Development of Second-Generation Mercury Watershed Simulation Technology: Grid-Based Mercury Model Version 2.0

User's Manual

(Updated)

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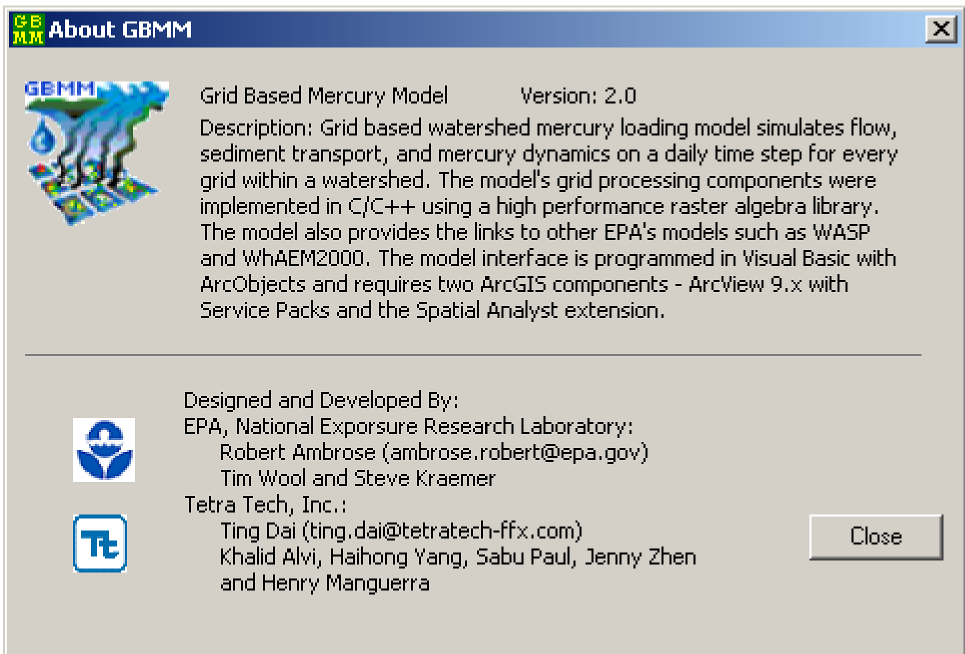
About GBMM 2.0



Contents

1. Introduction

This user's manual describes and explains how to use the features of the Grid-based Watershed Mercury Loading Model (GBMM). It also contains instructions for installing it and setting up the system. The appendices of the manual provide further reference information that the reader may find helpful in using the system.

The model has three key modeling components: Hydrology, Sediment, and Mercury. The model simulates time series of flow, sediment load, and mercury (methyl and divalent) load at user-specified assessment points. It also computes an average daily groundwater recharge for the study area and outputs a geo-referenced image file (*.tif) for the U.S. Environmental Protection Agency's (EPA's) groundwater model, WhAEM2000. GBMM can also be linked with an EPA's in-stream water quality model, the Water Analysis and Simulation Program (WASP), by characterizing streams into branches and segments using the user's criteria and generating time series for each segment.

Mercury (Hg) is a known toxic trace element that has been declared a primary pollutant by EPA, the United Nations Environmental Programme (UNEP), and many other environmental organizations. Out of 189 compounds identified as hazardous air pollutants in the 1990 Clean Air Act, mercury was singled out for separate study to examine anthropogenic (human-caused) emissions and to define thresholds at which mercury affects human health and the environment. Human and wildlife exposure to mercury is primarily due to the consumption of contaminated fish.

Watershed loadings potentially occur along the entire water way. Figure 1.1 shows the conceptual movement of mercury from the source to the consumers. Mercury in the atmosphere comes from natural sources (e.g., geologic features, oceans, forest fires, volcanoes) or anthropogenic sources (e.g., incinerators, coal combustion, industrial emissions). Figure 1.2 shows conceptual mercury transportation and transformation processes.

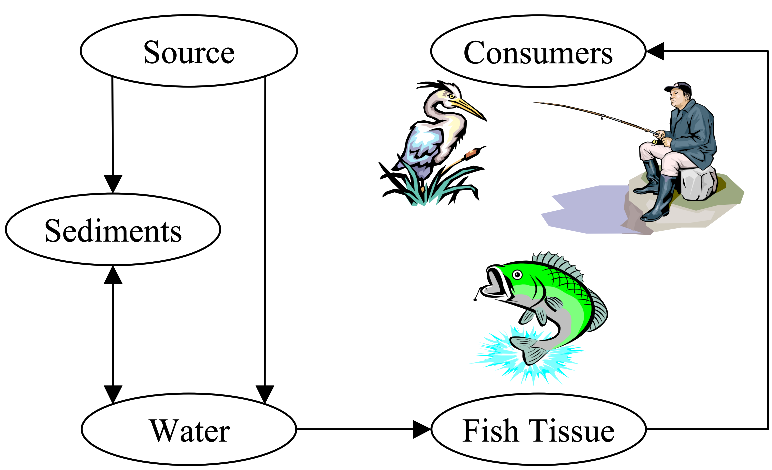


Figure 1.1. Movement of mercury from the source to the consumers.

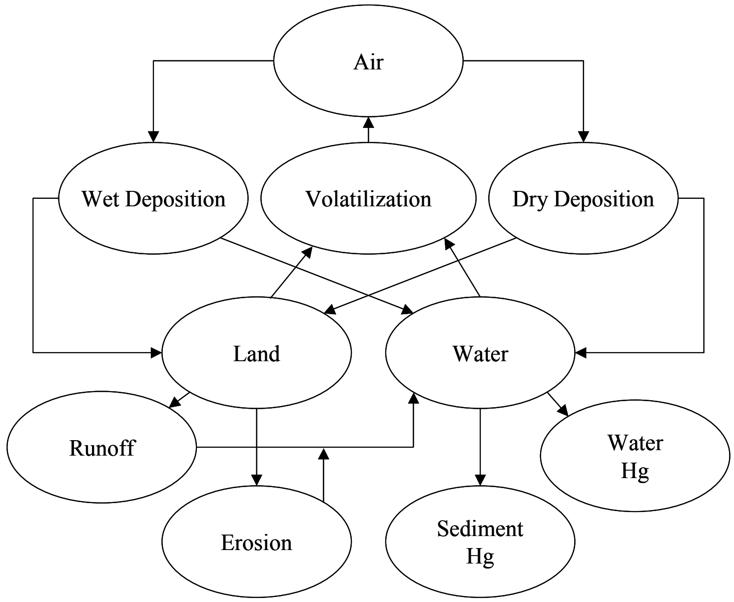


Figure 1.2. Mercury transportation and transformation processes.

1.1 First-Generation WCS Mercury Loading Model (MLM)

In 2000, EPA Region 4 and EPA's Office of Research and Development (ORD) developed mass balance mercury watershed technology and mercury Total Maximum Daily Loads (TMDLs) in six Georgia river basins (http://www.epa.gov-/region4/water/tmdl/georgia/index.htm). This technology uses the geographic information system (GIS)-based Watershed Characterization System (WCS) (Greenfield et al., 2002 or http://wcs.tetratech-ffx.com) to calculate soil mercury concentrations and loadings from pervious and impervious surfaces in individual subbasins. Figure 1.3 illustrates the structure of the WCS.

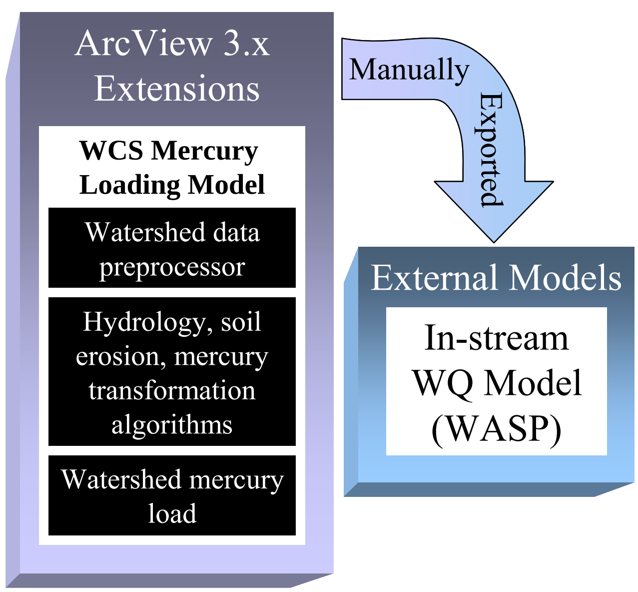


Figure 1.3. Structure of the first-generation WCS mercury loading model or MLM.

A simple spreadsheet calculation that includes travel time and reduction rate was used to calculate the delivery of mercury loads through the tributaries to the mainstem rivers. Version 5 of EPA's WASP model (WASP5) (Ambrose et al. 1993a, 1993b) was parameterized to simulate mercury fate in the mainstem rivers. The modeling approach was based largely on field characterization programs that measure mercury concentrations in soil, water, sediment, and fish.

1.2 Second-Generation Grid-based Watershed Mercury Loading Model

In 2004, EPA ORD (Athens) and Tetra Tech, Inc. (Fairfax) developed the second-generation GBMM (version 1.0). The GBMM 1.0 was designed to reconstitute, refine, and extend the WCS MLM through the tributary system to the mainstem rivers. The new watershed mercury model (Figure 1.4) was a system that consisted of four major parts:

- An ArcGIS 9 interface for spatial and tabular data management
- An enhanced *grid-based* watershed mercury loading model with hydrology and sediment modules (Appendix D)
- A seamless linkage to a spreadsheet post-processor for display and analysis of results
- Linkages to an in-stream water quality simulation model (WASP) and a groundwater model (WhAEM2000)

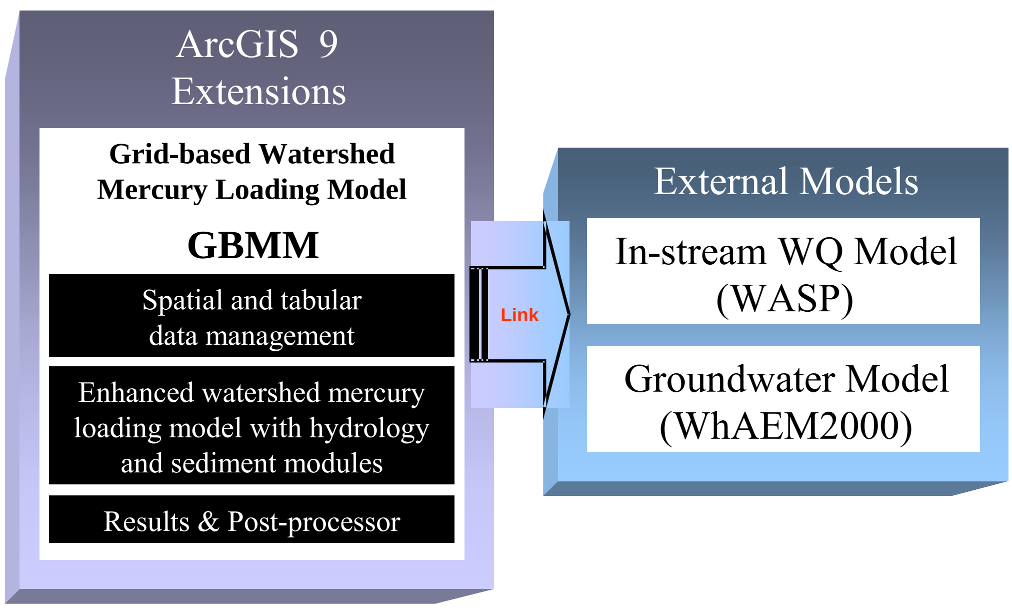


Figure 1.4. Structure of the second-generation grid-based watershed mercury loading model (version 1.0).

GBMM 1.0 simulates flow, sediment transport, and mercury dynamics on a daily time step across a grid-based landscape. In addition to all the algorithms in the original WCS mercury model, the enhanced GBMM 1.0 system added the following features:

- Grid-based algorithms
- Significant improvement in configuring the model and calculating loadings for multiple watersheds
- Chemical and physical parameters that vary with different soil-land cover combinations
- Wetland module
- Forest module
- Background mercury input from weathering
- Ability to calculate shallow groundwater output
- Simple tributary algorithm
- A linkage to the WASP model to simulate the transport and fate of mercury species in mainstem rivers
- A linkage to EPA's groundwater WhAEM2000 model
- ArcGIS 9 environment

However, due to the inefficient grid operation algorithms built in the ArcGIS 9 platform, GBMM 1.0's simulation performance suffered greatly, especially for studying large watersheds using high-resolution data (data grid size less than 30 meters).

In 2005, EPA ORD and Tetra Tech found an open source raster algebra library in C language (http://sourceforge.net/projects/libral/ written by Ari Jolma, professor of geoinformatics in Helsinki University of Technology) that could improve the basic grid operation performance substantially. Initial comparison showed that code using the C raster algebra library was over 10 times more efficient than the code using the ArcGIS' raster calculator for the same computational routines. Using the new C raster algebra library, EPA and Tetra Tech have modified core of GBMM 1.0 and upgraded it to GBMM 2.0.

GBMM 2.0 has the following major changes:

- New and easy installation.
- The GIS interface has more steps to guide model setup.
- A new manual watershed-clipping tool that a user can use to draw a boundary and clip data from a large dataset.
- GIS interface can process large grid datasets by dividing them into smaller tiles.
- All dynamic simulation processes (hydrology, erosion and sediment transport, and mercury transport and transformation) are coded in C/C++ using the high performance C raster algebra library

- The system has improved its data exchange capacity with the original WCS MLM, which still remains to be a simple and efficient tool for estimating annual average watershed mercury load.

The structure of the GBMM 2.0 is shown in Figure 1.5.

1.3 GBMM 2.0 System Components

The GBMM 2.0 has three major system components:

- An ArcGIS interface
- A GBMM C++ module
- A results postprocessor

The GIS interface is installed as a dynamic link library (DLL) equivalent to an ArcView 3.x extension. It was developed in Microsoft Visual Basic (VB) with ArcGIS ArcObjects. The GBMM C++ module was developed using C/C++ and the C raster algebra library. The GBMM results postprocessor was developed using Microsoft Excel 2000. The three components can work either as an integrated application or as three standalone programs.

The GBMM ArcGIS interface integrates all the three system components. It processes spatial data, feeds the processed input to GBMM C++ module, and calls the postprocessor to display and analyze the simulation results.

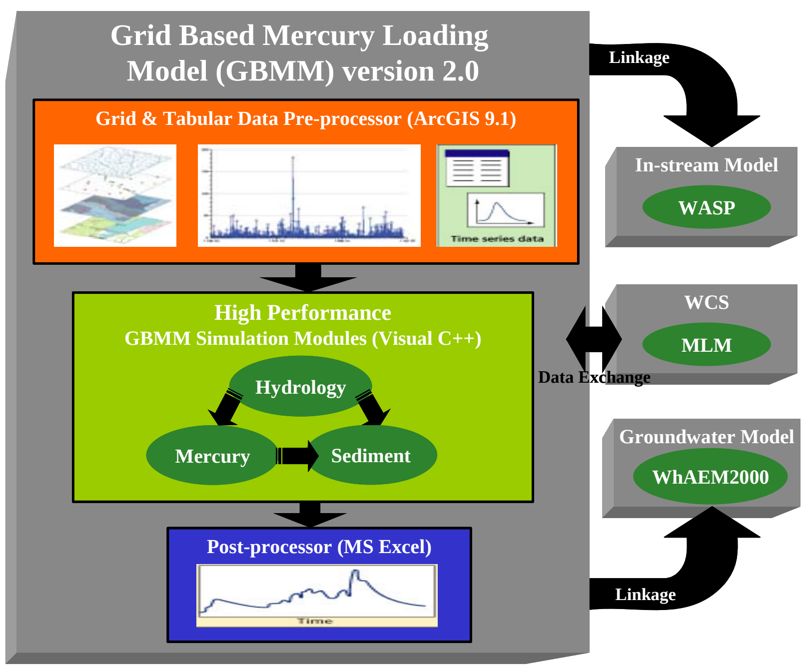


Figure 1.5. Structure of GBMM version 2.0. Using the open source raster algebra library, GBMM's performance has been improved substantially.

1.3.1 ArcGIS Interface

ArcGIS, Environmental Systems Research Institute (ESRI)'s new GIS software system, is the result of reengineering legacy GIS software such as ArcView 3.x and ArcInfo to make it consistent with current information technology and software standards. Microsoft VB is the standard interface language for ArcGIS (replacing Avenue scripting language), which makes it easier to integrate ArcGIS with other Microsoft applications such as Microsoft Excel and Microsoft Access. The GBMM 2.0's ArcGIS interface was developed using VB as a programming language for ArcObjects (components of ArcGIS 9.1). GBMM requires ArcGIS 9.x (ArcMap) with service packs and the Spatial Analyst extension.

GBMM ArcGIS interface contains the following major components:

Data Management and Processing

A data management interface uses and manipulates GIS layers and clips the required data in user-specified folders. Preprocessed data can be further edited, fed to the simulation modules, or used for different scenarios.

WASP Linkage

A linkage is provided between GBMM and EPA's existing water quality model, WASP (Wool et al., 2001), to simulate the water quality dynamics in any selected streams. The model segments streams on the basis of user-defined criteria (travel time or length) and simulates time series of flow, sediment load, and mercury load at each segment. These parameters, in turn, can be used as input to the WASP model.

WhAEM2000 Linkage

A linkage is provided between GBMM and EPA's steady-state groundwater model, WhAEM2000 (USEPA, 2000). The GBMM computes the average daily recharge grids for the study area and exports them as geo-referenced image files (*.tif) that can be used as input to the WhAEM2000 model.

WCS Linkage

The GBMM 2.0 can exchange data with WCS MLM. The soil moisture, soil mercury concentration, and watershed boundaries data can be imported into WCS MLM as initial conditions for simple analyses. The output from WCS can also be used as the simulation starting point for more detailed studies in GBMM.

1.3.2 GBMM C++ Simulation Module

The open source raster algebra library was modified and improved to replace the ArcGIS' raster calculator. All the GBMM modeling routines were re-coded in C++. As a result of using C++ and the new raster algebra library, GBMM 2.0 has achieved a new level of performance and is able to use the system memory more efficiently. The current model runs more than 10 times faster and can be applied on a larger study area than the previous model. The C++ simulation module includes three major components described below.

Hydrology Module

The hydrology module computes the water balance and travel time for each cell at each time step (daily) and simulates flow time series (hydrographs) at the user-defined assessment points.

Sediment Module

The sediment module predicts the sediment yield at the grid level and simulates sediment loading time series at the user-defined assessment points.

Mercury Module

The mercury module computes the mercury load at the grid level for different land uses. It simulates time series of methylmercury and divalent-mercury load at the user-defined assessment points and the watershed outlet.

1.3.3 GBMM Postprocessor

The GBMM postprocessor uses Microsoft Excel's excellent graphics and numeric data manipulation capacity to load and display the GBMM simulation results. The postprocessor provides three worksheets for you to view time series, analyze loading sources, and examine the mass balances between different model compartments.

2. Getting Started

2.1 System Requirements

The system requirements for running GBMM 2.0 include:

- Software: ArcMap 9.x with the latest patches and ArcGIS Spatial Analyst, Microsoft Excel 2000, and Windows 2000 or later versions.
- Hardware: Pentium 4 processor 1.6 GHz or better, 512 RAM, and minimum 1 GB free hard drive space.
- To run model for a large study area (e.g., > 2000 x 2000 grid cells), a 64-bit processor with Windows XP 64-bit operating system is recommended.

2.2 GBMM Installation

To install GBMM, double-click on GBMMSetup.exe (system setup file). It begins to install the system on your hard drive. Follow the simple installation steps, and four subfolders—DATA, DLLs, ETC, and DOCs—are created in the folder you have specified (e.g., D:\GBMM).

2.3 GBMM Directory Structure

After the installation, the setup file creates the following folders under the main application folder (e.g., D:\GBMM) on the hard drive:

- DATA: Contains the input GIS layers and tables as well as input time series data required to run the model. All the input datasets are recommended to be placed in the DATA folder. The sample input files are also installed in this folder. There are two sample data folders under this directory: DATA_30m (input grids having ~30 meter resolution or cell size) and DATA_90m (input grids having ~90 meter resolution or cell size).

  The sample study area is the Brier Creek basin in Georgia. The sample files include:
  - Digital Elevation Model (DEM) grid
  - MRLC grid (1992 Multi Resolution Land Characteristics data)
  - Soil grid
  - Climate station shape file
  - Climate data file
  - NHD drain shape file
  - NHD lake shape file
  - NHD stream shape file
  - Land use code and property lookup table
  - Land use code and curve number lookup table
  - Soil property table

- DLLs: Contains the ArcGIS GBMM extension GBMM.dll, a system registration script GBMM.reg, a system registration batch file GBMM.bat, a system de-registration script UGBMM.reg, and a system deregistration batch file UGBMM.bat.
- DOCs: Contains technical documents like this document (GBMM2_UserGuide), which describes the system operation procedures and provides a case study.
- ETC: Contains GBMM postprocessor spreadsheet GBMMpostprocessor.xls, GBMM C++ module GBMM.exe, a climate processing spreadsheet tool MetADAPT.xls, and a new WCS MLM extension wcs_mercury23.avx.
- New project file and folders: If you create or save a new project, GBMM system adds new project file and folders under the main application folder. For example, if the main application folder is D:\GBMM and you create a project called Tutorial, GBMM creates the following project file and folders:

    D:\GBMM
        DATA (*original folder*)
        DLLs (*original folder*)
        DOCs (*original folder*)
        ETC (*original folder*)
        Tutorial.mxd (*new* project file)
        Tutorial (*new* project folder)
            DATA (Empty or stores clipped data sets)
            INPUT (input files for GBMM C++ module)
            TEMP (GIS files generated by data processing steps)
            MERCURYOUT (GBMM simulation output)
            WASPLINK (Linkage files for WASP)
            WHAEMLINK (Linkage files for WhAEM 2000)

2.4 GBMM Input Data Files and Data Sources

2.4.1 General GIS Map Layers

GBMM ArcGIS interface requires the following GIS map layers for generating input files for the GBMM C++ module:

- Soil map (Grid)
- Land use (Grid)
- DEM (Grid)
- Climate location (point shape file)
- NHD stream (described in Section 2.4.3)

The GBMM interface has a data management window (Section 3.4) that asks you to provide the above listed map layers. Table 2.1 provides a description on the required GIS data layers (except NHD) and simple instructions on where to obtain the data.

Table 2.1 Required and Optional GBMM Input: General GIS Map Layers

Data	Description	Source
Soil Map	U.S. soil map in grid format showing major soil groups (special lookup ID values link to STATSGO Mapunits)	Provided with the installation package. (* see note below) Suggested spatial map projection: (see Appendix A, specifically section A.7 for projection) Type = Albers Equal-Area Conic Projection Reference System = GRS80 Parameters: Central Meridian = -96.0 Reference Latitude = 23 Lower Standard Parallel = 29.5 Upper Standard Parallel = 45.5 False Easting = 0 False Northing = 0 Datum = NAD 1983
Land use	Land use map (National Land Cover Dataset or NLCD 1992, 2001)	Data can be obtained from USGS. (Figure 2.2) http://seamless.usgs.gov/website/seamless/viewer.php Suggested projection: see Soil Map above.
DEM	Digital Elevation Model	Data can be obtained from USGS. http://seamless.usgs.gov/website/seamless/viewer.php Suggested projection: see Soil Map above
Climate Stations	National Climate Data Center (NCDC) Station Location	Locations of climate stations can be found from NCDC web site: http://www.ncdc.noaa.gov-/oa/climate/stationlocator.html Locations of climate stations can also be found in NCDC data CDs. You must convert latitude and longitude of climate station locations to a shape file (see Appendix A, section A.4)
Point Sources *(Optional)*	Point source location	You must convert latitude and longitude of point source location data to a shape file (see Appendix A, section A.4)

* The data were downloaded from "Soil Information for Environmental Modeling and Ecosystem Management" Web site (http://www.essc.psu.edu/soil_info/) (Figure 2.1) maintained by Pennsylvania State University.

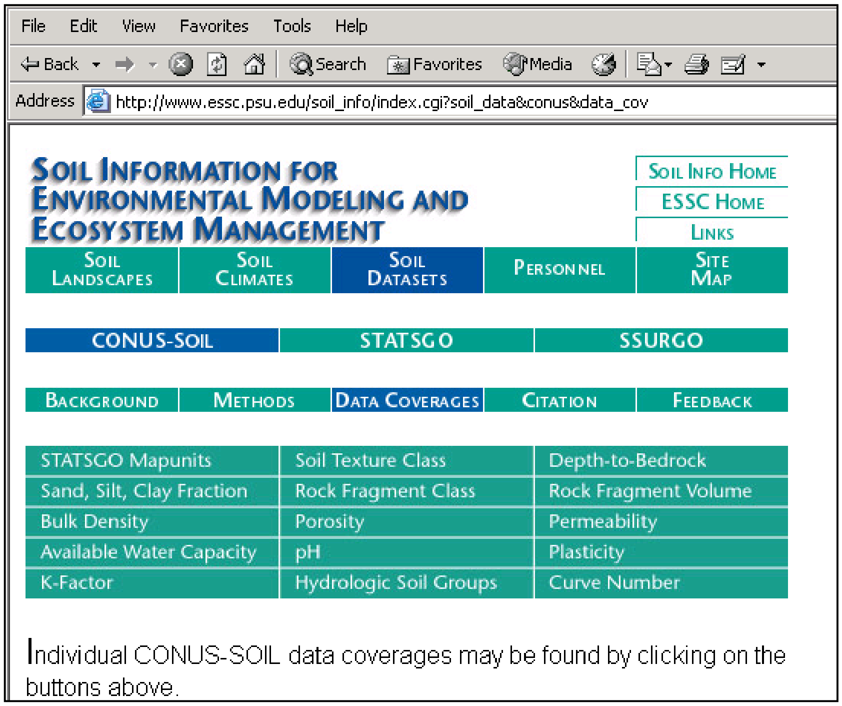


Figure 2.1. Soil Datasets Web site maintained by the Pennsylvania State University.

