for measured and simulated data by dividing baseflow estimates by the total measured or simulated streamflow. The calibration and validation process can be considered satisfactory if the estimated baseflow ratio for simulated flow is within 20% of the measured flow baseflow ratio (Bracmort et al., 2006). Because plant growth and biomass production can have an effect on the water balance, reasonable local/regional plant growth days and biomass production may need to be verified during model calibration. Annual local/regional evapotranspiration (ET) may also need to be verified or compared with measured estimates during model calibration.

Stricter performance ratings should generally be required during model calibration than during validation. This difference is recommended because parameter values are optimized during model calibration, but parameters are not adjusted in validation, which is possibly conducted under different conditions than those occurring during calibration. Although the importance of model calibration is well established, performance ratings can be relaxed if improper calibration procedures are employed.

It is necessary to note that although proper model calibration is important in reducing error in model output, experience has shown that model simulation results may contain substantial errors. Therefore, rather than provide a point estimate of a given quantity of model output, it may be preferable to provide an interval estimate with an associated probability that the value of the quantity will be contained by the interval (Haan et al., 1998). In other words, uncertainty analysis needs to be included in model evaluations. Uncertainty analysis is defined as the process of quantifying the level of confidence in a given model simulation output based on: (1) the quality and amount of measured data available, (2) the absence of measured data due to the lack of monitoring in certain locations, (3) the lack of knowledge about some physical processes and operational procedures, (4) the approximate nature of the mathematical equations used to simulate processes, and (5) the quality of the model sensitivity analysis and calibration. Detailed model uncertainty analysis is beyond the scope of this research, but more model output uncertainty information can be obtained from published literature.

Evaluation Time Step

Most of the literature reviewed used daily and/or monthly time steps (Saleh et al., 2000; Santhi et al., 2001; Yuan et al., 2001; Sands et al., 2003; Van Liew et al., 2003; Chu and Shirmohammadi, 2004; Saleh and Du, 2004; Singh et al., 2004; Bracmort et al., 2006; Singh et al., 2005; Van Liew et al., 2007), although a few used annual time steps (Gupta et al., 1999; Shirmohammadi et al., 2001; Reyes et al., 2004), and one used weekly time steps (Narasimhan et al., 2005). Therefore, the time steps considered in this article are the daily and monthly. Typically, model simulations are poorer for shorter time steps than for longer time steps (e.g., daily versus monthly or yearly) (Engel et al., 2007). For example, Yuan et al. (2001) reported an R^2 value of 0.5 for event comparison of predicted and observed sediment yields, and an R^2 value of 0.7 for monthly comparison. The NSE values were 0.395 and 0.656 for daily and monthly, respectively, for DRAINMOD-DUFLOW calibration, and 0.363 and 0.664 for daily and monthly, respectively, for DRAINMOD-W calibration (Fernandez et al., 2005). Similarly, the NSE values were 0.536 and 0.870 for daily and monthly, respectively, for DRAINMOD-DUFLOW validation, and 0.457 and 0.857 for daily and monthly, respectively, for DRAINMOD-W validation (Fernandez et al., 2005). Additional research work that supports the described findings includes that of Santhi et al. (2001), Van Liew et al. (2003), and Van Liew et al. (2007) using SWAT. The performance ratings presented in table 4 for RSR and NSE statistics are for a monthly time step; therefore, they need to be modified appropriately. Generally, as the evaluation time step increases, a stricter performance rating is warranted.

Project Scope and Magnitude

The scope and magnitude of the modeling project also affects model evaluation guidelines. The intended use of the model is an indication of the seriousness of the potential consequences or impacts of decisions made based on model results (U.S. EPA, 2002). For instance, stricter performance rating requirements need to be set for projects that involve potentially large consequences, such as congressional testimony, development of new laws and regulations, or the support of litigation. More modest performance ratings would be acceptable for technology assessment or "proof of principle," where no litigation or regulatory action is expected. Even lower performance ratings will suffice if the model is used for basic exploratory research requiring extremely fast turnaround or high flexibility.