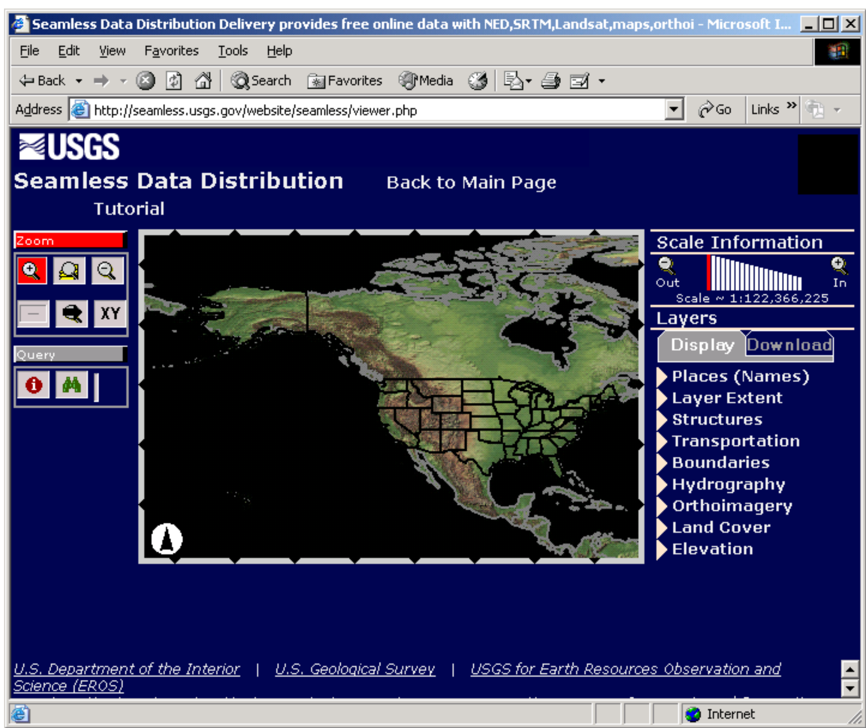


Figure 2.2. USGS Seamless Data Download site for obtaining land use and DEM data.

2.4.2 Input Tables

GBMM requires the following files as input tables:

- Land use lookup tables
- Land use-curve number lookup tables
- Climate data table
- Soil property data table
- Point source data table (optional if the point source shape file is not specified, see Table 2.1)

The GBMM interface has a data management window (Section 3.4) that asks you to provide the above listed data tables. Table 2.2 provides a description on the required data tables and simple instructions on where to obtain the data.

Table 2.2 Required and Optional GBMM Input: Data Tables

Data	**Description**	**Source**
Land Use Lookup Table	Lookup table contains the standard NLCD 1992 land cover code (http://landcover.usgs.gov/classes.asp). Each code has a series of corresponding land cover parameters used in the GBMM model. The lookup table contains the following fields: LUCODE: Land use code LUNAME: Land use description LUC: Land use crop management factor, corresponding to USLE C factor. LUP: Land use practice factor, corresponding to USLE P factor. GETCOVER: Vegetation ET cover coefficient for growing season NGETCOVER: Vegetation ET cover coefficient for non-growing season IMP: Imperviousness fraction LU_IRRIG: Irrigated land or not IMP_SAC: Sediment accumulation rate on impervious surface IMP_DCON: Impermeability values for disconnected pores in soil IMP_TOT: Total impermeability of the soil value TYPE: Land use type: Water (0), pervious land (1), impervious (2), and forest (3). **Note:** *TYPE controls linkages between land uses and simulation modules!* N: roughness coefficient LOOKUP: Temporary field for system internal use	A default table is included in installation package. You can modify the default table, but do not modify field names.
Land Use CN Lookup Table	Lookup table contains the combined soil hydrologic group (SHG) and NLCD	A default table is included in installation package. You can modify

Data	Description	Source
	land cover code (3-digit LU_CNCODE). The first digit of the combined code represents SHG (1 = A, 2 = B, 3 = C, and 4 = D); and the next two digits represent the standard NLCD land cover code (http://landcover.usgs.gov/classes.asp). Each combined code has a corresponding soil runoff curve number (CN field).	the default table, but do not modify field names.
Climate Data Table	Climate data table contains date, daily precipitation, daily average temperature, and data flags for stations corresponding to the climate shape file (See Table 2.1)	NCDC Summary of the Day CD (EarthInfo Inc. http://www.earthinfo.com). Select and export desired climate data, which can be easily formatted to GBMM required format using the included MetADAPT program. (See Appendix B)
Soil Property Table	Soil property table is linked to U.S. soil map through soil group lookup IDs, which correspond to STATSGO's Mapunits (Table 2.1).	Provided with the installation package. Data were downloaded from the same site as the U.S. soil map (Table 2.1) (http://www.essc.psu.edu-/soil_info/). Available water capacity, bulk density, K-factor, hydrologic soil group, depth to bedrock, permeability, and clay fraction are the major soil parameters required by GBMM and compiled in the soil attribute table.
Point Source Data Table	Required only if the shape file is provided (Table 2.1). This table is to provide point source time series corresponding to the point source locations in the shape file.	You must provide a time series text file containing the following data: Date, station_id, flow (cms), sediment load (kg/day), and mercury load (μg/day).

Details on Climate Data File

The required climate data file should contain four comma delimited columns, which are date (IDATE), station ID (STA_ID), daily precipitation in centimeter (PRCP_CM), daily average temperature in Celsius (TAVG_C) The precipitation flag (PRCP_FG, indicating whether the data value is actual or estimated) and temperature flag (TAVG_FG) are optional. One file includes data for multiple stations, and the data series of one station follow those of another station. A sample climate data file is shown below:

```
IDATE,STA_ID,PRCP_CM,TAVG_C,PRCP_FG,TAVG_FG
1/1/1980,090311,0.254,3.333,0.,0.
1/2/1980,090311,0.000,2.222,0.,0.
…
1/1/1980,090495,0.406,5.278,0.,0.
1/2/1980,090495,0.000,5.000,0.,0.
…
```

In the GBMM 2.0 installation package, a spreadsheet tool (Meteorological Data Analysis and Preparation Tool or MetADAPT) is provided to process the daily climate data (daily precipitation, daily maximum temperature, and daily minimum temperature) extracted from EarthInfo's NCDC Summary of the Day CD. More descriptions on how to use MetADAPT are provided in Appendix B.

2.4.3 National Hydrography Dataset (NHD)

NHD data are required by GBMM to characterize stream physical properties and network connections. NHD can be downloaded from a USGS FTP site (Figure 2.3). The original NHD is in ArcInfo coverage format. Some manipulations are required to extract required information for GBMM. GBMM requires the following NHD information:

- NHD Streams (nhd route.rch)
- NHD Rflow table (nhd.rflow)
- NHD Lakes (nhd region.wb)
- NHD Drains (nhd route.drain)

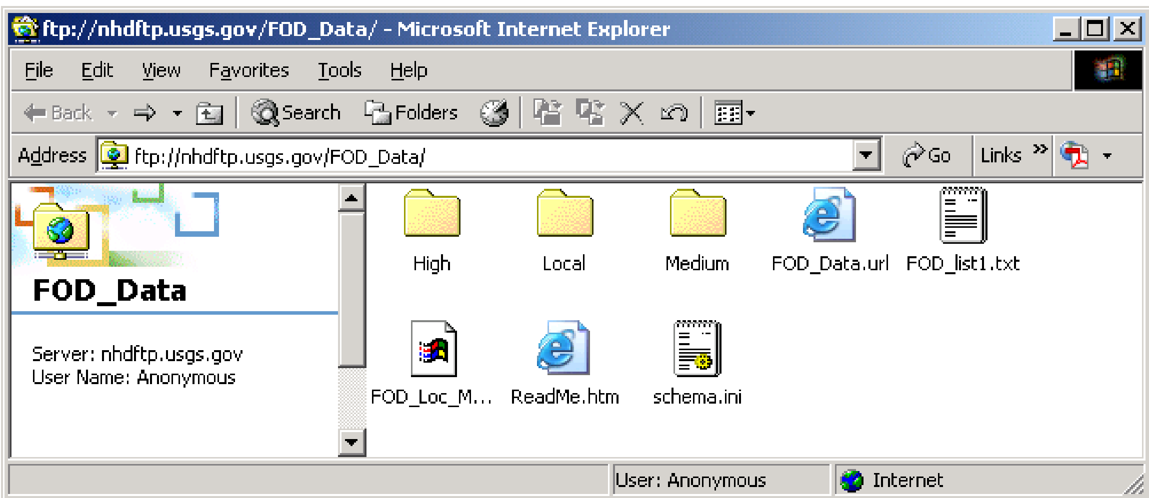


Figure 2.3 The USGS FTP site to obtain NHD files.

Table 2.3 provides a description on the required NHD data layers and simple instructions on where and how to obtain the data.

Table 2.3 Required GBMM Input: NHD Data Layers

Data	Description	Source
NHD_Streams	NHD stream reach data. The data layer for streams is NHD route.rch in the original NHD ArcInfo coverage.	Obtain NHD from the USGS' ftp site (ftp://nhdftp.usgs.gov/FOD_Data/). You may try the medium density NHD first although the high-density data are also available. The compressed NHD is organized in folders of 8-digit hydrologic unit code.

Data	Description	Source
		The compressed (*.tgz) NHD data need to be uncompressed to ArcInfo coverage first. You can then open the NHD coverage in ArcMap. Under the NHD folder, click to open **route.rch** layer and export the data as a stream shape file. Later, you must project the nhd stream file to the same projection as the other GIS data layers. The suggested spatial projection type for GBMM is Albers Equal-Area Conic projection (see Table 2.1).
NHD_RFlow Table	The nhd.rflow table contains stream connection information from node (comid_1) to node (comid_2)	The **nhd.rflow** info table is included in ArcInfo NHD coverage described above. The nhd.rflow table is in ArcInfo table format, and it can be exported to dbf format.
NHD_Lakes	The NHD region.wb file contains locations and shapes of lakes.	The **region.wb** coverage is under the NHD folder. Click to open region.wb layer and export the data as a lake shape file. Later, you must project the lake file to the same projection as the other data layers (see Table 2.1).
NHD_Drains	The NHD route.drain file contains unique segments IDs instead of merged segment IDs as in the stream (route.rch) file.	The **route.drain** coverage is under the NHD folder. Under the NHD folder, click to open route.drain layer and export the data as a drain shape file. Later, you must project the drain file to the same projection as the other data layers (see Table 2.1).

3. Step-by-Step GBMM Application Guide

This section provides step-by-step instructions on how to use GBMM 2.0.

3.1 Start ArcMap

- To start ArcMap, click the Windows **Start** menu, point to **Programs**, select **ArcGIS**, and then click **ArcMap** (Figure 3.1).

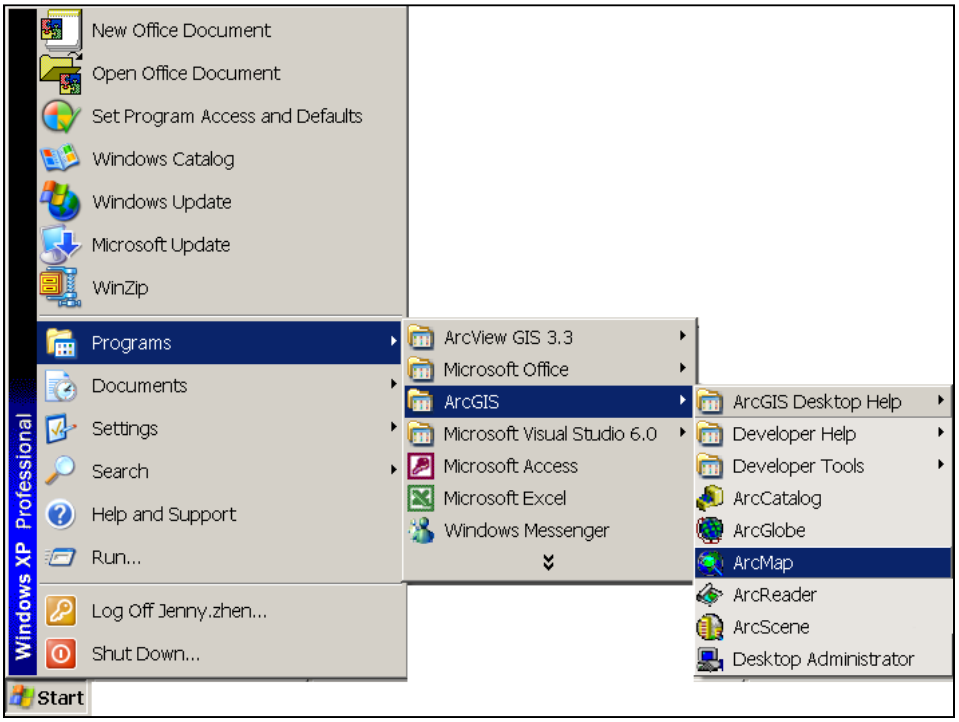


Figure 3.1. Starting ArcMap.

- ArcMap then prompts you to choose a project type. To start with a new project (also called *map* in ArcMap), select **A new empty map** option and click **OK** (Figure 3.2). The ArcMap window appears (Figure 3.3).

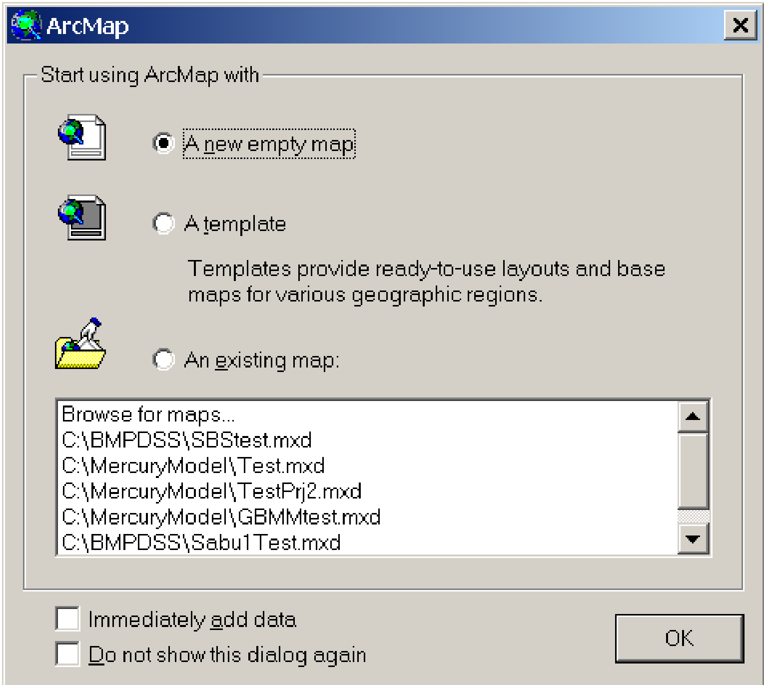


Figure 3.2. Start using ArcMap with a new empty map.

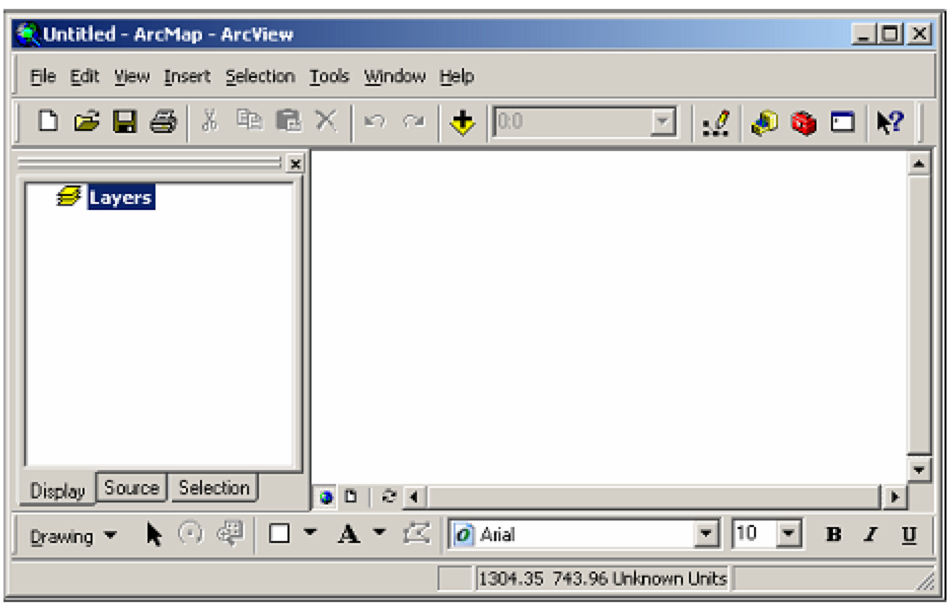


Figure 3.3. An untiltled ArcMap window. The left panel (also called table of contents) manages data layers, and the right panel displays spatial data layers.

3.2 Activate GBMM Interface Toolbar

After GBMM 2.0 has been properly installed (see Section 2.2), you can activate the GBMM Interface toolbar in ArcMap. To do this:

1. Right-click the Main Menu bar area. A list of available extensions is displayed (Figure 3.4).
2. Select the **Grid Based Mercury Model 2.0** extension. The Grid Based Mercury Model Interface toolbar appears in the ArcMap window (Figure 3.5).

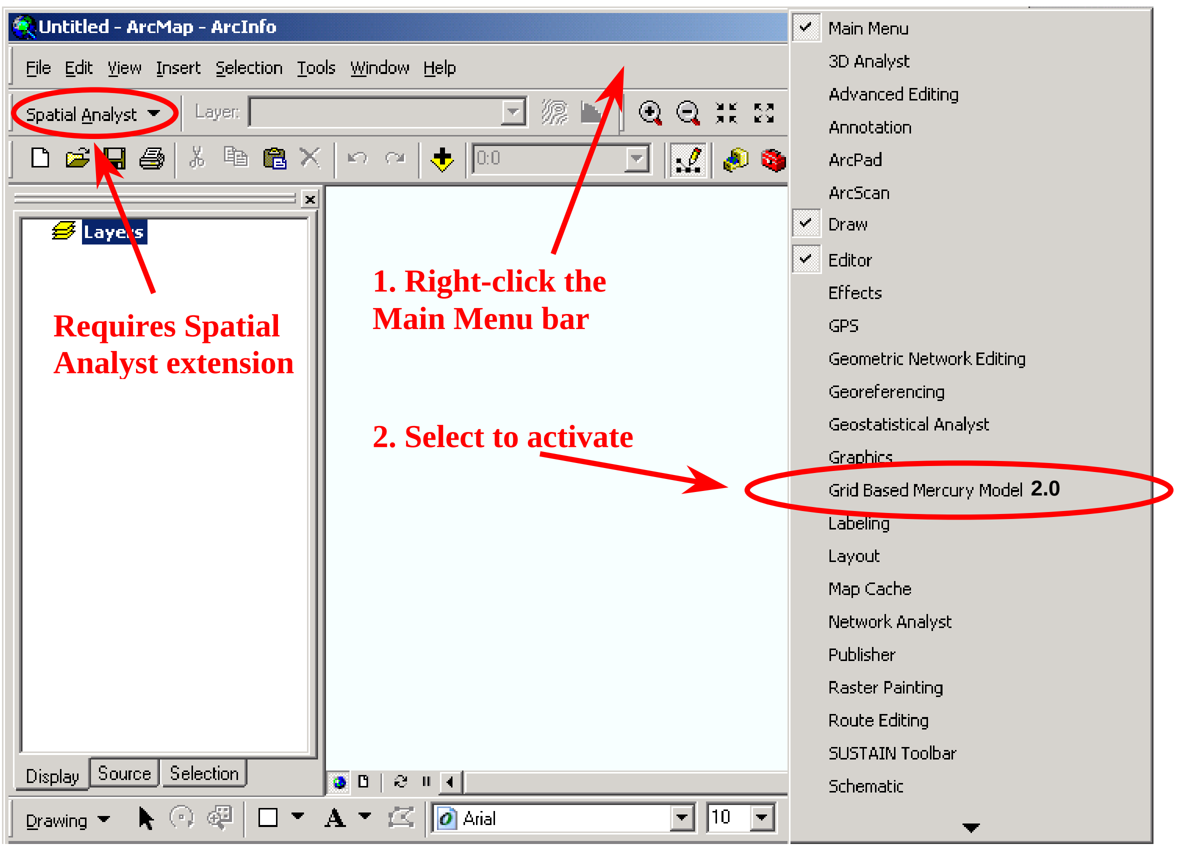


Figure 3.4. Activate "Grid Based Mercury Model" extension. Spatial Analyst extension is required to use GBMM ArcGIS extension.

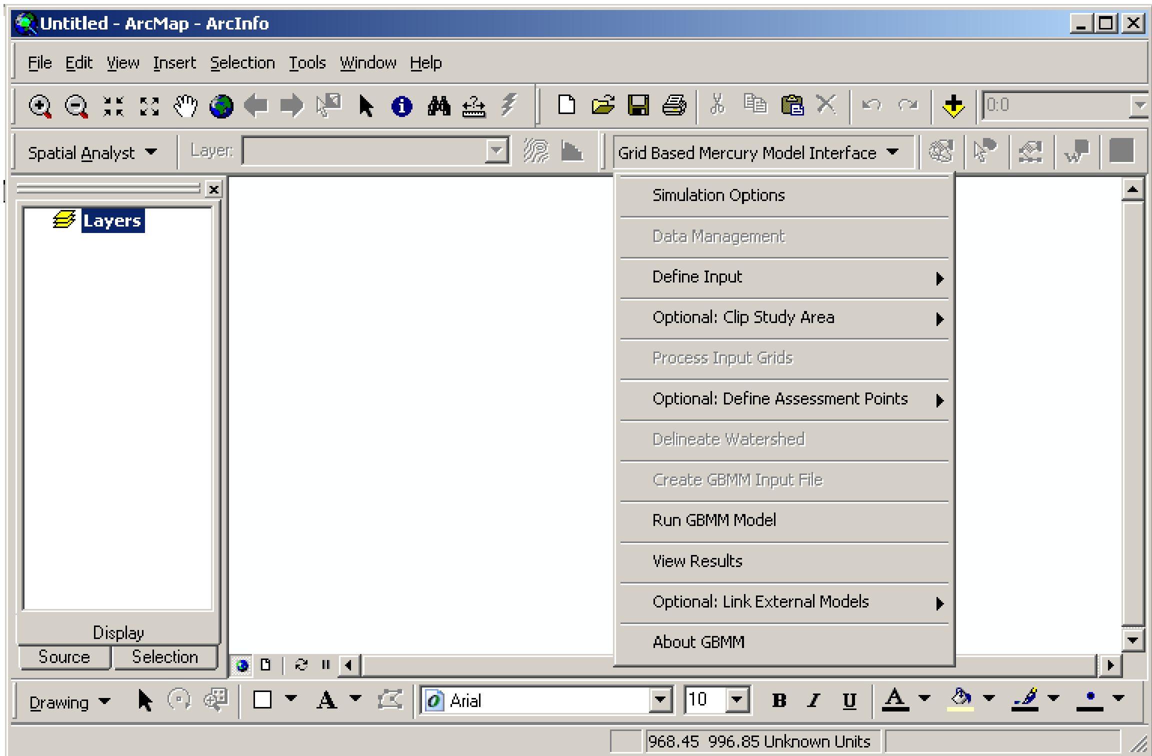


Figure 3.5. The Grid Based Mercury Model Interface toolbar.

The GBMM Interface toolbar contains a dropdown menu list and five tool buttons:

- Manual Watershed Clipping tool 
- Auto Watershed Clipping tool 
- Add Assessment Points tool 
- Select NHD Stream 
- Convert ASCII to Grid 

Before proceeding, you must save the current project and give the untitled ArcMap project a name. To do this:

1. Select the **File** menu, then click **Save** (or click the **Save** icon  on the toolbar) The Save As dialog box opens (Figure 3.6).
2. Enter the project's name in the File name field.
3. To save the file, click **Save**.

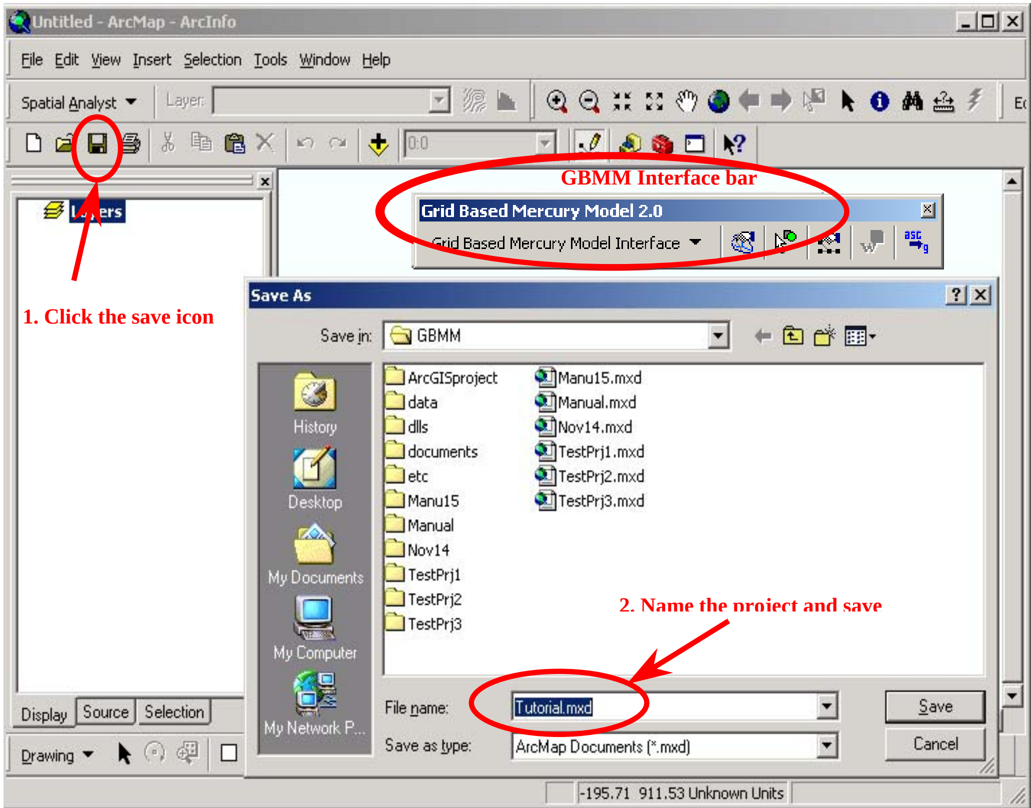


Figure 3.6. Save an ArcMap project.

If you click the first menu option Simulation Options on the GBMM Interface before saving the project, a message reminds you to save project first (Figure 3.7).

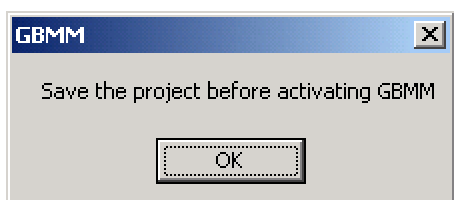


Figure 3.7. A message to remind you to save the project first.

3.3 Simulation Options

The first step when using the GBMM application is to set the simulation and model run options. To do this, click the **Grid Based Mercury Model Interface**, and then select **Simulation Options** (Figure 3.8). The Simulation Options dialog box appears (Figure 3.9).

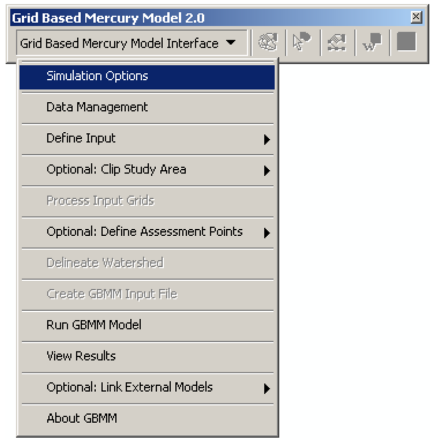


Figure 3.8. Select Simulation Options from the GBMM interface bar.

Three simulation options are available: Hydrology, Sediment, and Mercury. The Hydrology option runs only the hydrologic simulation of the model; the Sediment option runs both hydrologic and sediment simulation; and the Mercury option runs hydrologic, sediment, and mercury simulation.

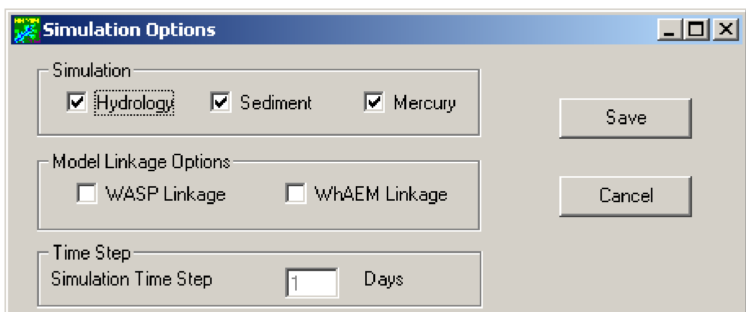


Figure 3.9. Simulation Options window.

The GBMM Interface also provides two Model Linkage Options: WASP Linkage and WhAEM Linkage. To generate flow and water quality time series data for each user-specified stream segment, select the **WASP Linkage** check box (also see Sections 3.8 and 3.13). You can then use WASP Stream Network Pre-processor in later steps to define stream segments. To have GBMM compute the average daily recharge grids for the study area and export them as geo-referenced image files (*.tif) that can be used as input to the WhEAM2000 model, select the **WhAEM Linkage** check box (also see Figure 3.40 and Section 3.13).

3.4 Data Management

After the Simulation Options have been set, the second step to using GBMM interface is to specify and load input data. This involves specifying input data, and the interface loads GIS data layers, lookup tables, and NHD stream layers. To do this, click the **Grid Based**

Mercury Model Interface, then select **Data Management**. The Data Management window appears (Figure 3.10). The Data Management window consists of three tabs: Map Layers, Tables, and NHD. You can specify the data files in one of two ways:

- Using the file navigation button ( ) next to each file input box.
- By clicking on the dropdown button of an input box, if the input data layers have already been loaded in the layers window (left side panel of the main ArcMap window) of the project.

On the Map Layers tab (Figure 3.10), you must specify a soil map, a land use map, DEM, and a climate station map. A point source map is optional.

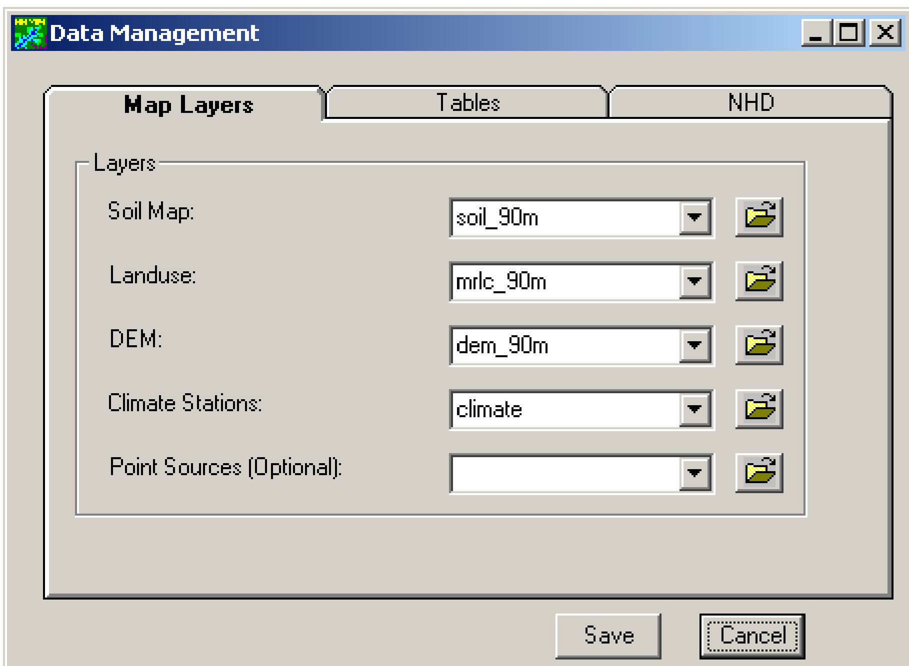


Figure 3.10 Data Management window–Map layers tab.

On the Tables tab (Figure 3.11), you must specify a land use parameter lookup table, a land use curve number lookup table, a climate data file, and a soil property table. A point source data table is required only if the point source map was specified on the Map Layers tab.

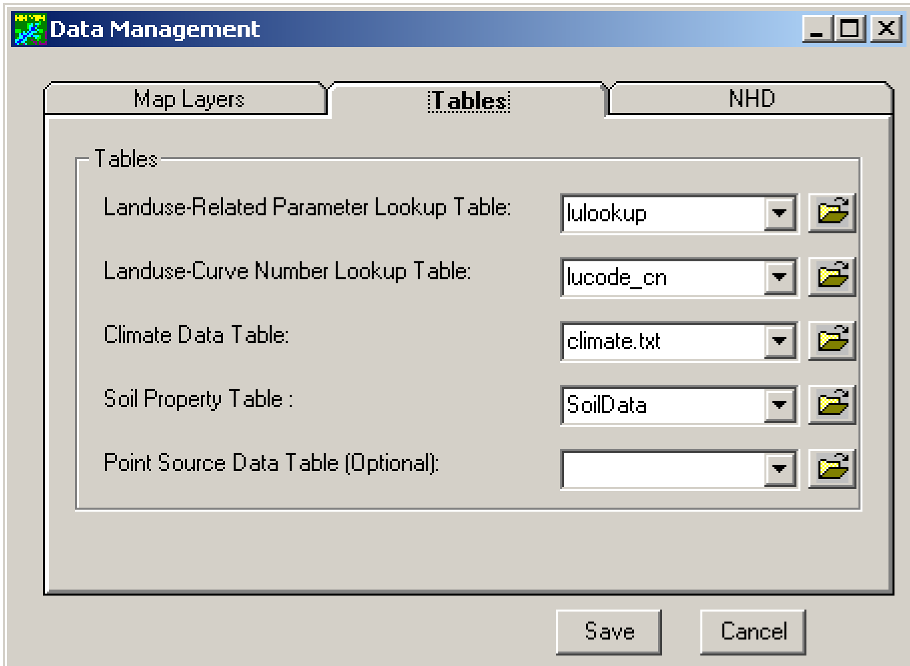


Figure 3.11 Data Management window–Tables tab.

On the NHD tab (Figure 3.12), you must specify an NHD streams layer and a NHD flow relation table (RFlow table); you must also specify an NHD drains layer if the WASP Linkage run option was selected on the Simulation Options dialog (Section 3.3). An NHD lakes layer is optional depending on your study area and objectives. For details on where to obtain the map layers, tables, and NHD, see Section 2.4.

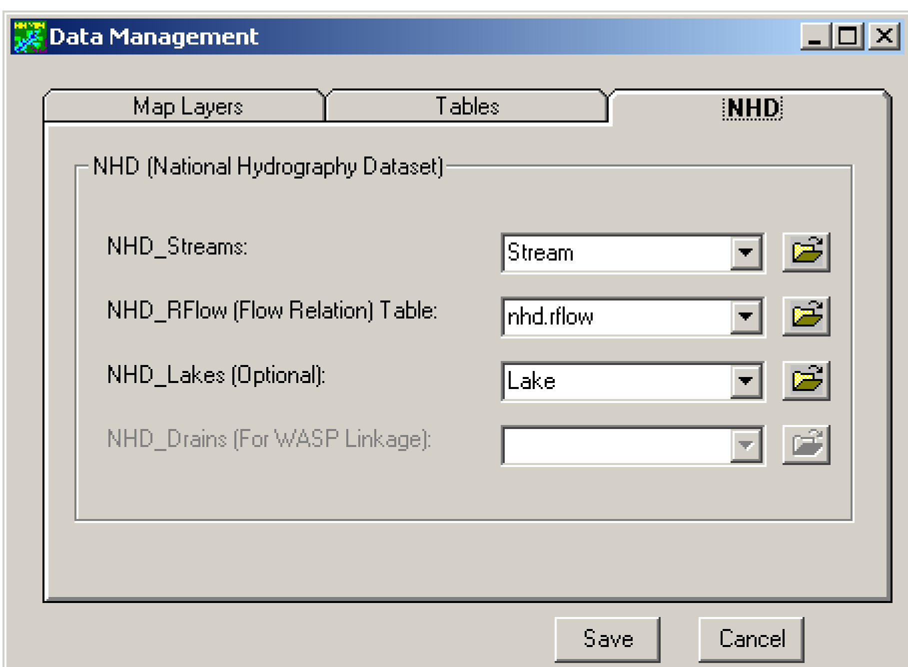


Figure 3.12 Data Management window–NHD tab.

3.5 Define Input (Hydrology, Sediment, and Mercury)

The third step in using GBMM is to define model input parameter values. This section describes the input parameter interfaces for hydrology, sediment, and mercury simulation, respectively.

3.5.1 Hydrology and Hydraulic Input

The first submenu under the Define Input menu is the Hydrology and Hydraulic Simulation Input. The hydrology and hydraulic input are grouped into four sections (tabs): Overland, Groundwater, Streams, and Lakes.

Overland Tab

In the overland tab (Figure 3.13), you are required to input initial soil moisture content and initial snow accumulation, to define the break points for CN modification, and to specify the 2-year 24-hour rainfall depth for the study area.

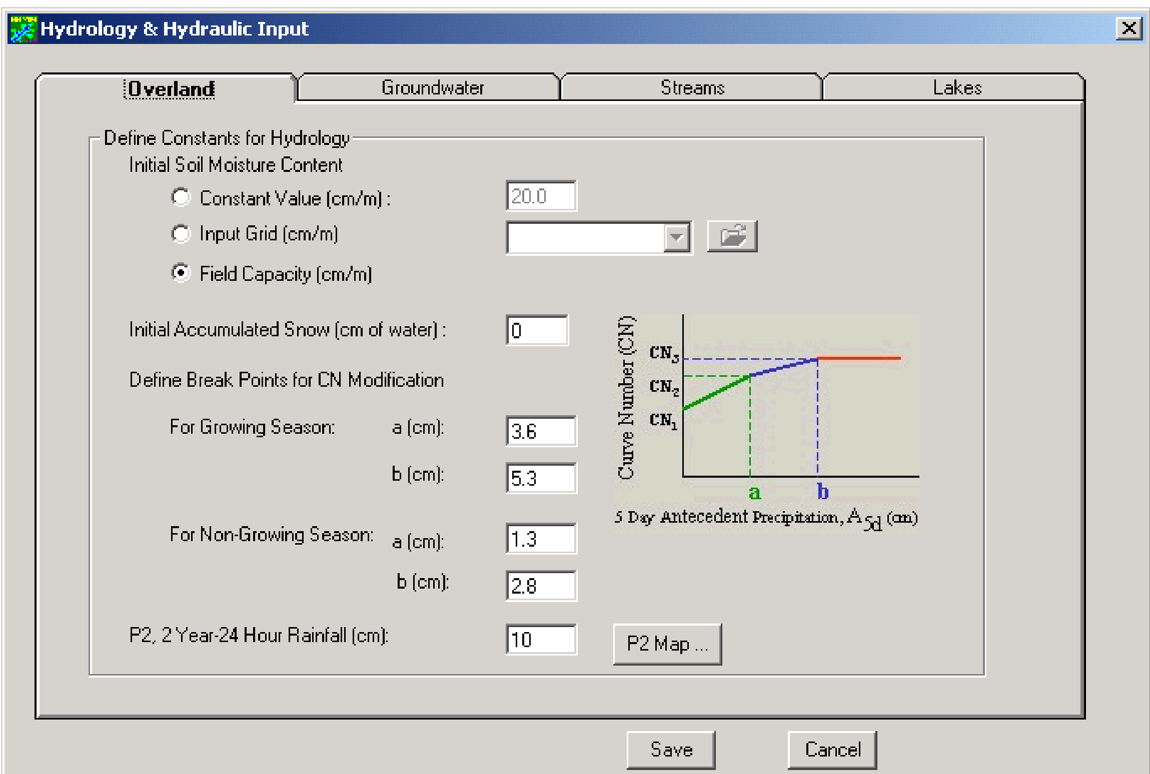
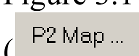


Figure 3.13. Hydrology and Hydraulic Input window–Overland tab.

Initial soil moisture content and Initial snow accumulation: You must provide these two initial conditions. It is likely that these values will be uncertain in many applications. However, they will not affect model results for more than two months of the simulation period. It is generally practical to assign some arbitrary initial values and to discard the simulation results of the first few months. For the initial soil moisture content, you can choose one of the three options: constant value for the entire study area, a moisture grid file that covers the study area, or soil field capacity values that are in the soil property table.

<u>*Break point 5-day antecedent precipitation (a and b) for CN modification*</u>: Curve numbers (CN) are used to calculate surface runoff in the model. The break point 5-day antecedent precipitation values are used to adjust CN (under the average moisture condition) on the basis of the current 5-day antecedent precipitation. The recommended values (Ogrosky and Mockus, 1964) for the break points *a* and *b* for the non-growing and growing seasons are as follows:

For non-growing season:	$a = 1.3$	$b = 2.8$
For growing season:	$a = 3.6$	$b = 5.3$

<u>*2-year 24-hour rainfall depth (P_2)*</u>: It is defined as 24-hour-duration storm for a return period of 2-year rainfall event. P2 is used to estimate the runoff travel time from a grid cell of the study area to the watershed outlet. A P2 map of United States, as shown in Figure 3.14, is provided in the tab. The map image can be displayed by clicking **P2 Map** (

). You can look up the P2 value for a specific study area on the map. It should be noted that the value shown in the map is in inches, while the required input unit is cm (1 inch = 2.54 cm).

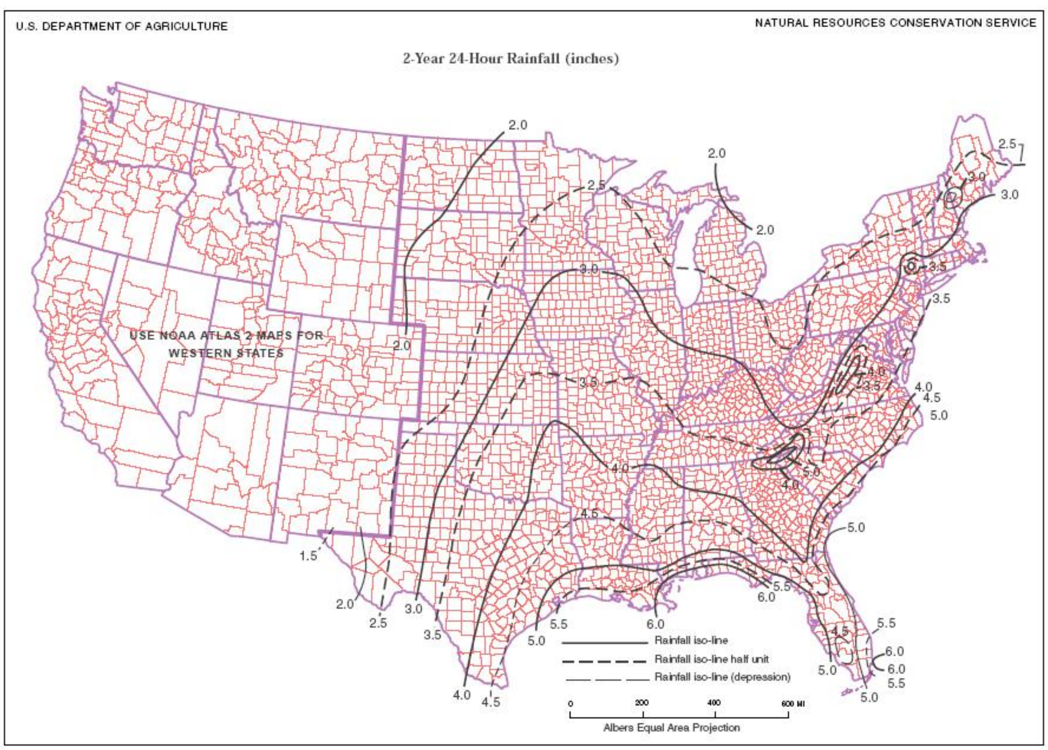


Figure 3.14. 2-year, 24-hour rainfall map of United States.

Groundwater Tab

On the Groundwater tab (Figure 3.15), you must input initial shallow groundwater depth, groundwater recession coefficient, ground water seepage coefficient, unsaturated zone soil depth, and depth from land surface to bedrock.

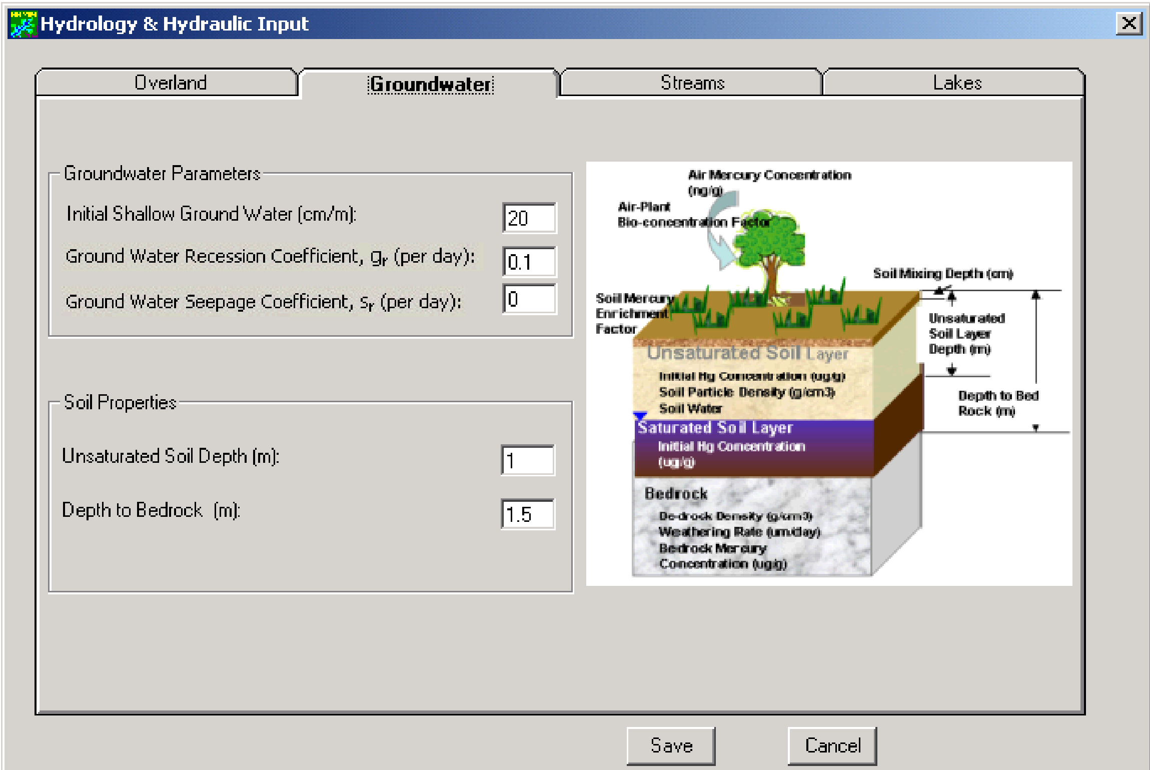


Figure 3.15 Hydrology and Hydraulic Input window–Groundwater tab.

Initial shallow groundwater (relative depth): It is a ratio of the initial groundwater depth (cm) to groundwater storage depth (m) (depth to bedrock minus unsaturated soil depth).

Groundwater recession coefficient: It can be estimated from stream flow records by standard hydrograph separation techniques (Chow, 1964). During periods of stream flow recession, it is assumed that runoff is negligible, hence a recession constant (r) can be estimated from two stream flows $F(t_1)$, $F(t_2)$ measured on day t_1 and day t_2 during the hydrograph recession by:

$$r = \frac{\ln F(t_1) - \ln F(t_2)}{t_2 - t_1} . \qquad \text{Equation 1}$$

Recession coefficient should be measured for a number of hydrographs and an average value should be used for the simulation. Typical values range from 0.01 to 0.2.

Groundwater seepage coefficient: No standard techniques are available for estimating the groundwater seepage coefficient. The most conservative approach is to assume a "0" seepage rate. Otherwise the seepage coefficient needs to be determined by calibration.

Unsaturated zone soil depth and depth to bedrock: You must input the unsaturated zone soil depth and depth to bedrock for a specific study area based on local soil information. The unsaturated soil depth can be approximated using the plant rooting depth. USDA's STATSGO soil database can be used to estimate the soil depth to bedrock. This information is already in the SoilData.dbf table of the system.

Streams

On the streams tab (Figure 3.16), you must input Manning's roughness coefficient, channel cross section right and left inverse slopes, and the coefficients for computing channel depth and width.

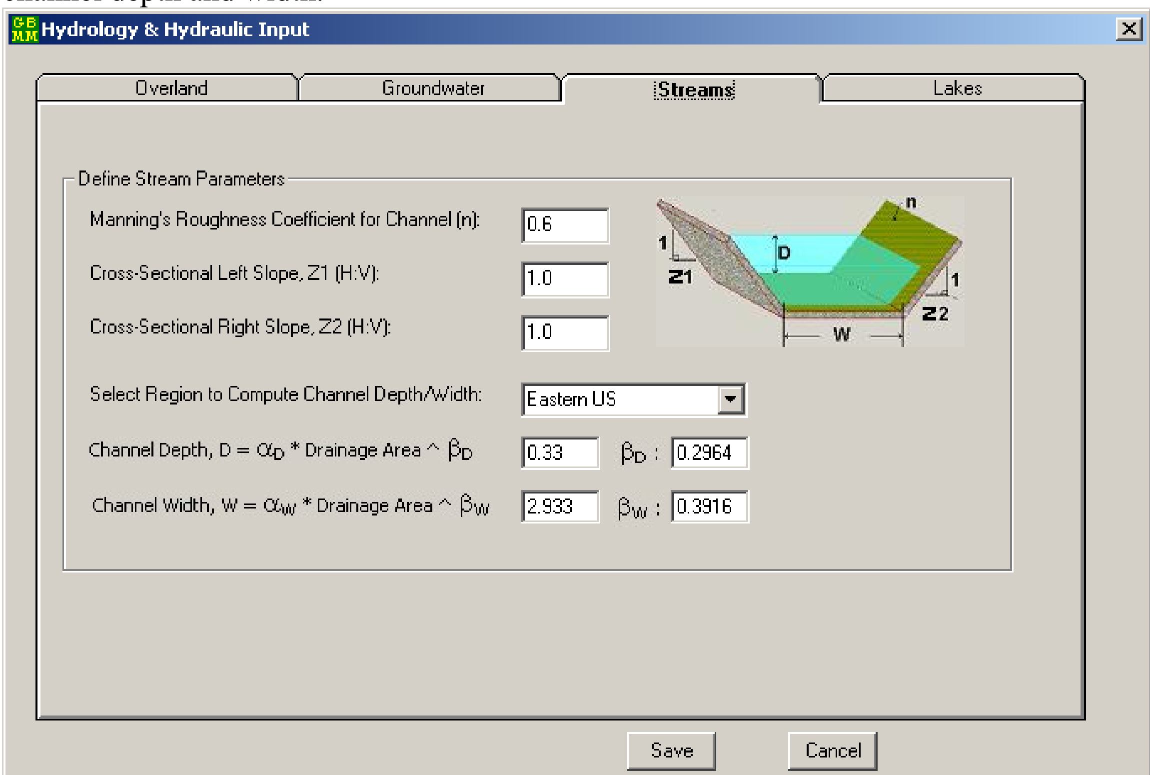


Figure 3.16 Hydrology and Hydraulic Input window–Streams tab.

Manning's roughness coefficient (n): Table 3.1 lists the reference values of Manning's roughness coefficient on known natural stream types (Bedient and Huber, 1992).

Table 3.1 Reference values of Manning's roughness coefficient

Natural Streams	Manning's n	
	Minimum	Maximum
Smooth and straight	0.025	0.033
Rough weeds and stones	0.045	0.060
Very weedy, deep pools	0.075	0.150

Cross-section left and right slopes, Z (H:V): You must provide the channel cross-section left and right Z value. The Z value is calculated as 1 divided by slope. For example, for a slope of 0.2, the Z value is 1/0.2, equals to 5.