Finally, according to the U.S. EPA (2002), if model simulation does not yield acceptable results based on predefined performance ratings, this may indicate that: (1) conditions in the calibration period were significantly different from those in the validation period, (2) the model was inadequately or improperly calibrated, (3) measured data were inaccurate, (4) more detailed inputs are required, and/or (5) the model is unable to adequately represent the watershed processes of interest.

A Case Study

Project Description

As a component of the CEAP-WAS, the Soil and Water Assessment Tool (SWAT2005; Arnold et al., 1998) was applied to the Leon River watershed in Texas. The watershed drains into Lake Belton, which lies within Bell and Coryell counties and provides flood control, water supply, and public recreation. The lake has a surface area of approximately 12,300 acres with a maximum depth of 124 feet. The total conservation storage is 372,700 ac-ft. The Lake Belton watershed (Leon River) covers approximately 2.3 million acres

within five counties in central Texas. The majority of the land use in the watershed is pasture, hay, and brushy rangeland (63%). Cropland comprises about 10% of the watershed area. The northwestern (upper) half of the watershed contains numerous animal feeding operations, mainly dairies. Currently, there are approximately 60 permitted dairies and 40 smaller dairies (not requiring permits), with approximately 70,000 total cows. The main goal of the study is to use SWAT2005 to predict the impact of land management on the watershed over long periods of time, with special focus on waste management practices.

To accomplish this goal, SWAT2005, with its many input parameters that describe physical, chemical, and biological processes, required calibration for application in the study watershed. Proper model calibration is important in hydrologic modeling studies to reduce uncertainty in model predictions. For a general description of proper model calibration procedures, refer to the previous discussion in the Additional Considerations section.

Model Evaluation Results Based on the Developed Guidelines

When these model performance ratings were applied to the SWAT2005 modeling in the Leon River (Lake Belton) watershed, the following results were obtained (figs. 2 and 3, table 5). Graphical results during calibration (fig. 2) and validation (fig. 3) indicated adequate calibration and validation over the range of streamflow, although the calibration results showed a better match than the validation results. NSE values for the monthly streamflow calibration and validation ranged from 0.66 to 1.00. According to the model evaluation guidelines, SWAT2005 simulated the streamflow trends well to very well, as shown by the statistical results, which are in agreement with the graphical results. The RSR values ranged

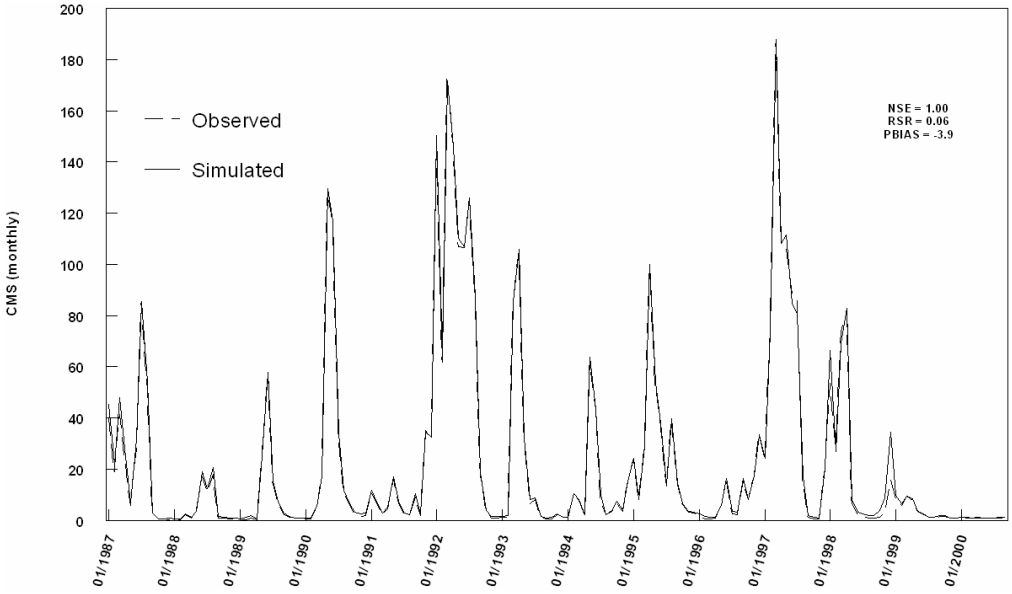

Figure 2. Monthly discharge (CMS) calibration for the Leon River sub-basin 6 WS outlet.