Coefficient for computing channel depth and width: The average channel depth and average channel width can be computed on the basis of the geographic region and drainage area (Rosgen, 1996) by using equations 2 and 3 respectively:

$$D = \alpha_D * A_d^{\beta_D}. \qquad \text{Equation 2}$$

where

D = channel depth (m)
α_D = regression coefficient for channel depth (Table 3.2)
A_d = drainage area (km^2)
β_D = regression coefficient for channel depth (Table 3.2)

$$W = \alpha_w * A_d^{\beta_w}. \qquad \text{Equation 3}$$

where

W = channel width (m)
α_w = regression coefficient for channel depth (Table 3.2)
A_d = drainage area (km^2)
β_w = regression coefficient for channel depth (Table 3.2)

The coefficient reference values for four regions (i.e., San Francisco Bay region, Eastern United States, Upper Green River, WY, and Upper Salmon River, ID) are provided in the interface and in Table 3.2. You may select a region that covers or is near the study area. You can also specify your coefficients to calculate the stream width and depth.

Table 3.2. Coefficients for channel depth and width for specific regions

Region	α_D	β_D	α_W	β_W
San Francisco Bay Region	0.378	0.2582	3.513	0.3692
Eastern United Sates	0.33	0.2964	2.933	0.3916
Upper Green River, Wyoming	0.3094	0.1923	1.579	0.3866
Upper Salmon River, Idaho	0.1593	0.2625	1.4968	0.4562

Source: Rosgen, 1996.

Lakes Tab

If the HND lakes map is loaded in the Data Management (Section 3.4), you must input threshold areas for lakes, initial water depth, bankfull depth, evaporation coefficient, orifice depth to bed, orifice diameter, orifice discharge coefficient, weir crest length, weir discharge coefficient, and lake bottom infiltration rate on the Lakes tab (Figure 3.17).

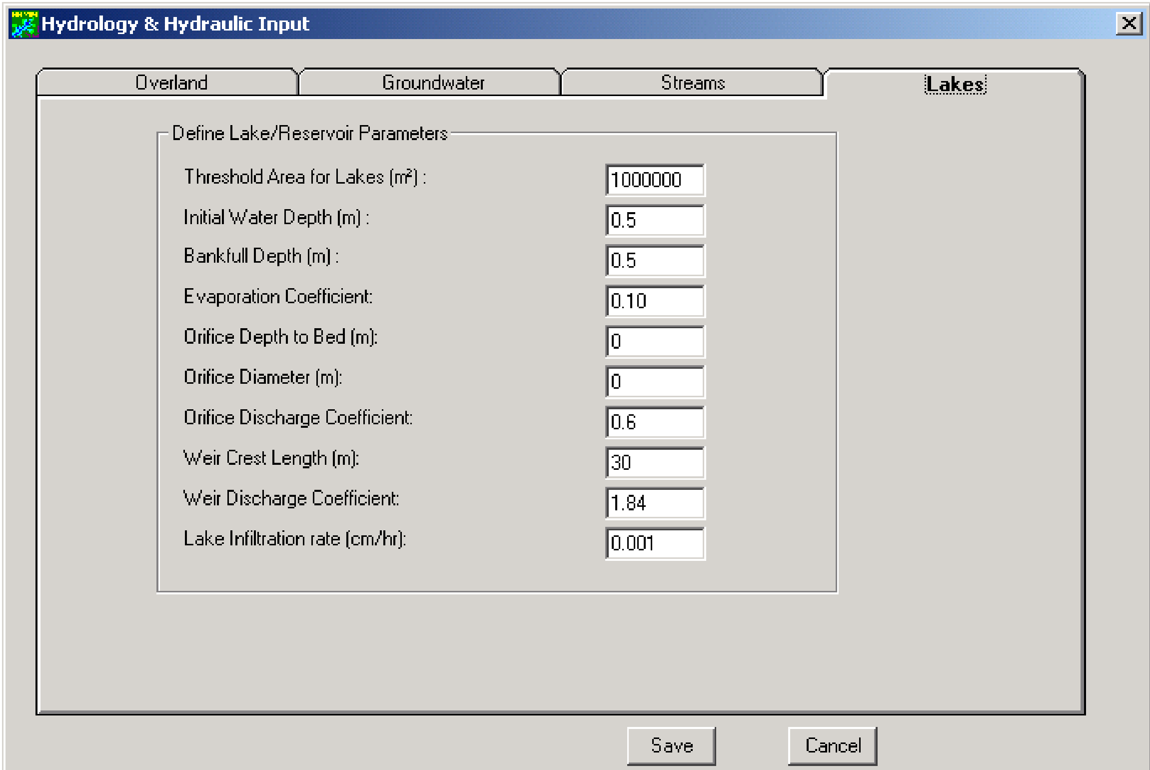


Figure 3.17 Hydrology and Hydraulic Input window–Lakes tab

Threshold areas for lakes: It defines the minimum lake surface area that is considered as a lake in the simulation. Lakes with surface area less than the threshold value will not be simulated.

Initial water depth and bankfull depth: The depth of water in a lake at the beginning of the simulation and the maximum depth of water that a lake can contain. These parameter values can be further specified for individual lakes in the input text files (Appendix C Card 270)

Evaporation coefficient: It is the ratio of the actual evaporation rates to the potential evaporation rate. Its value ranges from 0 to 1. Value 0 means no evaporation, and value 1 indicates the actual evaporation rate is the same as the potential evaporation rate.

Orifice depth to bed and orifice diameter: They are the depth of the water level above the orifice and the maximum width of the orifice.

Orifice discharge coefficient: The orifice discharge coefficient varies for various orifice shapes. The reference values for the four most common shapes are illustrated in Figure 3.18.

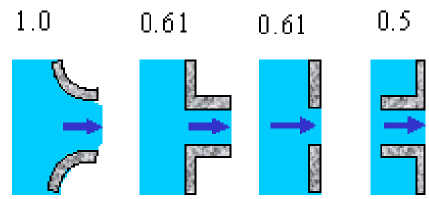


Figure 3.18 Orifice discharge coefficient.

Weir crest length: It is assumed that the weir has a rectangular shape. User needs to provide the weir crest length.

Weir discharge coefficient (C_w): The weir discharge coefficient value varies depending on the head on the crest and the weir height. Table 3.3 provides the reference values of C_w for sharp crested rectangular weirs.

Table 3.3. Coefficient C_w (metric unit) for rectangular sharp-crested weirs (Linsley et al., 1992)

H_d/h	Water head height h above weir, meter						
	0.06	**0.12**	**0.18**	**0.24**	**0.30**	**0.61**	**1.52**
0.5	2.31	2.28	2.27	2.27	2.27	2.26	2.26
1.0	2.07	2.05	2.04	2.03	2.03	2.03	2.03
2.0	1.95	1.93	1.92	1.92	1.91	1.91	1.90
10	1.85	1.83	1.82	1.82	1.82	1.82	1.81
∞	1.83	1.81	1.80	1.80	1.79	1.79	1.79

H_d: Height of the weir from the bed.

Lake bottom infiltration rate: This parameter is used to compute the volume of water lost by seepage through the bottom of the lake/wetland/reservoir. The saturated soil hydraulic conductivity (K_{sat}) can be used as a good estimate for the infiltration rate. Table 3.4 lists the reference values of saturated soil hydraulic conductivity.

Table 3.4 Referece values of saturated soil hydraulic conductivity (K_{sat}).

Soil Texture	K_{sat} (mm/hr)	
	Minimum	Maximum
Sandy	15.2	> 50.8
Loamy	0.51	15.2
Clayey	0.15	0.51
Cd horizon, Natric horizon, Fragipan, and Ortstein	0	0.15

3.5.2 Sediment Simulation Input

The input parameters related to sediment simulation are grouped into two tabs: Overland and Lake/Reservoir Routing.

Overland Tab

On the Overland tab (Figure 3.19), you can specify the initial sediment accumulation per unit area for pervious and impervious land, sediment accumulation rate and depletion rate on imperious land, sediment yield capacity, and coefficients for computing sediment delivery ratio.

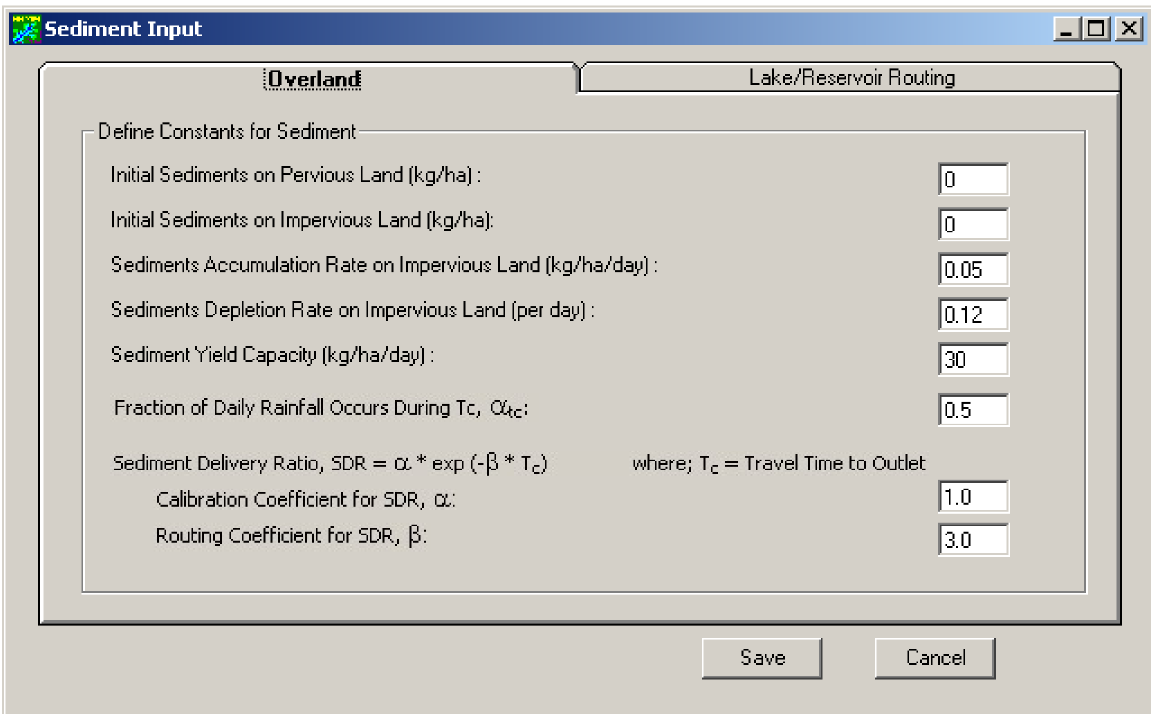


Figure 3.19 Sediment Input window–Overland tab.

<u>*Initial sediment accumulated per unit area for pervious and impervious land:*</u> It is the initial sediment available for transport. Default value of "0" is recommended for both pervious and impervious areas, if no specific information is available.

<u>*Sediment accumulation rate and depletion rate on imperious land:*</u> The typical and possible ranges of values of the two parameters are listed in Table 3.5 for urban impervious land. Generally speaking, the values are functions of land use, traffic density, and human activities (e.g. construction, street sweeping, etc.). The parameter should be calibrated if sufficient monitoring data are available.

Table 3.5 Typical and possible ranges of values for sediment accumulation rate and depletion rate.

Parameter	Typical Range		Possible Range	
	Min	Max	Min	Max
Sediment accumulation rate (kg/ha-day)	0.0	2.5	0.0	35.0
Sediment depletion rate (1/day)	0.03	0.2	0.01	1.0

Source: Donigian et al., 2003. (http://hspf.com/pdf/TMDL2003PaperDonigian.pdf)

Sediment yield capacity: It defines the maximum amount of sediment that is available from pervious land surface.

Coefficients for computing sediment delivery ratio (SDR): In GBMM, the SDR, the fraction of the gross soil loss from overland cells that actually reaches the channel through shallow concentrated flow is estimated as a function of travel time (Ferro and Minacapilli, 1995; Ferro and Porto, 2000).

$$SDR = \alpha * e^{-\beta * T_{tot}} . \qquad \text{Equation 4}$$

where

SDR = sediment delivery ratio of a grid cell to the assessment point
α = calibration coefficient
β = routing coefficient
T_{tot} = total travel time (overland + channel) for the specific cell along the flow path to the outlet or assessment point (hr)

The routing coefficient (β) is basin-specific parameter and it depends primarily on watershed morphological data (Ferroand Minacapilli, 1995). Fernandez (2003) estimated β with an inverse modeling approach and found that β is close to 1. Therefore, the default value of the routing coefficient is 1. The calibration coefficient (α) is provided as an adjusting parameter for the calibration process, the default value is 1. It is *highly* recommended that you calibrate both the coefficients using monitoring data.

Fraction of daily rainfall that occurs during the time of concentration (α_{tc}): This fraction should vary between 0 and 1. The default value is 0.5.

Lake/Reservoir Routing Tab

If the NHD lakes map is loaded for simulation (Section 3.4), you can specify the initial total suspended sediment (TSS) concentration in the lake, the equilibrium TSS concentration, TSS concentration first order decay rate, percent of clay, silt, and sand of inflow sediment on the Lake/Reservoir Routing tab (Figure 3.20).

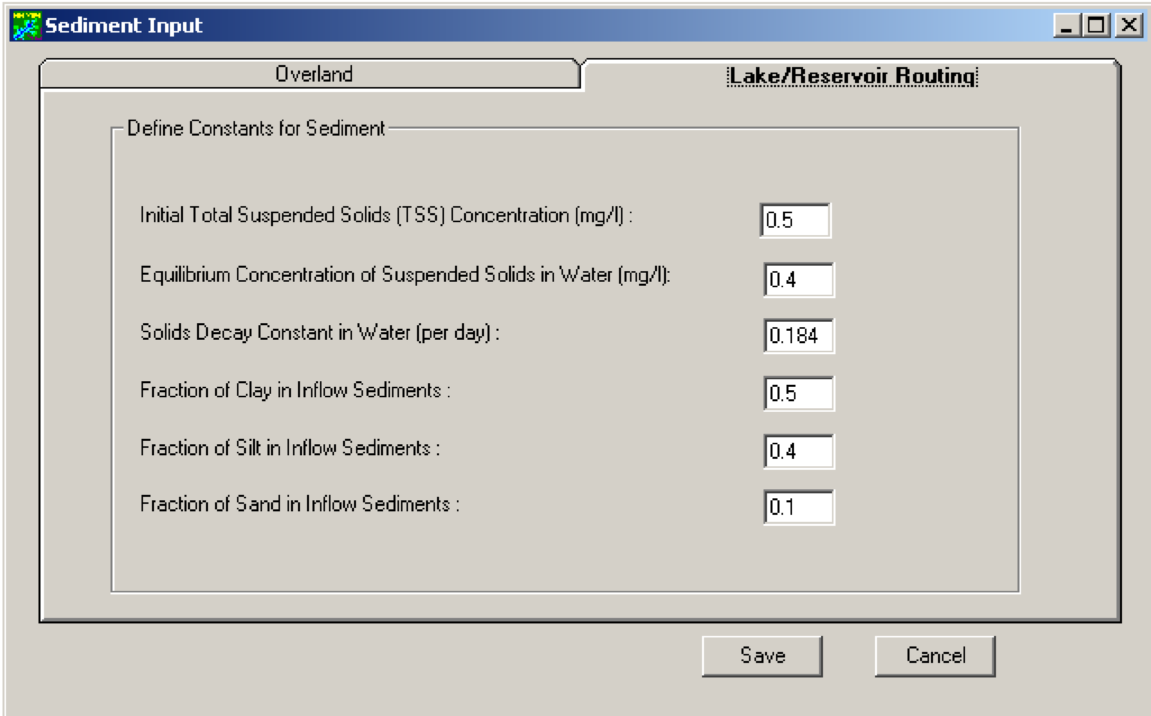


Figure 3.20 Sediment Input window–Lake/Reservoir Routing.

Initial TSS concentration: This parameter is site-specific and should be provided

Equilibrium TSS concentration: This parameter defines the TSS concentration when the water column of the lake/reservoir reaches equilibrium condition. The value can be estimated using lake/reservoir suspended solid concentration monitoring data.

Solid decay rate: If no specific information is available, a default value of 0.184 (1/day) is recommended. This value was derived by assuming that 99 percent of the 1-µm particles are settled within 25 days.

Percent clay, silt, and sand in inflow sediment: These parameter values are site-specific and should be provided.

3.5.3 Mercury Simulation Input

The input parameters specific to mercury simulation are grouped into five tabs: Mercury Data, Land, Forest, Water, and Benthic.

Mercury Data Tab

In the Mercury Data tab (Figure 3.21), you can specify the initial mercury concentration in watershed soil and mercury deposition fluxes from atmosphere (dry and wet deposition fluxes).

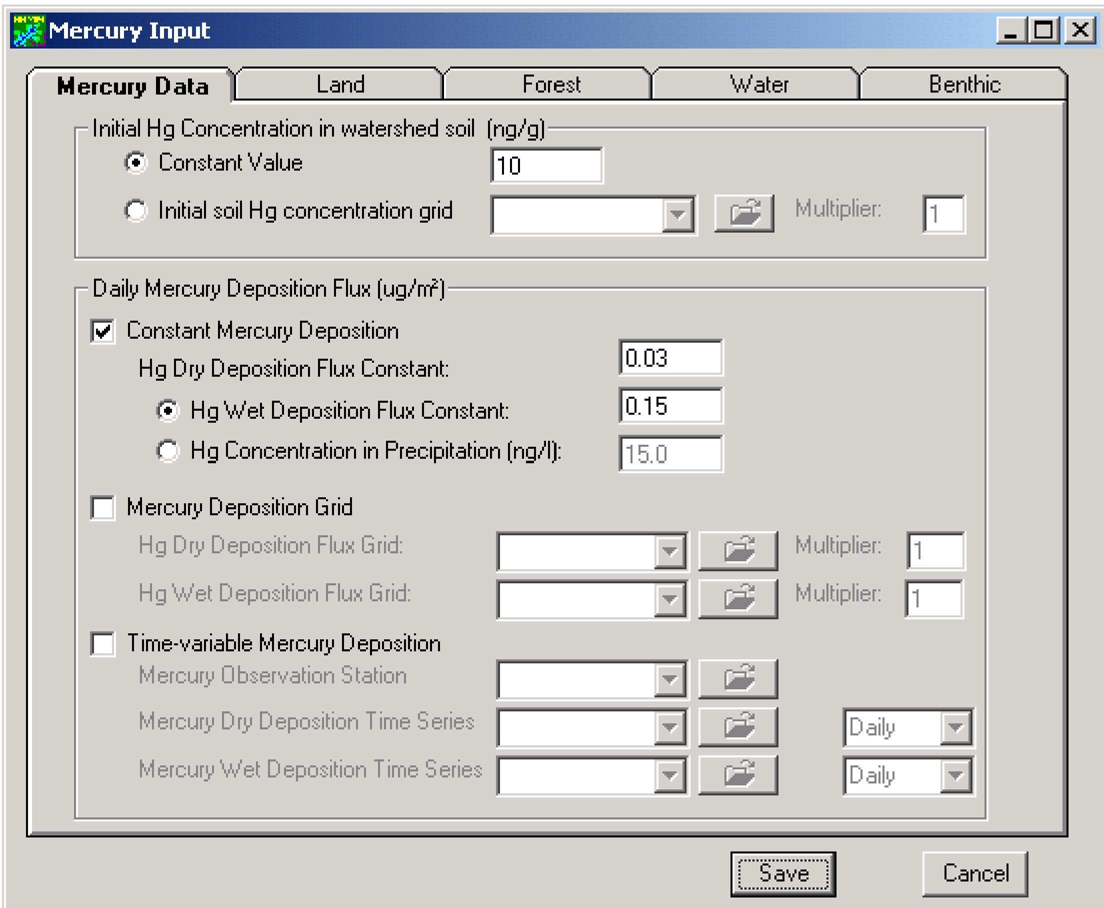


Figure 3.21 Mercury Simulation Input window–Mercury Data tab.

Initial mercury concentration in watershed soil: You can either input a constant value for the entire watershed or provide a grid file generated by a previous mercury simulation run or WCS MLM. Table 3.6 lists the measured mercury concentration in soil in the United States. The typical U.S. soil mercury concentration ranges from 8 to 117 ng/g. Soil mercury levels are usually less than 200 ng/g in the top layer, but values exceeding this level are not uncommon, especially in areas affected by anthropogenic activities (USEPA, 1997).

Table 3.6 Measured mercury concentration in soil (USEPA, 1997).

Study Description	Total Mercury (ng/g dry weight)	Methyl-mercury (ng/g dry weight)	% Methyl-mercury
Discovery Park, Seattle, WA	29 - 133	0.3-1.3	0.6-1.5
Wallace Falls, Cascades (WA)	155 - 244	1.0-2.6	0.5-1.2
Control Soil, New York State	117	4.9	4.2
Compost, New York State	213	7.3	3.3
Garden soil, New York State	406	22.9	5.3
Typical U.S. Soils	8 - 117	NA	NA

Mercury dry deposition flux ($\mu g/m^2$): You can choose to input mercury dry deposition flux using one of the three options, i.e., a constant, a grid, or deposition flux time series from observation stations.

Mercury dry deposition flux constant

Figure 3.22 shows the simulated annual mercury dry deposition flux for the United States main continent. Very few direct measurements of the dry deposition of gaseous and particulate mercury have been made (USEPA, 1997). Figure 3.22 is suggested to be used only if no site-specific Hg dry deposition data is available.

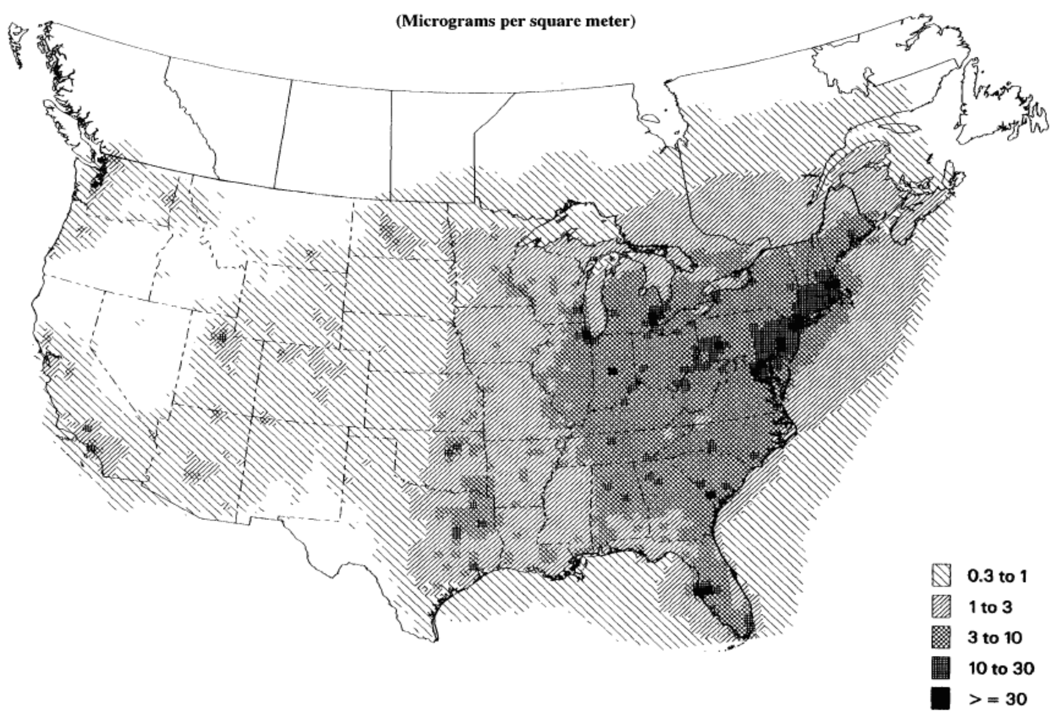


Figure 3.22 Simulated annual total Hg dry deposition (USEPA, 1997).

Mercury dry deposition flux grid

You can choose import a mercury dry deposition flux grid, which reflects spatial variability of dry deposition. If the study area is relatively large and there is more than one data point, it is recommended to generate a flux grid by using the approach described in Appendix A (A.9). (A sample U.S. mercury dry deposition map is provided with the system.)

Mercury dry deposition flux time series

You can define mercury dry deposition time series based on observed data. The data should be provided in a text file including the following fields: date and mercury dry deposition flux ($\mu g/m^2$), and these time series can be daily or monthly. At the same time, you must provide the locations of the observation stations in a shape file (see Appendix A for how to make a shape file using latitude and longitude).

Mercury wet deposition flux: Similar to inputting mercury dry deposition flux, you can choose input the mercury wet deposition using one of the three options, i.e., a constant (under this option, you can either input a constant mercury wet deposition flux or input a constant mercury concentration in precipitation), a grid, or deposition time series from observation stations.

Mercury wet deposition flux constant

You can either input constant mercury wet deposition flux or specify mercury concentration in precipitation. Table 3.7 lists the measured mercury wet deposition flux within the United States. Table 3.8 presents the measured mercury concentration in precipitation.

Mercury wet deposition flux grid

Similar to using dry deposition flux grid, you can choose import the mercury wet deposition flux grid. If the study area is relatively large and there is more than one data point, it is recommended to generate a flux grid by using the approach described in Appendix A (A.9). (A sample U.S. mercury wet deposition map is provided with the system.)

Mercury wet deposition flux time series

You can define mercury wet deposition time series using observed data. The data should be provided in a text file including the following fields: date and mercury wet deposition flux ($\mu g/m^2$), and these time series can be daily or monthly. At the same time, you must provide the locations of the observation stations in a shape file (for how to make a shape file using latitude and longitude, see Appendix A).

Table 3.7 Measured mercury wet deposition flux rate (USEPA, 1997).