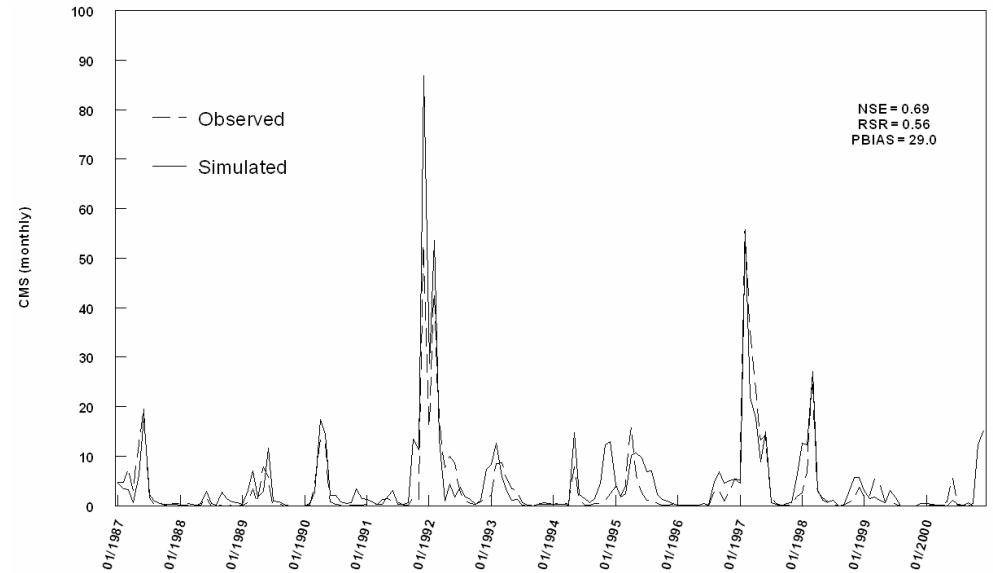

Figure 3. Monthly discharge (CMS) validation for the Leon River sub-basin 13.

Table 5. Results of SWAT2005 average monthly streamflow model output, Leon River watershed, Texas, based on the developed model evaluation guidelines.

	Evaluation Statistic					
	NSE		RSR		PBIAS	
Sub-basin	Calibration	Validation	Calibration	Validation	Calibration	Validation
6	1.00 (very good)	1.00 (very good)	0.03 (very good)	0.06 (very good)	-2.86 (very good)	-3.85(very good)
13	0.66 (good)	0.69 (good)	0.58 (good)	0.56 (good)	-4.89 (very good)	-29.04 (unsatisfactory)
21	0.81 (very good)	0.84 (very good)	0.43 (very good)	0.40 (very good)	-3.62 (very good)	0.41 (very good)
36	0.93 (very good)	0.85 (very good)	0.26 (very good)	0.39 (very good)	-0.28 (very good)	-2.94 (very good)
44	1.00 (very good)	0.78 (very good)	0.06 (very good)	0.46 (very good)	-1.58 (very good)	12.31 (good)
50	0.78 (very good)	--	0.46 (very good)	--	-1.10 (very good)	--
58	0.69 (very good)	--	0.55 (very good)	--	2.15 (very good)	--