Site	Wet Mercury Deposition Rates ($ug/m^2/yr$), Means
Ely, MN	17 in 1988 42 in 1989 6.7 in 1990
Duluth, MN	20 in 1988 6.5 in 1989 9.3 in 1990
Marcell, MN	17 in 1988 14 in 1989
Bethel, MN	13 in 1990
Cavalier, ND	6.1 in 1990
International Falls, MN	5.5 in 1990
Lamberton, MN	9.3 in 1990
Raco, MN	8.9 in 1990
Little Rock Lake, WI	4.5 from rain 2.3 from snow
Crab Lake, WI	4.4 from rain 0.8 from snow
Nothern MN	10-15
Pellston, MI	5.8 in year 1 5.5 in year 2 0.07 ug/m^2 (max 0.51) per rainfall event
South Haven, MI	9.5 in year 1 13 in year 2 0.12 ug/m^2 (max 0.85) per rainfall event
Dexter, MI	8.7 in year 1 9.1 in year 2 0.10 ug/m^2 (max 0.98) per rainfall event
Underhill Center, VT	9.3 0.07 ug/m^2 per rainfall event

Table 3.8 Measured mercury concentration in precipitation (USEPA, 1997).

Site	Mean Mercury Concentration in precipitation, ng/L Mean (Range)
Ely, MN	20 in 1988 51 in 1989 13 in 1990
Duluth, MN	23 in 1988 11 in 1989 13 in 1990
Marcell, MN	18 in 1988 18 in 1989
Bethel, MN	13 in 1990
Cavalier, ND	19 in 1990
International Falls, MN	9 in 1990
Lamberton, MN	15 in 1990
Raco, MN	10 in 1990
Little Rock Lake, WI	11 (3.2-15) in rain 6 in snow
Crab Lake, WI	7.9 in rain 3.3 in snow
Underhill Center, VT[a]	8.3
Broward County, FL Background Site near Atlantic Ocean (Site 1)	Total: 35 (15-56) Reactive: 1.0 (0.5-1.4)
Broward County, FL Inland (Site 2)	Total: 40 (15-73) Reactive: 1.9 (0.8-3.3)
Broward County, FL Inland (Site 3)	Total: 46 (14-130) Reactive: 2.0 (1.0-3.2)
Broward County, FL 300 m from MWC (Site 4)	Total: 57 (43-81) Reactive: 2.5 (1.7-3.7)

[a] Both the concentrations of mercury in precipitation and the amount of precipitation deposited/event increased in spring and summer. Most (66%) of the mercury in the spring and fall precipitation samples (only ones tested) was dissolved. The mean concentration of reactive mercury was 1.0 ng/L. Higher particulate concentrations were observed in the winter.

Land Tab

In the Land tab (Figure 3.23), you can specify air mercury concentration, air-plant bio-concentration factor (BCF), initial mercury concentration in shallow saturated groundwater, watershed soil mixing depth, soil reduction depth, soil particle density, mercury soil water partition coefficient, soil base reduction rate, mercury enrichment factor, bedrock density, chemical weathering rate, and bedrock mercury concentration.

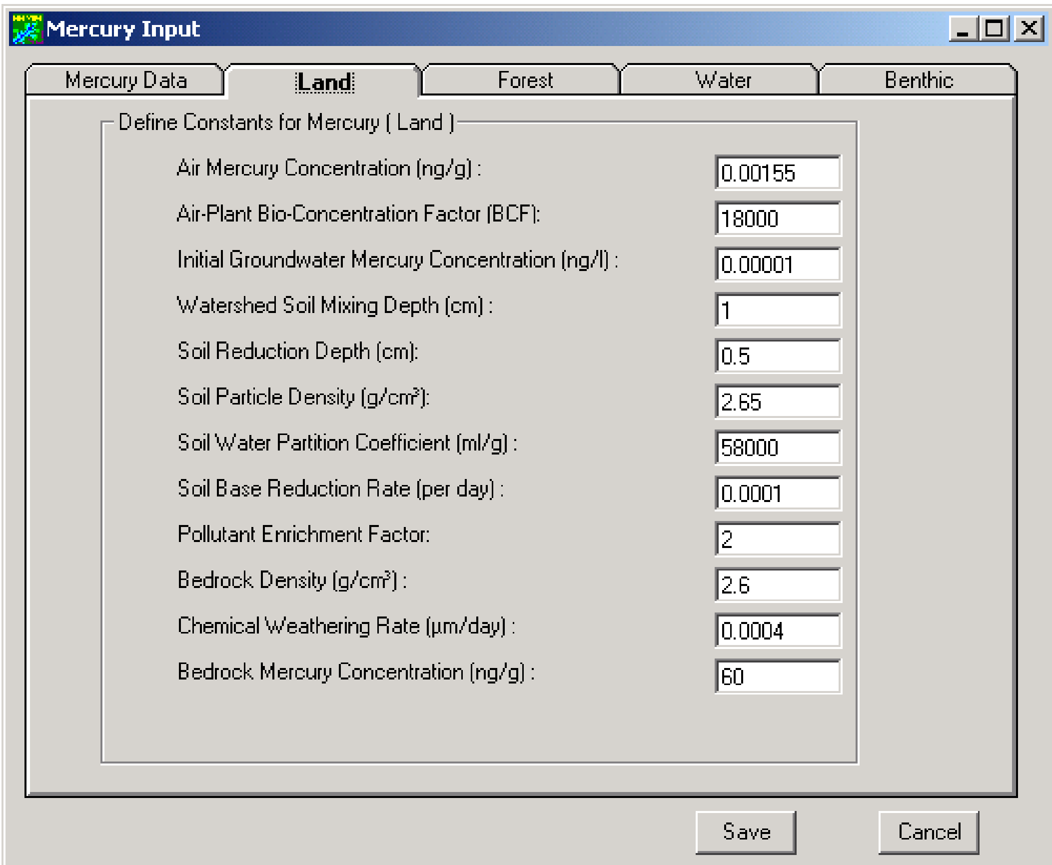


Figure 3.23 Mercury Simulation Input window–Land tab.

Air mercury concentration: Table 3.9 summarizes measured U.S. atmospheric mercury concentrations.

Table 3.9 Measured air mercury concentration (USEPA, 1997).

Total Atmospheric Mercury (ng/m^3)	**%Hg(II)**	**% Methylmercury**
Rural areas: 1 - 4 Urban areas: 10 - 170	1-25%[a]	0-21%[b]

[a] Higher fractions in urban areas
[b] Generally % methylmercury on low end of this range

Air-plant bio-concentration factor (BCF): It is defined as the ratio of the contaminant concentration in plants (on the basis of dry weight) to that in the air. Table 3.10 presents the measured mercury air-plant bio-concentration factor for various crops. It was assumed that mercury concentration in the aboveground, leafy parts of plants is almost entirely the result of air-to-plant transfer of mercury (USEPA, 1997; Mosbaek, 1988), and any atmospheric elementary mercury taken up by the plant is converted into divalent mercury and methylmercury in the plant tissue.

Table 3.10 Mercury air-plant bio-concentration factor (USEPA, 1997).

Crop	Hg^{2+}[a]		Methylmercury[a]	
	Default Value	Distribution	Default Value	Distribution
Leafy vegetables	18000	U[12000,24000]	5000	U[3300,6800]
Legume vegetables	1050	U[700,1400]	100	U[65,130]
Fruiting vegetables	22000	U[14000,29000]	1200	U[780,1600]
Rooting vegetables	0	NA	0	NA
Grains and cereals	1050	U[700,1400]	100	U[65,130]
Forage	18000	U[12000,24000]	5000	U[3300,6800]
Fruits	22000	U[14000,29000]	1200	U[780,1600]
Potatoes	0	NA	0	NA
Silage	18000	U[12000,24000]	5000	U[3300,6800]

[a] Based on elemental mercury air concentration, and speciation of divalent and methylmercury species based on Cappon (1981,1987).

Initial mercury concentration in groundwater: This parameter defines the mercury concentration in groundwater at the beginning of simulation. Table 3.11 lists the measured mercury concentrations in some areas of the United States.

Table 3.11 Measured mercury concentrations in ground/drinking water (USEPA, 1997).

Study Description	Total Mercury
Southern New Jersey domestic wells	Up to and exceeding 2000
Drinking/Tap water in U.S.	0.3-25
Washington State well	0.3

Watershed soil mixing depth: Indicates the average mixing depth that mercury is incorporated into soil. If no site-specific data is available, a default value of 1 cm is suggested for no till soil, and 20 cm for tillage soil. The value of soil mixing depth normally ranges from 0.5 to 5 cm for no till soil, and 10 to 30 cm for tillage soil.

Soil reduction depth: Defines the depth of soil where mercury is subject to mediation by sunlight. There is evidence that reduction in soil is mediated by sunlight, and occurs most rapidly within the upper 5 mm of the soil surface (Carpi and Lindberg, 1997). Therefore, the default value of the soil reduction depth is 5 mm.

Soil particle density: The default value is 2.65 g/cm^3.

Mercury soil water partition coefficient: It is defined as the equilibrium concentration in soil particle divided by concentration in soil water. Table 3.12 lists the default values and normal range of this coefficient for three species of mercury, i.e., elementary mercury, divalent mercury, and methylmercury.

Table 3.12 Typical values of mercury soil water partition coefficient (USEPA 1997).

Chemical	Default Value (mL/g)	Range
Hg^0	1000	--
HgII	58,000	24,000-270,000
Methylmercury	7,000	2,700-31,000

Soil base reduction rate (K_{rs}): It is defined as the reference soil reduction rate constant normalized to soil water content. There is evidence that reduction in soil is mediated by sunlight, is proportional to soil water content, and occurs most rapidly within the upper 5 mm of the soil surface (Carpi and Lindberg, 1997). As a result, the input reduction rate constant k_r is normalized to a reference depth of 5 mm and to 100% water content. The actual reduction rate constant used in the model is the product of k_{rs}, the soil water content and the ratio of the reference depth to the depth of the soil layer. Estimated values of the reference soil reduction rate constant are 0.0013 day^{-1} for tilled field and 0.0001 day^{-1} for forest sites (USEPA, 1997). Presumably the difference in rate constants is due to the significant shading under the forest canopy. Any given watershed should experience average rate constants somewhere between these estimates, depending on the landscape pattern. A value of 0.0005 day^{-1} is recommended for an average vegetated watershed; a value of 0.0013 day^{-1} should be used for calculating concentrations in tilled soil.

Pollutant/mercury enrichment factor: Enrichment refers to the fact that erosion favors the lighter soil particles, which have higher surface area to volume ratios and are higher in organic matter content. Concentrations of hydrophobic pollutants would be expected to be higher in eroded soil as compared to in-situ soil. While enrichment is best ascertained with sampling or site-specific expertise, generally it has been assigned values in the range of 1 to 5 for organic matter, phosphorus, and other soil-bound constituents of concern. The suggested default value of this parameter is 2, and the typical values range from 1.5 to 2.6.

Bedrock density: The default value of bedrock density is 2.6 g/cm^3.

Chemical weathering rate: Rock chemical weathering rates vary by rock types and climate conditions. Table 3.13 shows some examples.

Table 3.13 Rates of weathering of clean rock surfaces (μm/1,000 years) (Source: http://www.globalchange.umich.edu/globalchange1/current/lectures/soils/soils.html, accessed November 2005)

Rock Type	Cold climate	Warm, humid climate
Basalt	10	100
Granite	1	10
Marble	20	200

Bedrock mercury concentration: The typical mercury content of acidic rocks is 60 μg/kg (Jonasson and Boyle, 1979).

Forest Tab

In this tab (Figure 3.24), you can specify average annual evapotranspiration (ET), mercury air deposition leaf interception fraction and leaf adhering fraction, initial leaf litter for forest, and litter decomposition rate for deciduous forest, evergreen forest, and mixed forest.

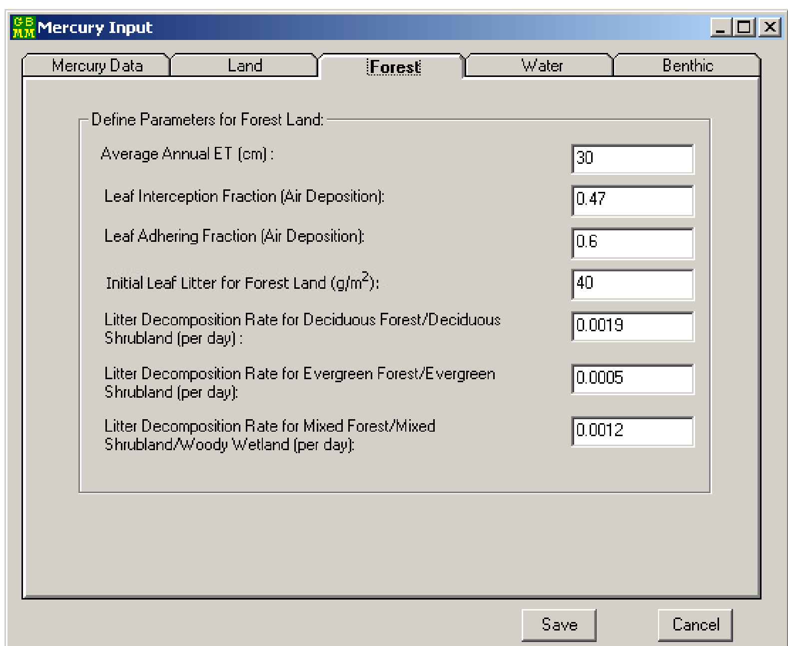


Figure 3.24 Mercury Simulation Input window–Forest tab.

Average annual ET: It represents the annual water loss due to evapotranspiration. Table 3.14 lists the default values and distribution of ET for eastern and western locations in the United States.

Table 3.14 Typical values of annual average evapotranspiration (USEPA, 1997).

Location	Default Value (cm/yr)	Distribution
Eastern Location	65	U(60,70)
Western Location	13	U(8,18)

Mercury air deposition leaf interception fraction: It defines the fraction of the total deposition within a unit area that is initially intercepted by vegetation. Table 3.15 lists the typical values and ranges of this parameter for various plants.

Table 3.15 Typical values of mercury air deposition leaf interception fraction for various plants (USEPA, 1997).

Crop	Default Value	Distribution	Range
Leafy vegetables	0.15	Log (0.16, 0.10)	0.08 - 0.38
Legume vegetables	0.008	Log(0.008, 0.004)	0.005 - 0.01
Fruiting vegetables	0.05	Log(0.05, 0.05)	0.004 - 0.08
Rooting vegetables	0	N/A	N/A
Grains and cereals	0	N/A	N/A
Forage	0.47	Norm(0.47, 0.3)	0.02 - 0.89
Silage	0.44	Log (0.44, 0.3)	
Fruits	0.05	Log (0.05, 0.05)	0.004 - 0.08
Potatoes	0	N/A	N/A

Mercury air deposition leaf adhering fraction: This unit-less parameter represents the fraction of the pollutant in wet deposition that adheres to the plant, is not washed off by precipitation and is used to estimate plant pollutant levels. A value of 1 is the most conservative; this implies that all of the pollutant that deposits onto the plant via wet deposition will adhere to the plant. The default value is 0.6, with a typical range of between 0.1 and 0.8.

Initial leaf litter for forestland: It defines the initial leaf litter mass (g/m^2) on ground for forestland. It should be determined based on local condition.

Litter decomposition rate for deciduous forest, evergreen forest, mixed forest, shrublands, and woody wetland: Based on a recent publication (Finzi et al., 2001), the litter decomposition rates are 0.0005, 0.0019, and 0.0012 per day for evergreen pine forest, deciduous forest, and mixed forest respectively.

Water Tab

In the Water tab (Figure 3.25), you can specify water column initial mercury concentration, net reduction loss factor, mercury reduction rate, net methylation loss factor, mercury methylation rate, biomass concentration, and fraction of methylmercury in total mercury. You can also specify biomass settling velocity, sediment resuspension velocity, sediment porewater diffusion coefficient, sediment water partition coefficient, and mercury decay rate in channel transport.

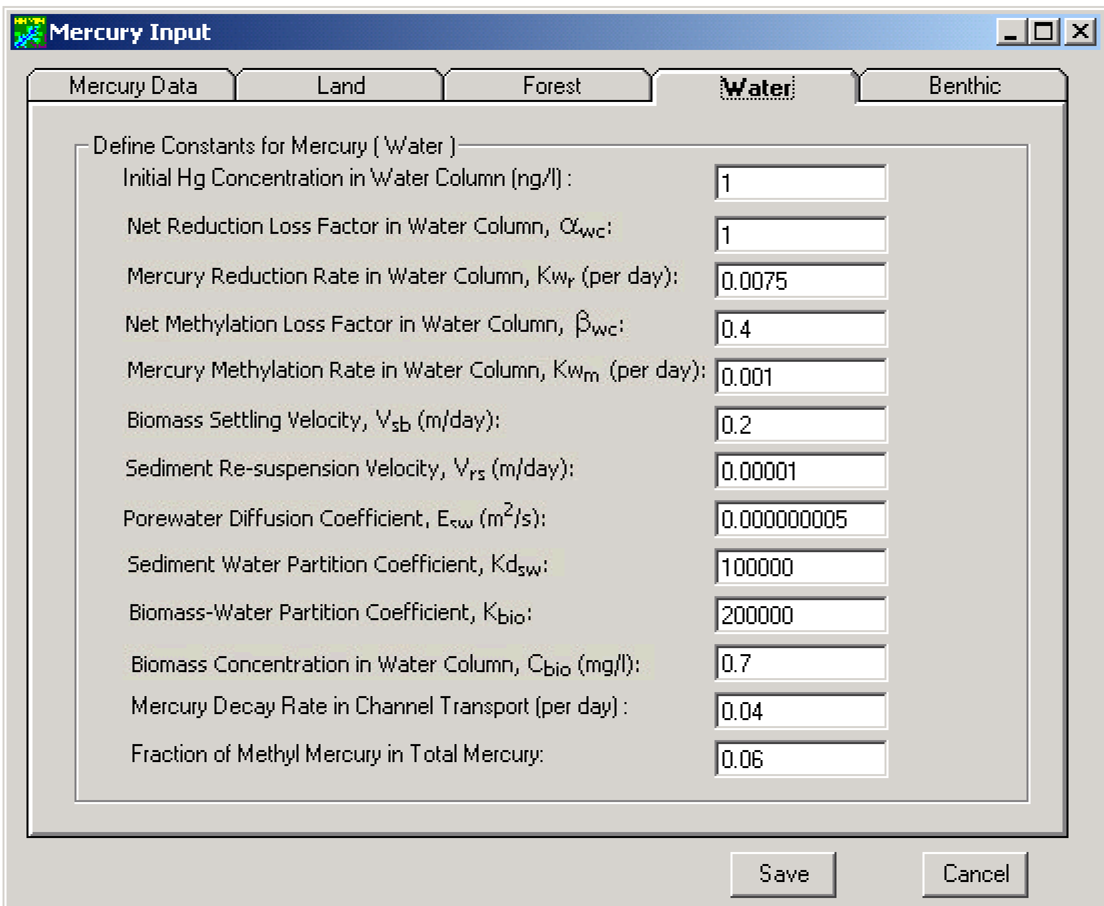


Figure 3.25 Mercury Simulation Input window–Water tab.

Initial mercury concentration in water column: Table 3.16 lists the measured total mercury and methylmercury concentrations in surface fresh water in the United States, and they can be used as the reference for determining the initial mercury concentration if no site-specific data is available.

Table 3.16 Measured mercury concentraions in surface fresh water (USEPA, 1997).

Study Description	Total Mercury (ng/L)	Methyl-mercury (ng/L)	% Methyl-mercury
Swedish lakes: 8 sites, 2-4 samples each.	1.35-15	0.04-0.8	1.0-12
Swedish mires: 8 sites, 4 samples each.	2.9-12	0.08-0.73	2-14
Lake Cresent, WA	0.163	<0.004	<2.5
Swedish runoff: 7 sites, 3 samples each.	2-12	0.04-0.64	1-6
Little Rock Lake: reference basin.	1.0-1.2	0.045-0.06	mean of 5
Lake Michigan (total)	7.2 microlayer 8.0 at 0.3m 6.3 at 10m		
Lake Champlain (filtered)	3.4 microlayer 3.2 at 0.3m 2.2 at 15m		
Lakes Rivers and Streams	0.04 - 74 1 - 7	NA	NA

Net reduction loss factor in water column: This is a calibration/adjustment factor for waterbody mercury reduction rate, and the default value is 1.

Mercury reduction rate in water column: A yearly-average water column reduction rate constant of 0.075 day^{-1} is a typical value for this parameter (USEPA, 1997).

Net methylation loss factor in water column: This is a calibration/adjustment factor for waterbody mercury methylation rate, and the default value is 0.4.

Mercury methylation rate in water column: For shallow lakes with little or no anoxia, the average water column methylation rate constant is about 0.001 day^{-1}. For deeper lakes with seasonal anoxia, the methylation rate constant should be increased to account for a higher microbial rate constant of 0.01 day^{-1} (USEPA, 1997).

Biomass settling velocity: The settling of phytoplankton solids depends on several factors, including the density, size, shape, and physiological state of the cells and the turbulence of the flow. A value of 0.2 m/day (73 m/year) is close to mid-range and is suggested as the default value (USEPA, 1997).

Sediment resuspension velocity: Resuspension from a sediment bed is caused by shear stress in the overlying water. Shear stress in streams is caused primarily by flow velocity. In lakes, shear stress may be caused by wind-driven residual currents and waves. In addition, biotic activity can cause some resuspension. For a small lake 5 meters deep with a short fetch (approximately 100 m), wave-induced resuspension should be almost zero under most wind conditions. A commonly used default value of sediment resuspension velocity is 0.0037 m/year or 0.00001 m/day.

Sediment pore water diffusion coefficient: The default value for this parameter is 0.000000005 m^2/s.

Suspended sediment water partition coefficient: Table 3.17 contains typical values and ranges for mercury suspended sediment water partition coefficient.

Table 3.17 Mercury suspended sediment water partition coefficient (USEPA, 1997).

Chemical	Default Value (L/kg)	Range
Hg^0	1000	--
HgII	100,000	1,380-270,000
Methylmercury	100,000	94,000-250,000

Biomass concentration in water column: This measures the density of biomass in the water column. User should provide values based on local monitoring data. The default value is 0.7 mg/l in the GBMM interface.

Mercury decay rate in channel transport: The default value for this parameter is 0.04 day^{-1}.

Fraction of methylmercury in total mercury in water column: The reference values of fraction of methylmercury in the epilimnion ranges from 0.046 to 0.15 (USEPA, 1997). The default value is 0.06.

Benthic Tab

In the Benthic tab (Figure 3.26), you can specify benthic sediment initial mercury concentration, net reduction loss factor, mercury reduction rate, net methylation loss factor, mercury methylation rate, bed depth, bed porosity, and solid concentration. You can also specify sediment burial velocity and benthic bed sediment/pore water partition coefficient.

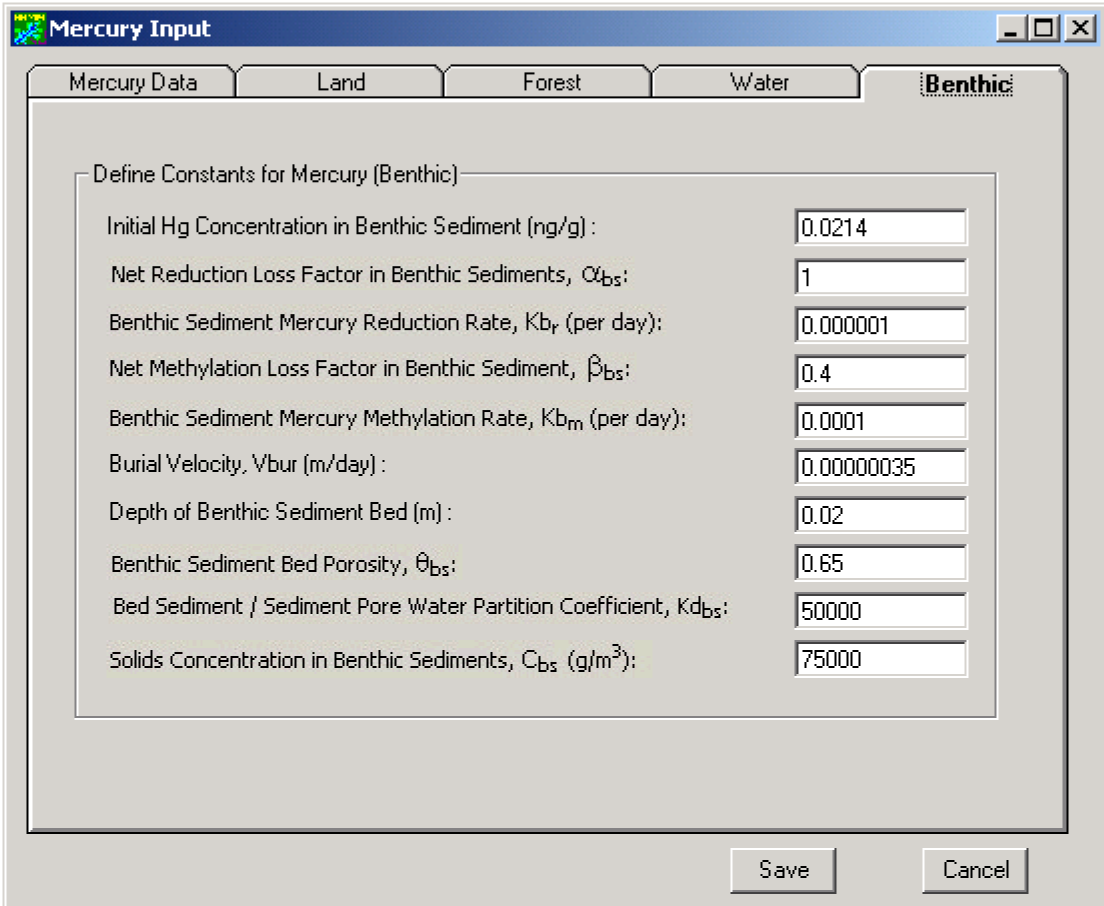


Figure 3.26 Mercury Simulation Input window–Benthic tab.

Initial benthic sediment mercury concentration: The value for this parameter should be provided using local information. If no site-specific data is available, Table 3.18 can be used as a reference for estimating the initial benthic sediment mercury concentration.

Table 3.18 Mercury Concentrations in Sediment from US Sites (USEPA, 1997)

Region	States	Concentration Range (µg/g-dry weight)	Median Concentration (µg/g-dry weight)
North Atlantic	ME, MA , RI, CT, NY, NJ	0.007-5.00	0.14
Middle Atlantic	DE, MD, VA	0.010-0.84	0.12
South Atlantic	NC, SC, GA, FL (east coast)	0.002-0.27	0.03
Eastern Gulf of Mexico	FL (west coast), AL, MS	0.007-0.98	0.05
Western Gulf of Mexico	LA, TX	0.009-0.34	0.04
Pacific	CA, OR, WA, HI, AK	0.009-2.20	0.08

Net reduction loss factor in benthic sediment: This is a calibration/adjustment factor for benthic sediment mercury reduction rate, and the default value is 1.

Benthic sediment mercury reduction rate: A whole-sediment reduction rate constant of 10^{-6} day^{-1} is selected as the default value (USEPA, 1997).

Net methylation loss factor in benthic sediment: This is a calibration/adjustment factor for benthic sediment mercury methylation rate, and the default value is 0.4.

Benthic sediment mercury methylation rate: The yearly-average methylation rate constant in the upper sediment layer is about 0.0001 day^{-1} on a whole-sediment basis. More oxygenated water during the winter months probably has significantly lowered methylation rate than those during the summer months.

Burial velocity: Increased sediment burial velocity is associated with lower resuspension rates and less transfer of sediment mercury to the water column. A typical value for this parameter is 0.13 mm/year or 0.00000035 meter/day.

Depth of benthic sediment bed: This parameter should be provided by from monitoring data. The GBMM interface uses 0.02 meter as a default value.

Benthic sediment bed porosity: The typical range of this parameter is 0.90-0.95.

Benthic bed sediment and pore water partition coefficient: It is defined as equilibrium concentration in benthic bed sediment solid divided by concentration in pore water. The default value used in GBMM interface is 50,000 ml/g. More values are provided in Table 3.19.

Table 3.19 Mercury sediment water partition coefficient (USEPA, 1997).

Chemical	Default Value (mL/g)	Range
Hg^0	3000	--
HgII	50,000	16,000-990,000
Methylmercury	3000	2,200-7,800

Solid concentration in benthic sediment: The default value is 75,000 g/m^3.

3.6 Optional: Clip Study Area

The GBMM GIS interface provides two optional tools for clipping study areas (Figure 3.27):

- Manual clipping tool
- Automatic clipping tool

Use the clipping tools to define the extents of actual study areas from large datasets and to avoid slow performance associated with large datasets during the data processing and simulation steps. (Manual clipping tool executes faster than the automatic tool but with less accurate resulting boundaries.)

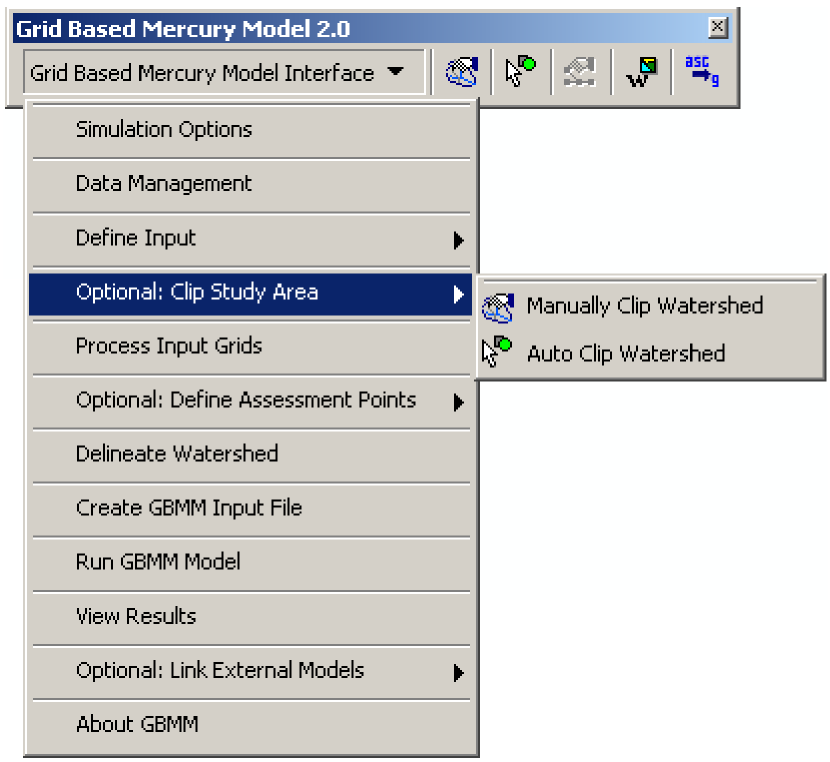


Figure 3.27 Clip Study Area menu with two clipping tools: a mannual clipping tool and an automatic clipping tool.

3.6.1 Manually Clip Watershed

You can use the manual clipping tool ( ) to manually draw a polygon to define the desired study area (Figure 3.28). All the GIS layers are clipped using your polygon. Before it begins to clip the study area, a dialog prompts for you to give a new project name (Figure 3.29) for the new area. If you enter a new project name and click **OK**, a new project (*.mxd) with the given name is created in the same directory as the current project. In addition, a new project folder with the same name is created and all the clipped data layers are saved in the DATA subfolder of the new project folder (see

Section 2.3). Now, you can decide whether to continue on the current project or exit to work on the newly clipped project (Figure 3.30).

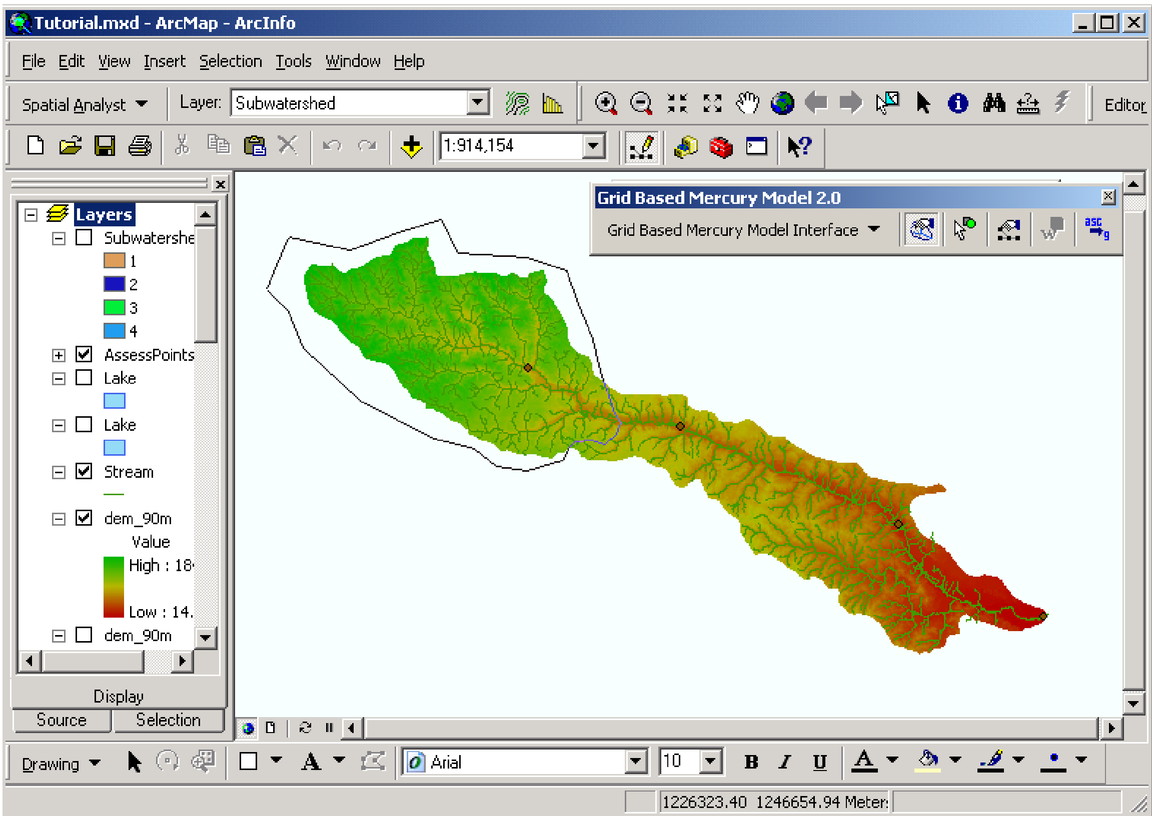


Figure 3.28 Clip a new study area manually: Draw a polygon to define the area.

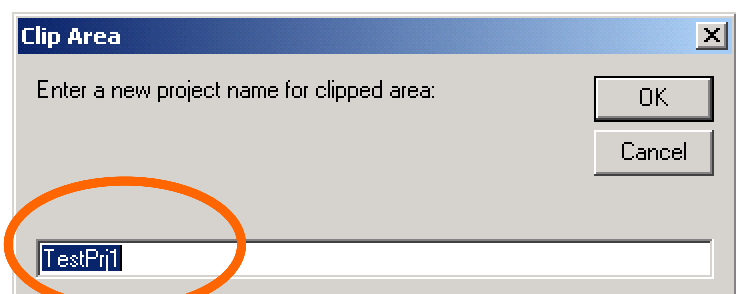


Figure 3.29 A dialog asks for a project name for the area to be clipped.

Figure 3.30. A comfirmation window after the completion of manual clipping process.

3.6.2 Auto Clipping Watershed

You can use the automatic clipping tool () to define the desired watershed by placing an outlet point on a stream. To do this, place the cross-hair mouse pointer on the outlet point and left-click the mouse button (Figure 3.31). A dialog box prompts for you to confirm the clipping action at the newly placed outlet (Figure 3.32).

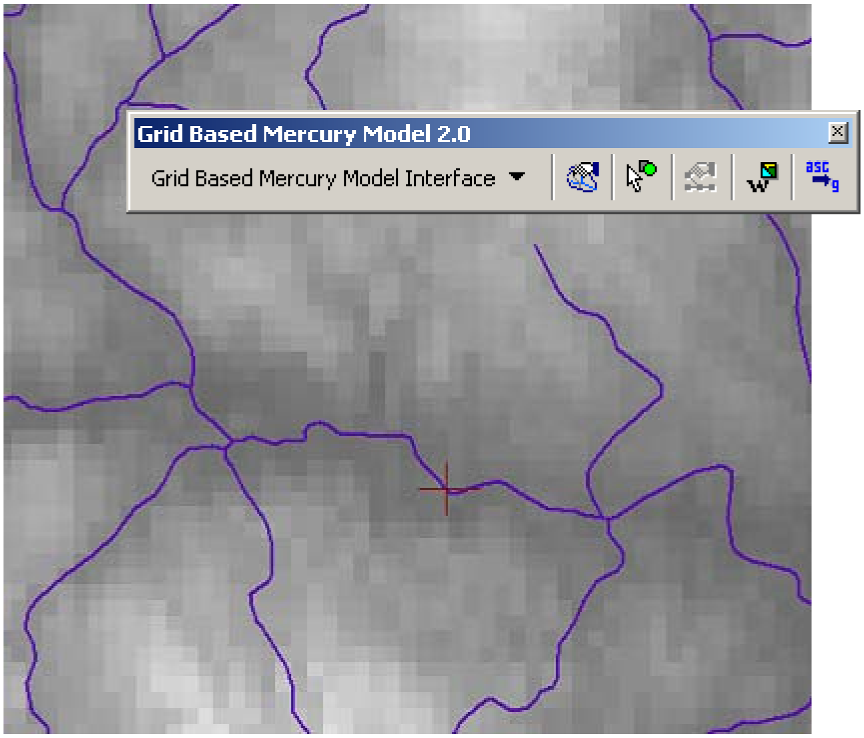


Figure 3.31. Place an outlet point on a stream for automatically clipping a watershed.

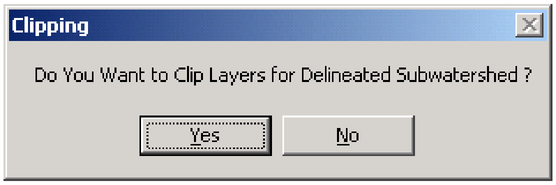


Figure 3.32. Confirmation dialog before the system clips the study area.

After the confirmation and some processing time, another dialog box prompts for you to input the snapping radius so that your outlet can be accurately snapped onto the nearest stream (Figure 3.33). A value of two to three times the DEM grid cell size is recommended for the snapping distance.

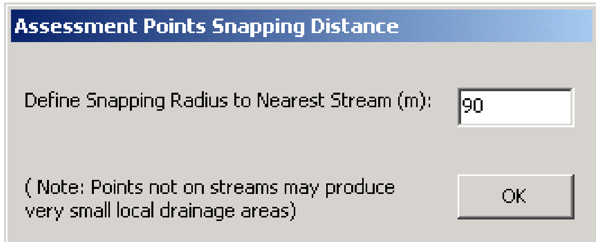


Figure 3.33. Define a radius to snap user-placed points to the nearest stream.

Once you have entered the snapping radius, the system delineates and displays an area based on the outlet. You can examine the watershed and ensure that watershed boundary is correct. After the confirmation of the newly delineated watershed boundary, you are asked to give a name to the new project (Figure 3.29). After clicking on **OK**, a new project with the given name (*.mxd) is created in the same directory as the current project. In addition, a new project folder with the same given name is created and all the clipped data layers are saved in the DATA subfolder under the new project folder (see Section 2.3). Now, you can decide whether to continue on the current project or exit to work on the newly clipped project.

3.7 Process Input Grids

This step is to process the current input data (data loaded from the Data Management step and model parameter values specified in the Define Input step) and derive all the necessary input grids for the GBMM C++ module.

Because this step involves many grid operation processes, it may take a few minutes to hours to complete depending on the size of study area (measured by numbers of rows and columns).

The major processes involved in this step include: filling DEM sinkholes, burning NHD streams on DEM surface, calculating flow direction and flow accumulation, deriving slopes, computing slope length and USLE length-slope factor, and generating grids for runoff curve number, landscape roughness, channel hydraulic radius, lake outlets, runoff travel tome, climate station Thiessen polygon, and forest litter decomposition rates. All the processed grids are stored in the project TEMP subfolder.

Click the Process Input Grids submenu, a window displays for choosing a method to calculate the USLE slope length (Figure 3.34). The slope length is an important parameter to estimate source erosion (sheet and rill erosion). The first option is to derive slope length from the DEM of the study area. *This option should be applied only when high-resolution DEM data (grid size less than or equal to 30 meters)* are used. You should also specify a maximum value for the slope length, and the default is 100 meters. Deriving slope length on the basis of the DEM usually takes long time to complete. The second option is for you to specify slope length directly. This slope length is applied uniformly across the landscape. If low resolution DEM data (grid size larger than 30 meters), the second option is recommended. The third option is for the situation when slope length and USLE length-slope factor have already been calculated by the system during previous GBMM setup operations.

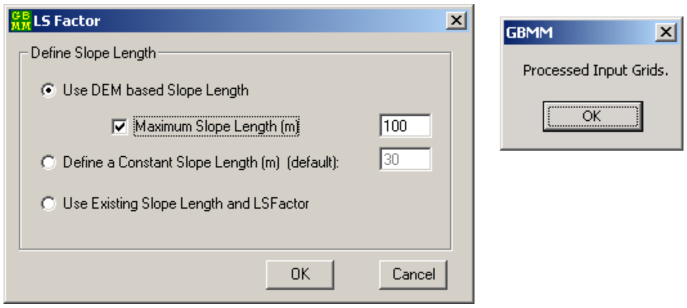


Figure 3.34. Options for calculate slope length. The first option should be applied only to high resolution DEM (grid size less than 30 meters). The image on the right shows a message at the completion of processing the input grids

3.8 Assign Assessment Point

This step is to allow you to manually add assessment points in the watershed, and GBMM exports simulation results for every assessment point. By clicking the **Add Assessment Points** tool  or the **Define Assessment Points** submenu, you can place points anywhere in the watershed (Figure 3.35). After each point, the system prompts you for whether to continue or stop. If you choose to continue, you can add one more point. You can continue to as add as many points as needed.

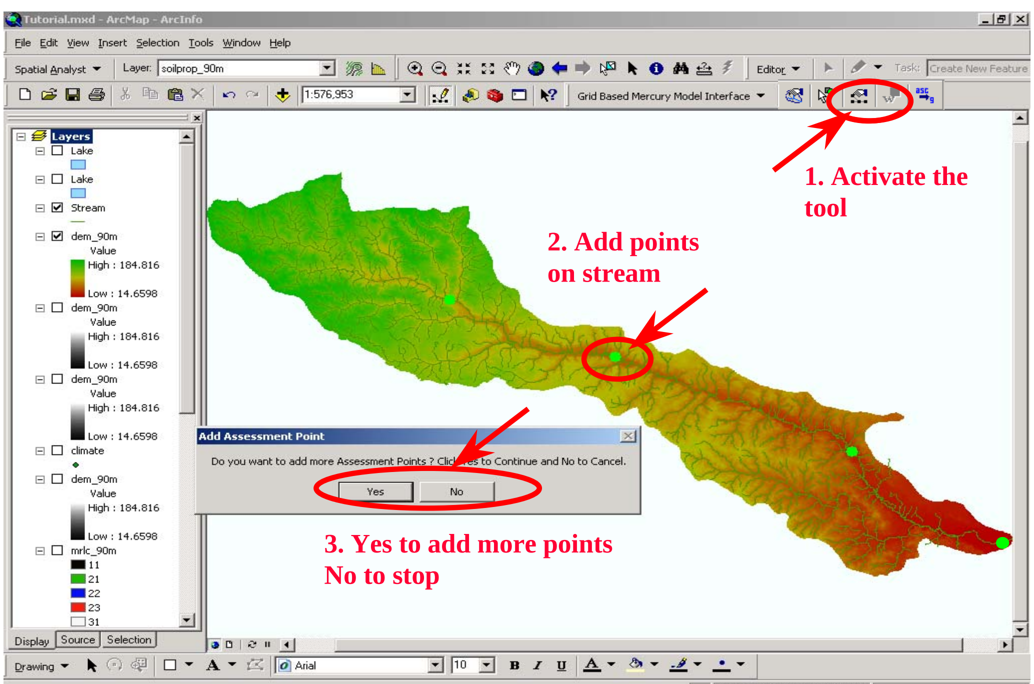


Figure 3.35. Steps to add assessment point in the watershed. GBMM exports simulation results for every assessment point.

WASP Stream Network Pre-processor

This option is available only if the WASP linkage option is selected (Section 3.3) and the NHD drain layer is loaded (Section 3.4). To set up WASP linkage with GBMM interface:

1. Activate and display the NHD drain map layer.
2. Select target streams from NHD drain layer. Select streams manually using the GBMM **Select NHD Streams** tool  and modify the selections using the ArcMap Select Features  tool. You can select streams (draw a rectangle area) by stream levels using the Select NHD Streams tool.
3. Click on WASP Stream Network Preprocessor under the **Optional: Define Assessment Points** submenu (Figure 3.36). If the streams selected are not continuous, the system displays a message, and you must select the missing links manually to make all the selected streams continuous.

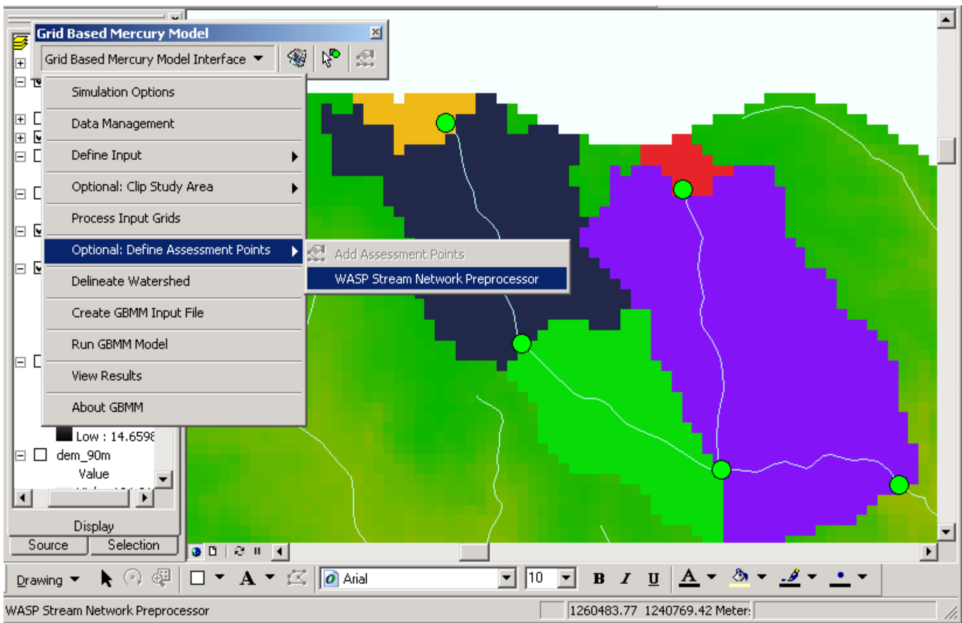


Figure 3.36. The optional WASP Stream Network Preprocessor submenu.

4. If the selected streams are continuous, a new window (Figure 3.37) asks you to define criteria for stream segmentation. You can select travel time (hr) or segment length (m) for stream segmentation.

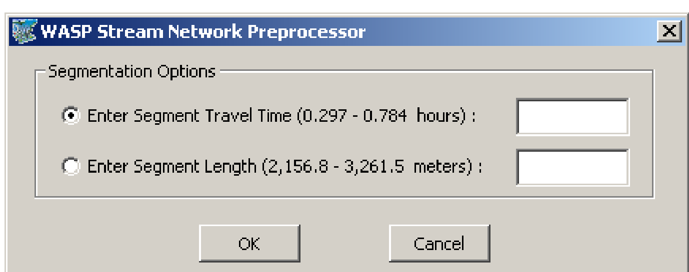


Figure 3.37. Defining the criteria for stream segmentation.

5. Click **OK**. The stream segmentation is processed, and the segmentation points are placed on the streams and displayed for you to check. To change the segmentation, you can repeat the above steps.
6. In the next step, **Delineate Watershed** (see Section 3.9), the system will use the segmentation points (also called "assesspoints") to delineate WASP watersheds, and save the stream segments table and headwater flow path table in the INPUT folder.

3.9 Delineate Watershed

This step is to delineate watershed boundaries on the basis of assessment points (including WASP segmentation points) or the default outlet and to trace the watershed connections. By clicking the **Delineate Watershed** submenu, the GBMM system delineates subwatershed boundaries for all the existing points. Each assessment point or WASP point has a corresponding subwatershed area. The entire study area should have only one outlet to run GBMM properly. Figure 3.38 shows the steps of delineating watersheds and the subwatershed areas delineated at the assessment points.

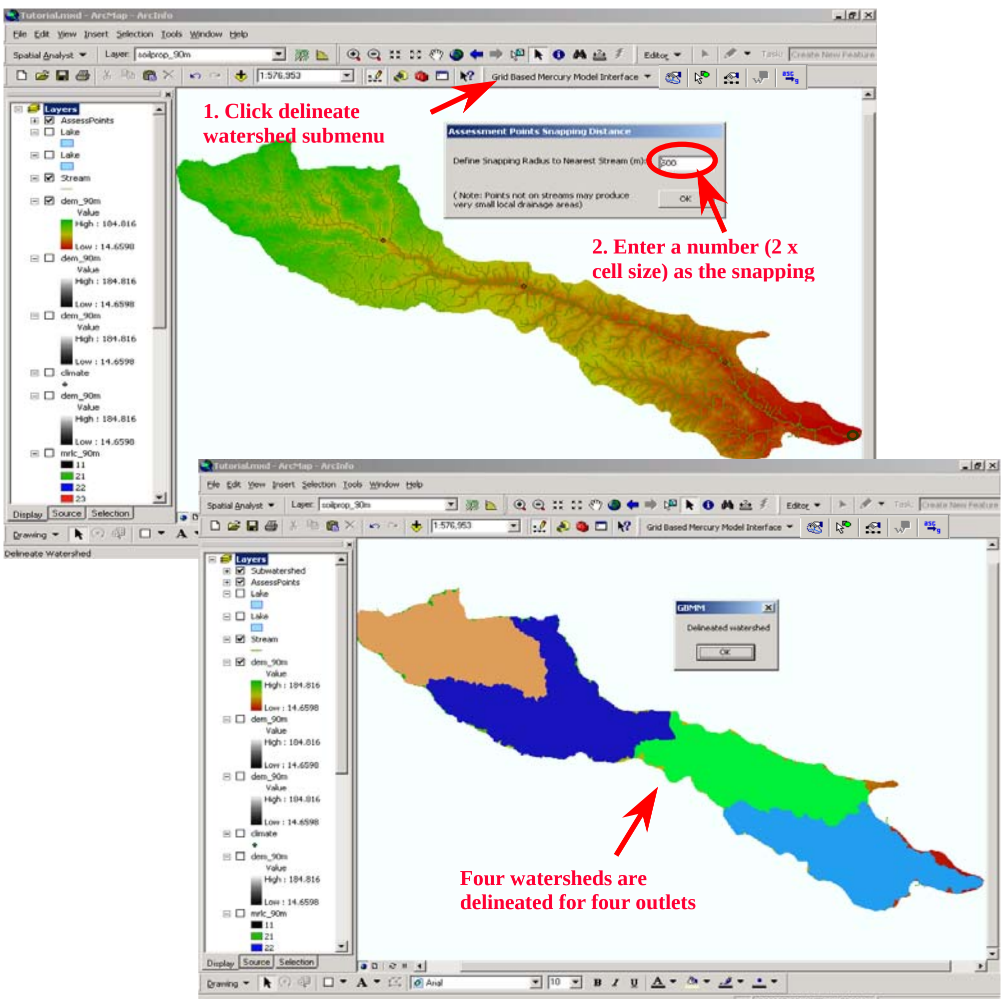


Figure 3.38. Delineate watershed on the basis of assessment points and outlet. The system traces the connectivities between the subwatersheds.

3.10 Generate GBMM Input File

This is the final step to preparing the input file for GBMM C++ module. Click the **Generate GBMM Input File** submenu. The system displays the Create Model Input File window (Figure 3.39) and the File Path tab prompts you for a name for the new input file. The input file to GBMM C++ module is a structured text file (Appendix C), which arranges input parameter names, values, and annotations in sections or Cards similar to the traditional FORTRAN input file.