from 0.03 to 0.58 during both calibration and validation. These values indicate that the model performance for streamflow residual variation ranged from good to very good. The PBIAS values varied from −4.89% to 2.15% during calibration and from −29.04% to 12.31% during validation. The average magnitude of simulated monthly streamflow values was within the very good range (PBIAS < ±10) for each sub-basin during calibration (table 5). However, simulated values fell within unsatisfactory, good, and very good ranges during validation for various sub-basins. Aside from one indication of unsatisfactory model performance, SWAT2005 simulation of streamflow was "good" to "very good" in terms of trends (NSE), residual variation (RSR), and average magnitude (PBIAS). As apparent from this evaluation of the Leon River watershed, situations might arise that generate conflicting performance ratings for various watersheds and/or output variables.

In situations with conflicting performance ratings, those differences must be clearly described. For example, if simulation for one output variable in one watershed produces unbalanced performance ratings of "very good" for PBIAS, "good" for NSE, and "satisfactory" for RSR, then the overall performance should be described conservatively as "satisfactory" for that one watershed and that one output variable. However, it would be preferable to describe the performance in simulation of average magnitudes (PBIAS) as "very good," in simulation of trends (NSE) as "good," and in simulation of residual variation (RSR) as "satisfactory." Similarly, if performance ratings differ for various watersheds and/or output types, then those differences must be clearly described.

Summary and Conclusions

Most research and application projects involving watershed simulation modeling utilize some type of predefined, project-specific model evaluation techniques to compare simulated output with measured data. Previous research has produced valuable comparative information on selected model evaluation techniques; however, no comprehensive standardization is available that includes recently developed statistics with corresponding performance ratings and applicable guidelines for model evaluation. Thus, the present research selected and recommended model evaluation techniques (graphical and statistical), reviewed published ranges of values and corresponding performance ratings for the recommended statistics, and established guidelines for model evaluation based on the review results and project-specific considerations. These recommendations and discussion apply to evaluation of model simulation related to streamflow, sediments, and nutrients (N and P).

Based on previous published recommendations, a combination of graphical techniques and dimensionless and error index statistics should be used for model evaluation. In addition to hydrographs and percent exceedance probability curves, the quantitative statistics NSE, PBIAS, and RSR were recommended. Performance ratings for the recommended statistics, for a monthly time step, are presented in table 4. In general, model simulation can be judged as "satisfactory" if NSE > 0.50 and RSR ≤ 0.70, and if PBIAS ± 25% for streamflow, PBIAS ± 55% for sediment, and PBIAS ± 70% for N and P for measured data of typical uncertainty. These PBIAS ratings, however, should be adjusted if measurement uncertainty is either very low or very high. As indicated by these PBIAS ratings, it is important to consider measured data uncertainty when using PBIAS to evaluate watershed models. In addition, general guidelines for manual calibration for flow, sediment, and nutrients were presented (fig. 1). Additional considerations, such as single-event simulation, quality and quantity of measured data, model calibration procedure considerations, evaluation time step, and project scope and magnitude, which affect these guidelines, were also discussed. The guidelines presented should be adjusted when appropriate to reflect these considerations. To illustrate the application of the developed model evaluation guidelines, a case study was provided.

Finally, the recommended model evaluation statistics and their respective performance ratings, and the step-by-step description of how they should be used, were presented together to establish a platform for model evaluation. As new and improved methods and information are developed, the recommended guidelines should be updated to reflect these developments.

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APPENDIX

Reported Values of NSE and PBIAS for Various Constituents

Table A-1. Daily and monthly surface runoff calibration and validation value ranges.[a]

Watershed - Model (Reference)	Statistic	Calibration Value Ranges		Validation Value Ranges	
		Daily	Monthly	Daily	Monthly
Warner Creek, Maryland - SWAT (Chu and Shirmohammadi, 2004)	NSE PBIAS	--	0.35	--	0.77
Black Creek, Indiana - SWAT (Bracmort et al., 2006)	NSE PBIAS	--	0.62 to 0.80	--	0.63 to 0.75

[a] In tables A-1 through A-9, a dash (--) indicates no value reported for the statistic used; a blank space indicates that the statistic was not used.