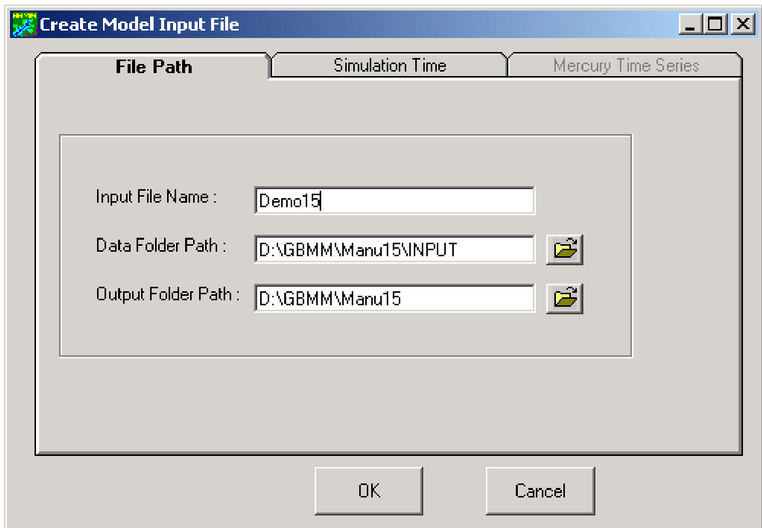


Figure 3.39. Interface for specifying a input file name for GBMM C++ module.

On the Simulation Time tab of the Create Model Input File form (Figure 3.40), you can specify the simulation period and the climate data period to be used with the simulation. You can also specify the average duration (days) of groundwater recharge for WhAEM.

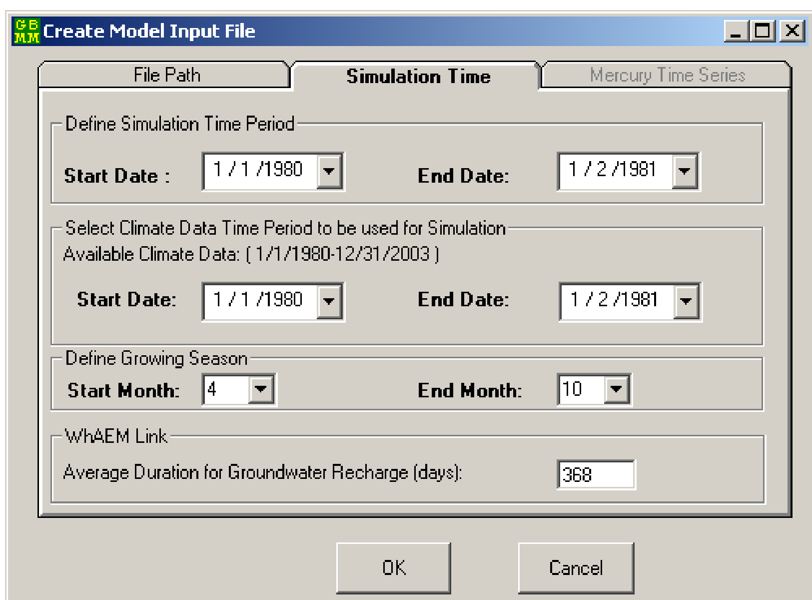


Figure 3.40. Interface for specifying simulation time period, for selecting climate data time, and for outputing WhAEM link files.

There are three rules to select the climate data period:

1. The climate data period should be within the simulation time period.
2. The climate data period should be the same as the simulation period if the simulation period is shorter than one year.
3. The climate data period should be at least one year if the simulation period is longer than one year.

The GBMM model is able to loop or reuse the climate data if the data period (minimum one year) is shorter than the simulation period.

The Mercury Time Series tab of the Create Model Input File form is for you to select time periods of the available dry and wet mercury deposition time series to be used with the simulation. To enable the tab, you must select the Time-Variable Mercury Deposition option in the Define Input > Mercury Simulation Input step (see Figure 3.21).

After specifying all the required inputs on the Create Model Input File form, you can click **OK** to start creating the input file and supporting input grids for GBMM C++ module. It may take a few minutes to complete the process.

Upon the completion of this step, i.e., creating the input file and supporting grids for GBMM C++ module, at least 15 files are created in the project input folder. The 15 files include:

Files required by GBMM C++ module (all the grids have the same numbers of rows and columns):

- Curve number for pervious area (ASCII grid)
- Curve number for impervious area (ASCII grid)
- Litter decomposition rate based on forest types (Kdcomp, ASCII grid)
- USLE LS factor for calculating erosion (ASCII grid)
- MRLC land use (ASCII grid)
- Soil type code (ASCII grid)
- Stream travel time (ASCII grid)
- Subwatershed boundaries (ASCII grid)
- Thiessen polygon for climate station (ASCII grid)
- Total runoff travel time (ASCII grid)
- Climate data text (text file)
- Input file for GBMM C++ module (text file)

Files not required by GBMM C++ module:

- Climate data availability summary (text file)
- GIS interface data tracking file (text file)
- Stream network connectivity (text file)

3.11 Run GBMM Model

Click the **Run GBMM Model** submenu, and the GBMM C++ module is activated (Figure 3.41). The GBMM C++ module interface has an ooptional text window, an input path box, and four command buttons. The four command buttons are:

- Browse: Use this to navigate to the folder that contains the model input file (*.inp). Once you select the correct *.inp file, the input file is loaded and can be displayed in the optional text window. You can edit the input files in the optional text window (not recommended for new users).
- Edit Input File: Use this to expand the interface to show the optional text window. You can also make changes to the input file in the text window.
- Run Model: Execute the GBMM C++ module. When the GBMM C++ module is running properly, it displays a progress bar showing simulation progress and time elapsed (Figure 3.42). Depending on the watershed size and simulation period, it may take a few minutes to hours to complete the simulation.
- Exit: Use this to exit GBMM C++ module.

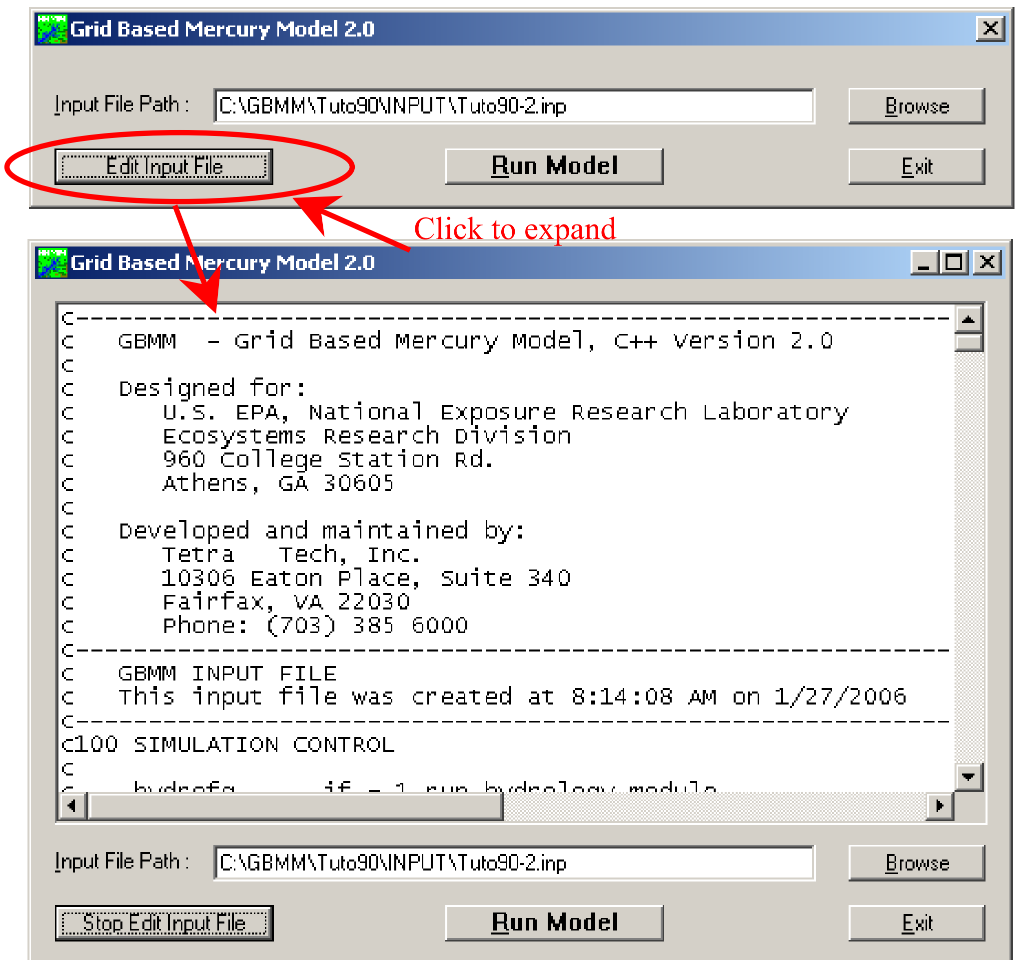


Figure 3.41. The GBMM C++ interface for loading the model input file. You can edit the input file in the optional text window by clicking the **Edit Input File** button.

After loading the input file, click **Run Model**, and the GBMM C++ module starts the simulation. Upon the completion of the simulation, a message box is displayed to inform you of the final status (Figure 3.43).

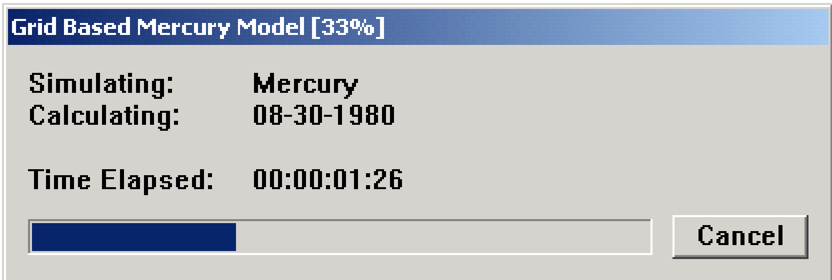


Figure 3.42. This window shows the progress of a simulation.

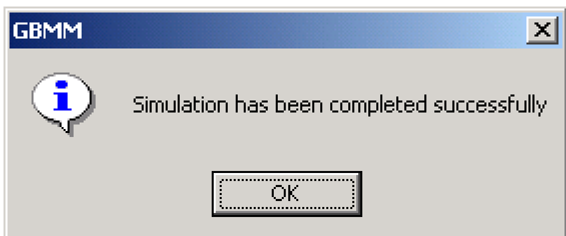


Figure 3.43. This message box informs you of the complete of simulation.

3.12 View Results

To view the simulation results, a seamless link to a Microsoft Excel spreadsheet is made through the View Results submenu. Click **View Results** under the GBMM Interface (Figure 3.44) and a spreadsheet (GBMMPostprocessor.xls) opens. You can visualize the simulated time series using the spreadsheet.

The postprocessor has a simple interface (Figure 3.45). First, you need to use the navigation button to find the project folder. For example, if the project is called *tutorial.mxd* on D:\GBMM, the project folder path should be D:\GBMM\Tutorial. Second, you can select a result file corresponding to an outlet or assessment point from the results file list. And third, you can choose to view one of the three types of simulation results, i.e., time series, source load summary, and mass balance summary.

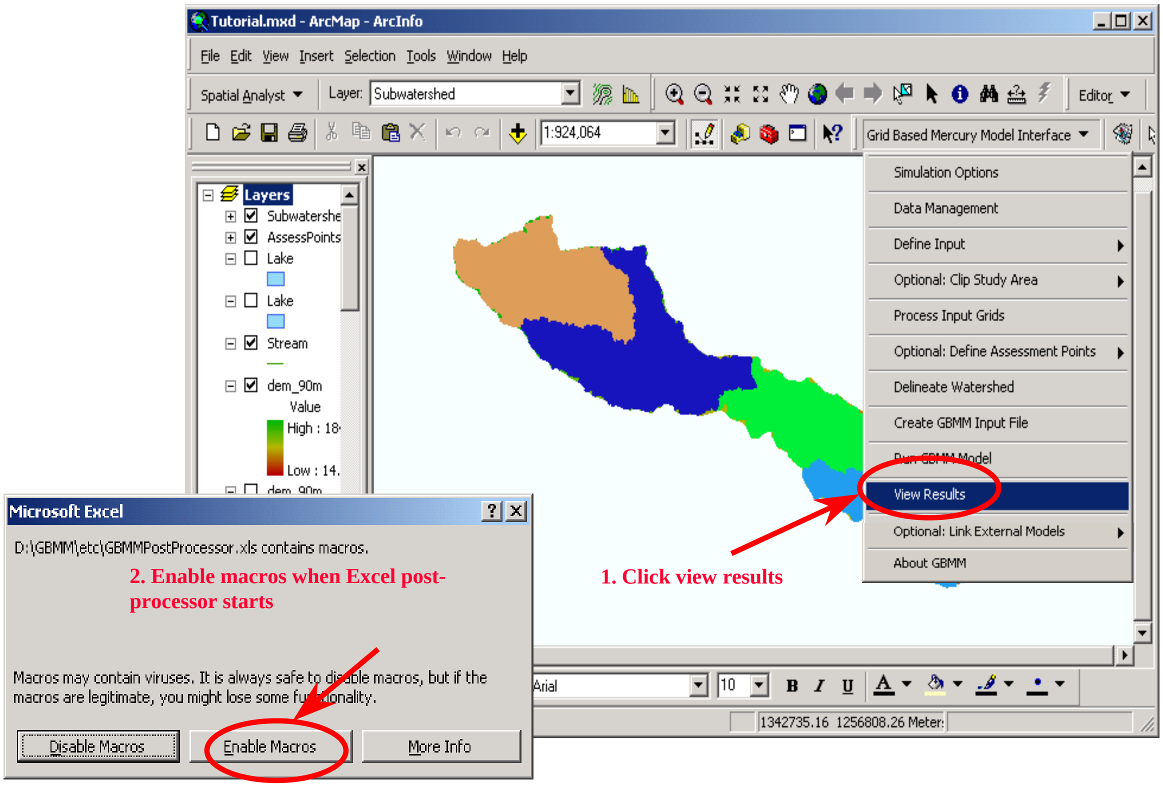


Figure 3.44. Click on the View Results menu from the GBMM Interace bar to open the postprocessor.

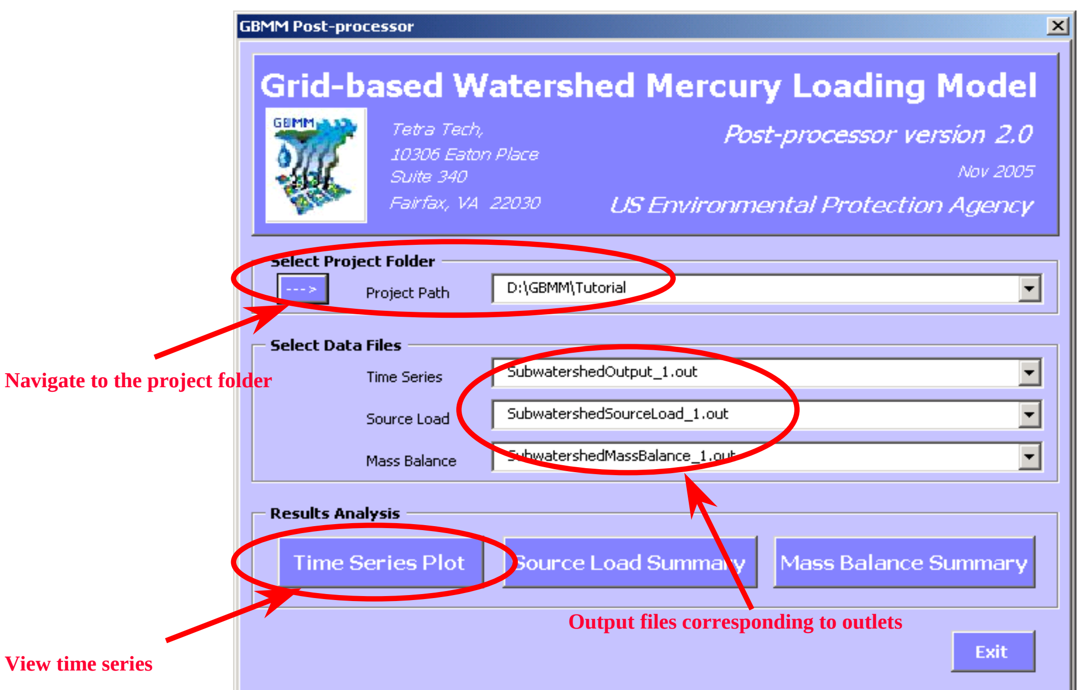


Figure 3.45. The interface of the postprocessor.

Flow Time Series Output

The flow time series (in cubic meters per sec) is generated at each user-defined assessment point or for each WASP stream segment. An output example is shown in Figure 3.46.

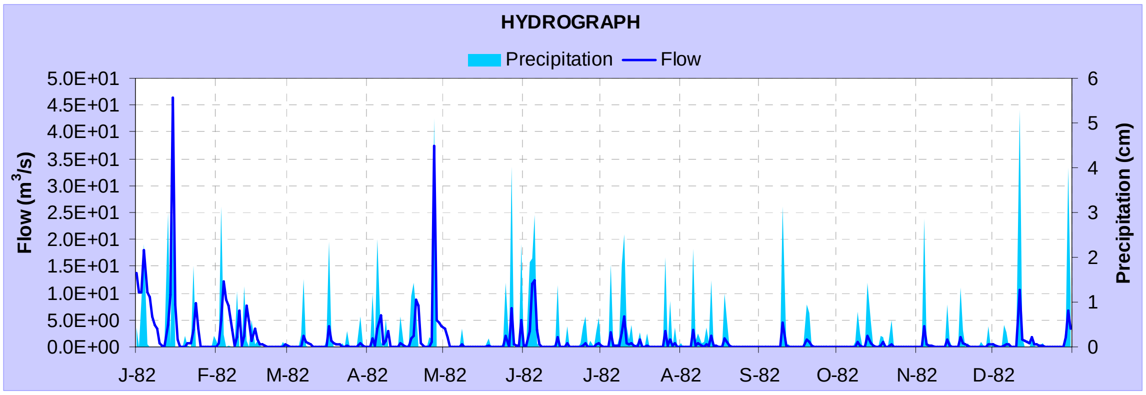


Figure 3.46. Hydrograph at an assessment point.

Sediment Load Time Series Output

The sediment load time series (in kg per day) is generated at each user-defined assessment point or for each WASP stream segment. An output example is shown in Figure 3.47.

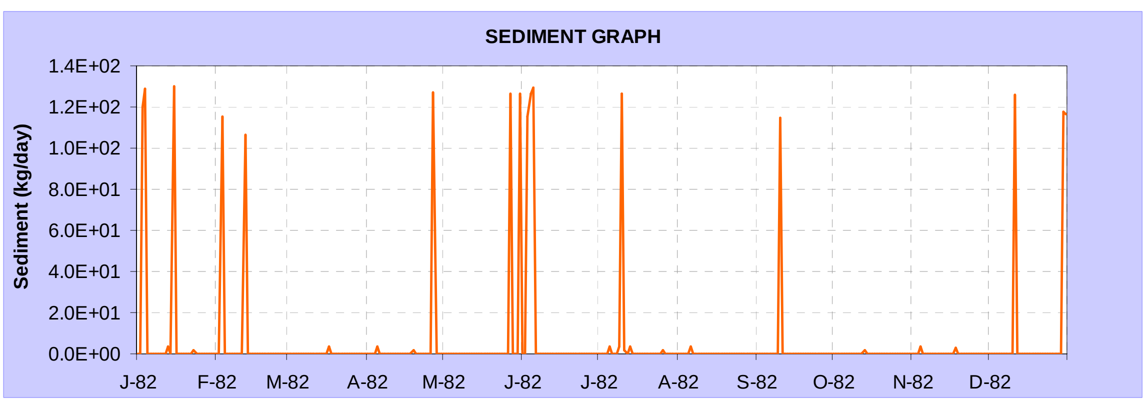


Figure 3.47. Sediment load time series at an assessment point.

Methylmercury Load Time Series Output

The time series for the methylmercury load (in micrograms per day) is generated at each user-defined assessment point or for each WASP stream segment. An output example is shown in Figure 3.48.

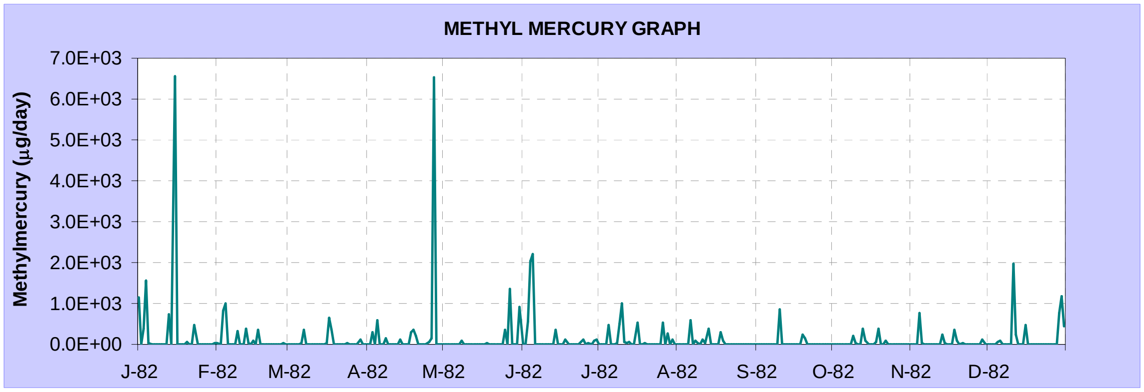


Figure 3.48. Methylmercury load time series at an assessment point.

Divalent Mercury Load Time Series Output

The time series for divalent mercury load (in micrograms per day) is generated at each user-defined assessment point or for each WASP stream segment. An output example is shown in Figure 3.49.

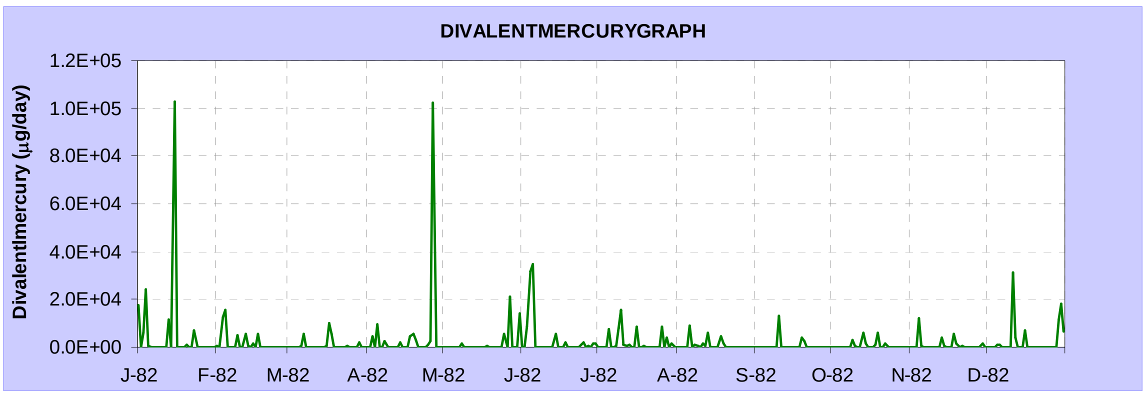


Figure 3.49. Divalent Mercury load time series at an assessment point.

Water and Mass Balance Time Series Output

The time series for the water and mass balance per day are generated for the watershed at each user-defined assessment point or for each WASP stream segment. The daily time series data are further summarized into monthly and yearly mass balance table (Table 3.20) and charts (Figure 3.50–3.55).