Table A-2. Daily and monthly sediment calibration and validation value ranges.

Watershed - Model (Reference)	Statistic	Calibration Value Ranges		Validation Value Ranges	
		Daily	Monthly	Daily	Monthly
Bosque River, Texas - SWAT (Saleh et al., 2000)	NSE PBIAS	--	--	--	0.81
Bosque River, Texas - SWAT (Santhi et al., 2001)	NSE PBIAS	--	0.69 to 0.80	--	0.23 to 0.70
Bosque River, Texas - SWAT (Saleh and Du, 2004)	NSE PBIAS	-2.50	0.83	-3.51	0.59
Bosque River, Texas - HSPF (Saleh and Du, 2004)	NSE PBIAS	0.11	0.72	0.23	0.88
Hellbranch Run, Ohio - HSPF (Engelmann et al., 2002)[a]	NSE PBIAS	--	0.49	--	-2.46
Black Creek, Indiana - SWAT (Bracmort et al., 2006)	NSE PBIAS	--	0.86 to 0.92	--	0.68 to 0.75

[a] In Borah and Bera (2004).

Table A-3. Daily and monthly organic N calibration and validation value ranges.

Watershed - Model (Reference)	Statistic	Calibration Value Ranges		Validation Value Ranges	
		Daily	Monthly	Daily	Monthly
Bosque River, Texas - SWAT (Saleh et al., 2000)	NSE PBIAS	--	--	--	0.78
Bosque River watershed, Texas - SWAT (Santhi et al., 2001)	NSE PBIAS	--	0.57 to 0.58	--	0.43 to 0.73

Table A-4. Daily and monthly NO_3−N calibration and validation value ranges.

Watershed - Model (Reference)	Statistic	Calibration Value Ranges		Validation Value Ranges	
		Daily	Monthly	Daily	Monthly
Bosque River, Texas - SWAT (Saleh et al., 2000)	NSE PBIAS	--	--	--	0.37
Plymouth, North Carolina - DRAINMOD-W (Fernandez et al., 2005)	NSE PBIAS	0.36	0.66	0.46	0.86
Plymouth, North Carolina - DRAINMOD-DUFLOW (Fernandez et al., 2005)	NSE PBIAS	0.40	0.66	0.54	0.87
Bosque River, Texas - SWAT (Santhi et al., 2001)	NSE PBIAS	--	-0.08 to 0.59	--	0.64 to 0.75

Table A-5. Daily and monthly total N (organic N + NO_3−N) calibration and validation value ranges.

Watershed - Model (Reference)	Statistic	Calibration Value Ranges		Validation Value Ranges	
		Daily	Monthly	Daily	Monthly
Bosque River, Texas - SWAT (Saleh et al., 2000)	NSE PBIAS	--	--	--	0.86
Plymouth, North Carolina - DRAINWAT (Amatya et al., 2004)	NSE PBIAS	--	--	0.19	0.76

Table A-6. Daily and monthly PO_4−P calibration and validation value ranges.

Watershed - Model (Reference)	Statistic	Calibration Value Ranges		Validation Value Ranges	
		Daily	Monthly	Daily	Monthly
Bosque River, Texas - SWAT (Saleh et al., 2000)	NSE PBIAS	--	--	--	0.94
Bosque River, Texas - SWAT (Santhi et al., 2001)	NSE PBIAS	--	0.53 to 0.59	--	0.53 to 0.81
Black Creek, Indiana - SWAT (Bracmort et al., 2006)	NSE PBIAS	--	0.78 to 0.84	--	0.51 to 0.74

Table A-7. Daily and monthly organic P calibration and validation value ranges.

Watershed - Model (Reference)	Statistic	Calibration Value Ranges		Validation Value Ranges	
		Daily	Monthly	Daily	Monthly
Bosque River, Texas - SWAT (Saleh et al., 2000)	NSE PBIAS	--	--	--	0.54
Bosque River, Texas - SWAT (Santhi et al., 2001)	NSE PBIAS	--	0.59 to 0.70	--	0.39 to 0.72

Table A-8. Daily and monthly total P calibration and validation value ranges.

Watershed - Model (Reference)	Statistic	Calibration Value Ranges		Validation Value Ranges	
		Daily	Monthly	Daily	Monthly
Black Creek, Indiana - SWAT (Bracmort et al., 2006)	NSE PBIAS	--	0.51	--	0.37

Table A-9. Daily and monthly streamflow calibration and validation value ranges (continued).

Watershed - Model (Reference)	Statistic	Calibration Value Ranges		Validation Value Ranges	
		Daily	Monthly	Daily	Monthly
Bosque River, Texas - SWAT (Saleh et al., 2000)	NSE PBIAS	--	--	--	0.56
Eight watersheds in southwest Oklahoma - SWAT (Van Liew et al., 2003)	NSE PBIAS	0.56 to 0.58	0.66 to 0.79	-0.37 to 0.72	-1.05 to 0.89

(continued)

Table A-9 (continued). Daily and monthly streamflow calibration and validation value ranges.

Watershed - Model (Reference)	Statistic	Calibration Value Ranges		Validation Value Ranges	
		Daily	Monthly	Daily	Monthly
Eight watersheds in southwest Oklahoma - HSPF (Van Liew et al., 2003)	NSE	0.64 to 0.72	0.74 to 0.82	-1.37 to 0.87	-3.35 to 0.92
	PBIAS				
Plymouth, North Carolina - DRAINMOD-W (Fernandez et al., 2005)	NSE	0.83	0.85	0.87	0.93
	PBIAS				
Plymouth, North Carolina - DRAINMOD-DUFLOW (Fernandez et al., 2005)	NSE	0.68	0.76	0.81	0.92
	PBIAS				
Bosque River, Texas - SWAT (Santhi et al., 2001)	NSE	--	0.79 to 0.83	--	0.62 to 0.87
	PBIAS				
Six watersheds in Texas - SWAT (Narasimhan et al., 2005)[a]	NSE	--	0.52 to 0.90	--	0.55 to 0.81
	PBIAS				
Bosque River, Texas - SWAT (Saleh and Du, 2004)	NSE	0.17	0.50	0.62	0.78
	PBIAS				
Bosque River, Texas - HSPF (Saleh and Du, 2004)	NSE	0.72	0.91	0.70	0.86
	PBIAS				
Plymouth, North Carolina - DRAINWAT (Amatya et al., 2004)	NSE	--	--	0.71 to 0.84	0.85
	PBIAS				
Muscatatuck River, Indiana - SWAT (Vazquez-Amábile and Engel, 2005)	NSE	-0.23 to 0.28	0.59 to 0.80	-0.35 to 0.48	0.49 to 0.81
	PBIAS				
Warner Creek, Maryland - SWAT (Chu and Shirmohammadi, 2004)	NSE	--	0.52	--	0.63
	PBIAS				
Eight CRR-catchment test cases - XNJ (local simplex) (Gan and Biftu, 1996)	NSE	0.89 to 0.94	--	0.37 to 0.88	--
	PBIAS	-4.0 to 0.0	--	-16.0 to 34.0	--
Eight CRR-catchment test cases - NAM (SCE-UA) (Gan and Biftu, 1996)	NSE	0.82 to 0.92	--	0.41 to 0.88	--
	PBIAS	-16.7 to 15.5	--	-31.9 to 37.0	--
Eight CRR-catchment test cases - SMAR (SCE-UA) (Gan and Biftu, 1996)	NSE	0.86 to 0.91	--	0.86 to 0.91	--
	PBIAS	-20.9 to 12.0	--	-32.9 to 31.7	--
Eight CRR-catchment test cases - SMAR (local simplex) (Gan and Biftu, 1996)	NSE	0.74 to 0.90	--	0.00 to 0.85	--
	PBIAS	-6.0 to 0.0	--	-27.0 to 44.0	--
Eight CRR-catchment test cases - SMAR (local simplex) (Gan and Biftu, 1996)	NSE	0.74 to 0.90	--	0.00 to 0.85	--
	PBIAS	-6.0 to 0.0	--	-27.0 to 44.0	--
Eight CRR-catchment test cases - XNJ (SCE-UA) (Gan and Biftu, 1996)	NSE	0.89 to 0.95	--	0.45 to 0.88	--
	PBIAS	-13.9 to 24.4	--	-31.5 to 30.8	--
Eight CRR-catchment test cases - NAM (local simplex) (Gan and Biftu, 1996)	NSE	0.81 to 0.92	--	0.43 to 0.87	--
	PBIAS	-4.0 to 0.0	--	-16.0 to 44.0	--
Eight CRR-catchment test cases - SMA (SCE-UA) (Gan and Biftu, 1996)	NSE	0.87 to 0.94	--	0.31 to 0.89	--
	PBIAS	-7.6 to 1.3	--	-58.6 to 20.1	--
Eight CRR-catchment test cases - SMA (local simplex) (Gan and Biftu, 1996)	NSE	0.85 to 0.93	--	0.29 to 0.88	--
	PBIAS	-11.9 to 6.4	--	-54.8 to 47.2	--
Eight CRR-catchment test cases - SMA (local simplex) (Gan and Biftu, 1996)	NSE	0.85 to 0.93	--	0.29 to 0.88	--
	PBIAS	-11.9 to 6.4	--	-54.8 to 47.2	--
Eight CRR-catchment test cases - SMA (local simplex) (Gan and Biftu, 1996)	NSE	0.85 to 0.93	--	0.29 to 0.88	--
	PBIAS	-11.9 to 6.4	--	-54.8 to 47.2	--
Eight CRR-catchment test cases - SMA (local simplex) (Gan and Biftu, 1996)	NSE	0.85 to 0.93	--	0.29 to 0.88	--
	PBIAS	-11.9 to 6.4	--	-54.8 to 47.2	--
Iroquois River, Illinois and Indiana - HSPF (Singh et al., 2004)	NSE	0.81	0.88	0.70	0.82
	PBIAS				
Iroquois River, Illinois and Indiana - SWAT (Singh et al., 2004)	NSE	0.79	0.89	0.73	0.83
	PBIAS				
Ariel Creek, Pennsylvania - SWAT (Peterson and Hamlett, 1998)[b]	NSE	0.04	0.14	--	--
	PBIAS				
Ali Efenti, Greece - SWAT (Varanou et al., 2002)[b]	NSE	0.62	0.81	--	--
	PBIAS				
University of Kentucky Animal Research Center - SWAT (Spruill et al., 2000)[b]	NSE	0.19	0.89	-0.04	0.58
	PBIAS				
Iroquois River, Illinois and Indiana - HSPF (Singh et al., 2005)	NSE	0.81	0.88	0.69 to 0.71	0.80 to 0.87
	PBIAS				

(continued)

Table A-9 (continued). Daily and monthly streamflow calibration and validation value ranges.

Watershed - Model (Reference)	Statistic	Calibration Value Ranges		Validation Value Ranges	
		Daily	Monthly	Daily	Monthly
Iroquois River, Illinois and Indiana - SWAT (Singh et al., 2005)	NSE	0.79	0.88	0.70 to 0.83	0.80 to 0.93
	PBIAS				
Black Creek, Indiana - SWAT (Bracmort et al., 2006)	NSE	--	0.73 to 0.84	--	0.63 to 0.73
	PBIAS				
Five USDA-ARS experimental watersheds - SWAT (Van Liew et al., 2007)	NSE	0.30 to 0.76	0.48 to 0.90	-1.81 to 0.68	-2.50 to 0.89
	PBIAS	2.9 to -91.7	--	2.7 to -155.6	--

[a] Weekly values.
[b] In Borah and Bera (2004).