Table 3.20. Water and mass balance summary table

WATER AND MASS BALANCE															
Year	**Parameters**	**Unit**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
1982	Precipitation	cm	1.21E+01	7.28E+00	5.67E+00	1.41E+01	8.40E+00	1.11E+01	1.17E+01	6.71E+00	5.01E+00	4.25E+00	6.37E+00	1.22E+01	1.05E+02
1982	Surface Runoff	cm	4.53E+00	9.55E-01	5.73E-01	3.73E+00	1.17E+00	2.44E+00	1.41E+00	6.69E-01	5.19E-01	4.12E-01	6.28E-01	1.80E+00	1.88E+01
1982	Evapotranspiration	cm	2.29E+00	3.01E+00	5.09E+00	6.06E+00	1.02E+01	1.21E+01	1.15E+01	6.88E+00	4.45E+00	3.50E+00	3.08E+00	3.04E+00	7.11E+01
1982	Percolation	cm	5.63E+00	4.39E+00	3.54E-01	3.61E+00	1.01E-01	3.53E-01	2.10E-01	1.40E-01	4.84E-02	6.28E-02	2.25E-01	9.33E-01	1.61E+01
1982	Soil water content	cm	1.05E+01	1.03E+01	9.29E+00	1.01E+01	6.18E+00	5.73E+00	2.40E+00	1.06E+00	1.11E+00	1.13E+00	2.93E+00	5.43E+00	-1.08E+00
1982	Sediment available at the surface	kg/ha	1.57E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01
1982	Sediment load at the outlet	kg/ha	3.47E-02	2.00E-02	3.25E-04	1.19E-02	2.28E-02	3.35E-02	1.27E-02	3.04E-04	1.03E-02	1.44E-04	5.80E-04	3.25E-02	1.80E-01
1982	Sediment remaining at the surface	kg/ha	1.57E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.56E+01
1982	Mercury atmospheric deposition	ug/m2	4.24E-01	3.23E-01	4.34E-01	4.65E-01	3.82E-01	4.68E-01	5.20E-01	4.85E-01	3.29E-01	4.01E-01	4.34E-01	4.37E-01	5.10E+00
1982	Mercury loss due to runoff	ug/m2	8.35E-03	1.84E-03	1.12E-03	6.86E-03	2.28E-03	4.57E-03	2.80E-03	1.37E-03	1.07E-03	8.26E-04	1.30E-03	3.57E-03	3.59E-02
1982	Mercury loss due to erosion	ug/m2	7.00E-05	4.00E-05	1.00E-06	2.40E-05	4.60E-05	6.70E-05	2.60E-05	1.00E-06	2.10E-05	0.00E+00	2.00E-06	6.50E-05	3.63E-04
1982	Mercury loss due to leaching	ug/m2	1.02E-02	7.95E-03	6.55E-04	6.75E-03	1.94E-04	6.89E-04	4.03E-04	2.72E-04	9.40E-05	1.22E-04	4.38E-04	1.79E-03	2.96E-02
1982	Mercury loss due to soil reduction	ug/m2	2.58E-02	2.28E-02	2.29E-02	2.41E-02	1.54E-02	1.40E-02	6.19E-03	2.72E-03	2.76E-03	2.90E-03	7.20E-03	1.38E-02	1.61E-01
1982	Mercury mass in soil	ug/m2	1.60E+02	1.60E+02	1.61E+02	1.61E+02	1.62E+02	1.62E+02	1.62E+02	1.63E+02	1.63E+02	1.64E+02	1.64E+02	1.65E+02	4.88E+00

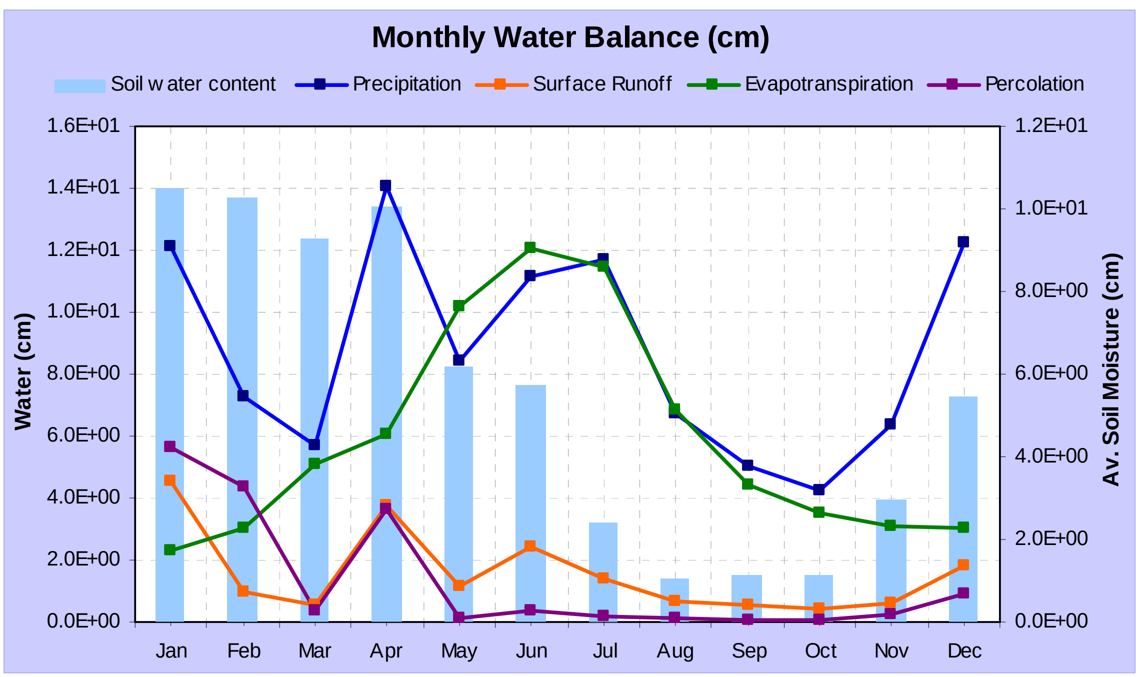


Figure 3.50. Monthly water balance chart for a watershed

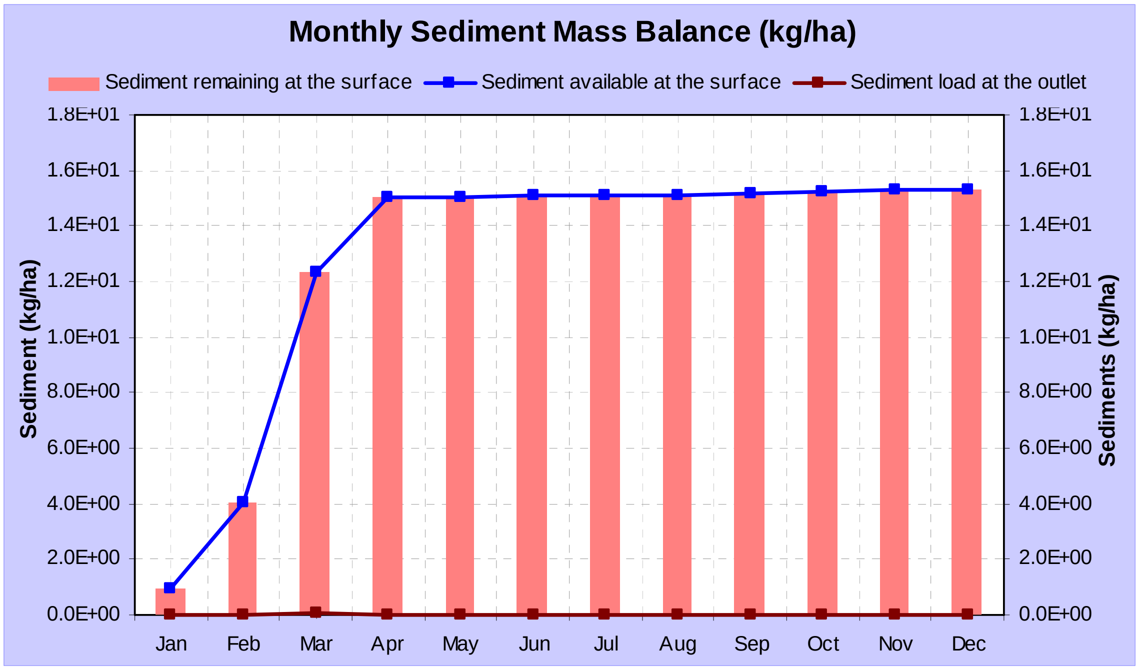


Figure 3.51. Monthly sediment balance chart for a watershed

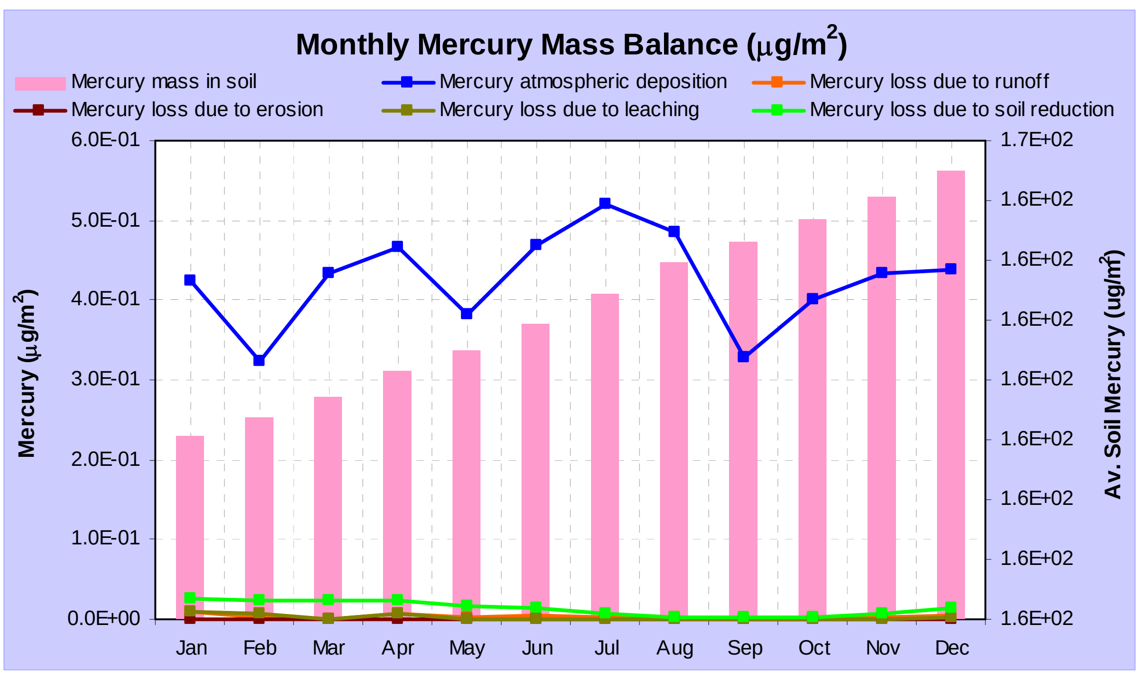


Figure 3.52. Monthly mercury balance chart for a watershed

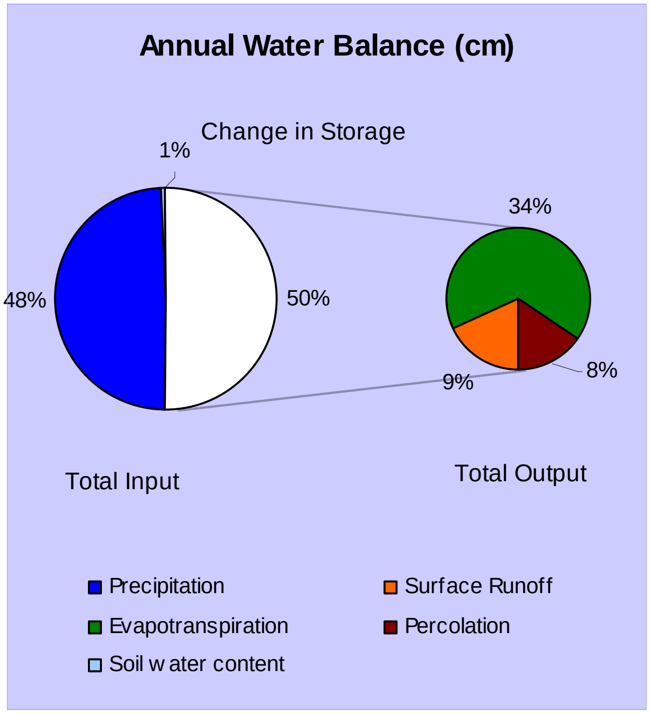


Figure 3.53. Yearly water balance chart for a watershed

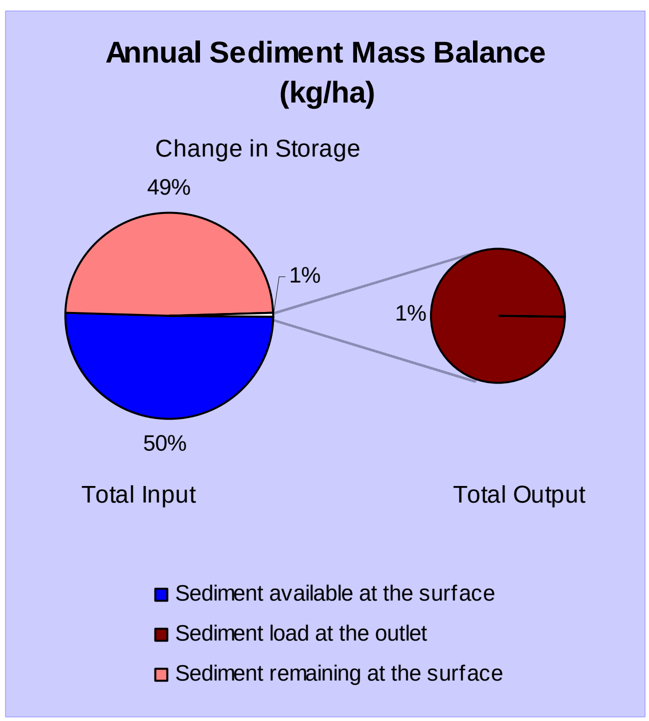


Figure 3.54. Yearly sediment balance chart for a watershed

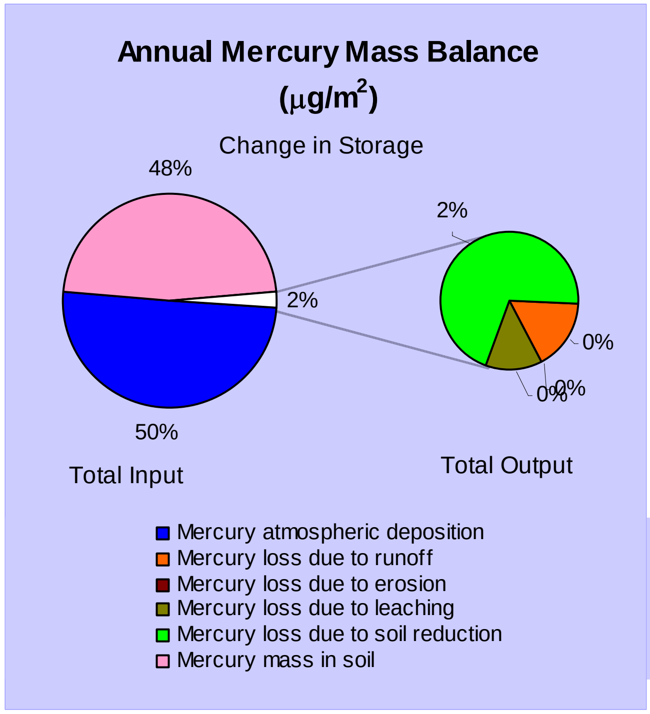


Figure 3.55. Yearly mercury balance chart for a watershed

Land Use Based Runoff and Load Time Series Output (Source Analysis)

The daily runoff and load time series for each land use type are generated for the delineated watershed at each user-defined assessment point or for each WASP stream segment. The daily time series data are further summarized into monthly and yearly load tables (Table 3.21–3.23) and charts (Figure 3.56–3.61) for each land use type.

Table 3.21. Monthly and yearly runoff summary by land use.

SURFACE RUNOFF FROM DIFFERENT LAND SOURCES (m^3)															
Year	Source	Area (m^2)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1982	Transitional	2.72E+06	1.34E+05	2.79E+04	1.29E+04	1.47E+05	3.73E+04	1.16E+05	4.27E+04	4.17E+03	4.61E+03	9.10E+03	4.15E+03	6.92E+04	6.09E+05
1982	High Intensity Residential	3.73E+05	4.33E+04	2.41E+04	1.76E+04	5.09E+04	3.23E+04	3.93E+04	4.13E+04	2.41E+04	1.87E+04	1.18E+04	2.20E+04	4.29E+04	3.68E+05
1982	Open Water	4.13E+05	4.88E+04	2.81E+04	2.01E+04	5.66E+04	3.52E+04	4.35E+04	4.56E+04	2.63E+04	2.04E+04	1.39E+04	2.53E+04	4.85E+04	4.12E+05
1982	High Intensity Commercial	1.35E+06	1.57E+05	8.75E+04	6.41E+04	1.85E+05	1.17E+05	1.43E+05	1.50E+05	8.75E+04	6.79E+04	4.30E+04	8.00E+04	1.56E+05	1.34E+06
1982	Woody Wetlands	9.18E+06	1.08E+06	6.08E+05	4.40E+05	1.26E+06	7.90E+05	9.67E+05	1.02E+06	5.90E+05	4.57E+05	3.00E+05	5.52E+05	1.07E+06	9.12E+06
1982	Herbaceous Wetlands	2.43E+04	2.83E+03	1.57E+03	1.15E+03	3.32E+03	2.11E+03	2.57E+03	2.70E+03	1.58E+03	1.22E+03	7.73E+02	1.44E+03	2.80E+03	2.41E+04
1982	Pasture/Hay	2.15E+06	7.61E+04	3.11E+03	4.83E+02	5.22E+02	1.49E+03	2.07E+04	1.91E+03	0.00E+00	0.00E+00	5.00E+02	0.00E+00	3.56E+03	1.08E+05
1982	Row Crops	5.35E+07	2.15E+06	1.86E+05	6.49E+04	2.28E+06	2.57E+05	1.21E+06	2.46E+05	0.00E+00	2.28E+00	7.68E+04	7.86E+03	5.40E+05	7.02E+06
1982	Other Grasses	2.92E+05	1.04E+04	0.00E+00	0.00E+00	7.38E+01	2.12E+02	2.95E+03	1.74E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.79E+02	1.40E+04
1982	Deciduous Forest	1.30E+07	4.22E+05	2.48E+04	1.81E+02	0.00E+00	0.00E+00	3.70E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.32E+03	4.90E+05
1982	Evergreen Forest	1.66E+07	5.34E+05	4.46E+04	3.29E+02	0.00E+00	0.00E+00	4.62E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.14E+04	6.37E+05
1982	Bare Rock/Sand/Clay	2.43E+04	1.43E+03	1.05E+03	4.58E+02	1.01E+03	9.50E+01	3.84E+02	8.12E+02	5.00E-01	7.83E+00	8.55E+02	1.22E+02	2.12E+03	8.34E+03
1982	Mixed Forest	8.42E+06	2.74E+05	1.24E+04	8.74E+01	0.00E+00	0.00E+00	2.41E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.11E+03	3.14E+05
1982	Quarries/Strip Mines/Gravel	1.07E+06	4.81E+04	4.34E+03	7.04E+02	5.92E+04	1.25E+04	4.39E+04	9.38E+03	6.60E+01	1.03E+03	0.00E+00	2.74E+02	1.63E+04	1.96E+05
1982	Low Intensity Residential	1.69E+06	4.40E+04	4.39E+03	1.21E+04	9.40E+04	1.13E+04	8.21E+03	9.11E+03	7.52E+03	4.78E+03	0.00E+00	2.07E+03	3.17E+04	2.29E+05

Table 3.22. Monthly and yearly sediment load summary by land use.

SEDIMENT LOAD FROM DIFFERENT LAND SOURCES (kg)															
Year	Source	Area (m^2)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1982	Transitional	2.72E+06	8.02E+00	3.21E+00	1.61E+00	4.81E+00	3.21E+00	4.82E+00	9.62E+00	1.61E+00	1.61E+00	1.60E+00	3.20E+00	4.82E+00	4.81E+01
1982	High Intensity Residential	3.73E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1982	Open Water	4.13E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1982	High Intensity Commercial	1.35E+06	2.17E-04	1.24E-04	2.17E-04	2.79E-04	1.55E-04	2.79E-04	3.41E-04	3.10E-04	9.30E-05	1.86E-04	2.17E-04	2.17E-04	2.64E-03
1982	Woody Wetlands	9.18E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1982	Herbaceous Wetlands	2.43E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1982	Pasture/Hay	2.15E+06	4.67E+00	0.00E+00	0.00E+00	1.64E+00	2.69E+00	2.35E+00	1.05E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.80E+00	1.42E+01
1982	Row Crops	5.35E+07	3.58E+02	2.15E+02	0.00E+00	1.22E+02	2.43E+02	3.55E+02	1.22E+02	0.00E+00	1.11E+02	0.00E+00	0.00E+00	3.48E+02	1.87E+03
1982	Other Grasses	2.92E+05	1.14E-04	0.00E+00	0.00E+00	4.30E-05	8.60E-05	8.90E-05	4.50E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.00E-05	4.67E-04
1982	Deciduous Forest	1.30E+07	2.85E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.64E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.50E+00
1982	Evergreen Forest	1.66E+07	1.26E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.31E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.99E+00
1982	Bare Rock/Sand/Clay	2.43E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1982	Mixed Forest	8.42E+06	1.01E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.82E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.59E+00
1982	Quarries/Strip Mines/Gravel	1.07E+06	8.08E+00	4.08E+00	1.99E+00	3.95E+00	4.08E+00	6.13E+00	7.87E+00	1.77E+00	1.80E+00	0.00E+00	3.23E+00	6.13E+00	4.91E+01
1982	Low Intensity Residential	1.69E+06	3.18E-04	8.50E-05	8.80E-05	1.83E-04	1.95E-04	3.02E-04	4.17E-04	1.09E-04	1.11E-04	0.00E+00	1.12E-04	2.37E-04	2.16E-03

Table 3.23. Monthly and yearly mercury load summary by land use.

MERCURY LOAD FROM DIFFERENT LAND SOURCES (μg)															
Year	Source	Area (m^2)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1982	Transitional	2.72E+06	2.55E+04	5.38E+03	2.50E+03	2.83E+04	7.23E+03	2.24E+04	8.48E+03	8.43E+02	9.32E+02	1.84E+03	8.91E+02	1.38E+04	1.18E+05
1982	High Intensity Residential	3.73E+05	8.55E+03	4.77E+03	3.51E+03	1.02E+04	6.52E+03	7.95E+03	8.42E+03	4.95E+03	3.86E+03	2.45E+03	4.58E+03	8.98E+03	7.47E+04
1982	Open Water	4.13E+05	9.60E+03	5.56E+03	3.99E+03	1.13E+04	7.08E+03	8.77E+03	9.27E+03	5.37E+03	4.19E+03	2.87E+03	5.25E+03	1.01E+04	8.34E+04
1982	High Intensity Commercial	1.35E+06	3.10E+04	1.73E+04	1.28E+04	3.70E+04	2.37E+04	2.89E+04	3.06E+04	1.80E+04	1.40E+04	8.90E+03	1.66E+04	3.26E+04	2.71E+05
1982	Woody Wetlands	9.18E+06	2.11E+05	1.20E+05	8.73E+04	2.51E+05	1.59E+05	1.95E+05	2.06E+05	1.21E+05	9.38E+04	6.19E+04	1.14E+05	2.22E+05	1.84E+06
1982	Herbaceous Wetlands	2.43E+04	5.58E+02	3.12E+02	2.29E+02	6.67E+02	4.26E+02	5.19E+02	5.50E+02	3.24E+02	2.52E+02	1.60E+02	3.00E+02	5.87E+02	4.88E+03
1982	Pasture/Hay	2.15E+06	1.32E+04	5.34E+02	8.28E+01	1.22E+02	3.10E+02	3.61E+03	3.48E+02	0.00E+00	0.00E+00	8.58E+01	0.00E+00	6.46E+02	1.89E+04
1982	Row Crops	5.35E+07	3.76E+05	3.62E+04	1.11E+04	3.94E+05	4.89E+04	2.15E+05	4.47E+04	0.00E+00	2.21E+03	1.32E+04	1.35E+03	9.96E+04	1.24E+06
1982	Other Grasses	2.92E+05	1.79E+03	0.00E+00	0.00E+00	1.27E+01	3.65E+01	5.07E+02	2.98E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.07E+01	2.41E+03
1982	Deciduous Forest	1.30E+07	8.17E+04	4.88E+03	3.59E+01	0.00E+00	0.00E+00	7.36E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.31E+03	9.53E+04
1982	Evergreen Forest	1.66E+07	1.02E+05	8.65E+03	6.43E+01	0.00E+00	0.00E+00	9.01E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.32E+03	1.22E+05
1982	Bare Rock/Sand/Clay	2.43E+04	2.72E+02	2.02E+02	8.83E+01	1.94E+02	1.83E+01	7.42E+01	1.59E+02	9.73E-02	1.53E+00	1.69E+02	2.43E+01	4.23E+02	1.63E+03
1982	Mixed Forest	8.42E+06	5.28E+04	2.43E+03	1.72E+01	0.00E+00	0.00E+00	4.76E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.40E+02	6.06E+04
1982	Quarries/Strip Mines/Gravel	1.07E+06	9.25E+03	9.11E+02	1.77E+02	1.14E+04	2.50E+03	8.57E+03	1.99E+03	5.22E+01	2.42E+02	0.00E+00	1.26E+02	3.35E+03	3.86E+04
1982	Low Intensity Residential	1.69E+06	8.67E+03	8.67E+02	2.40E+03	1.88E+04	2.29E+03	1.66E+03	1.85E+03	1.54E+03	9.83E+02	0.00E+00	4.29E+02	6.62E+03	4.62E+04

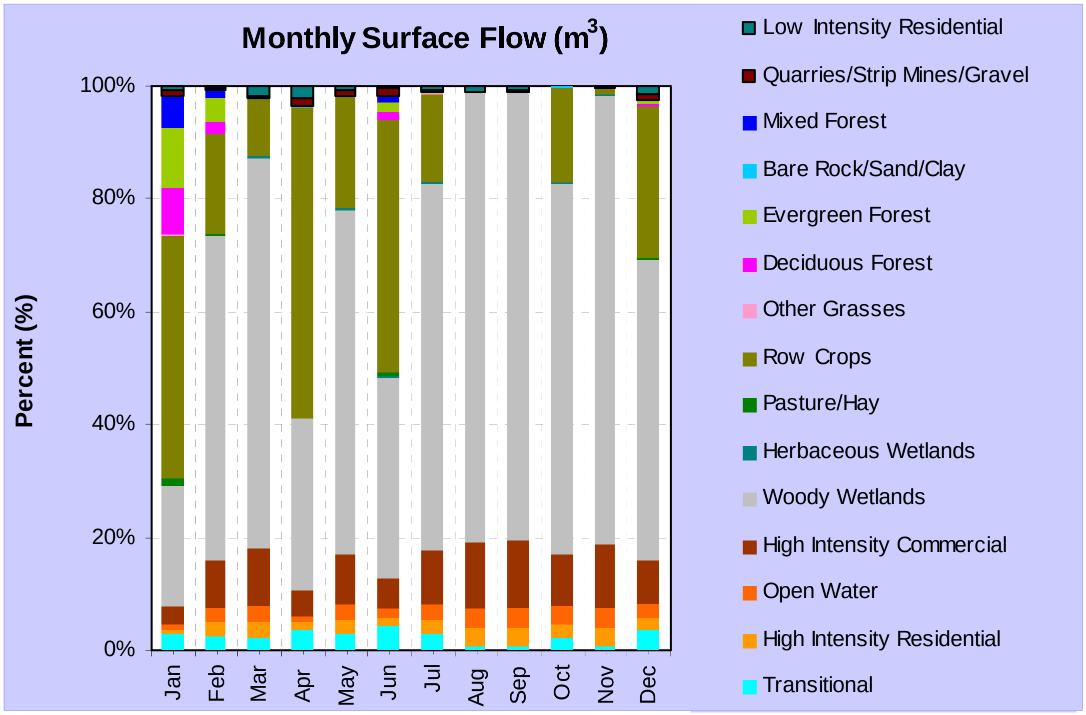


Figure 3.56. Monthly runoff by land use at an assessment point.

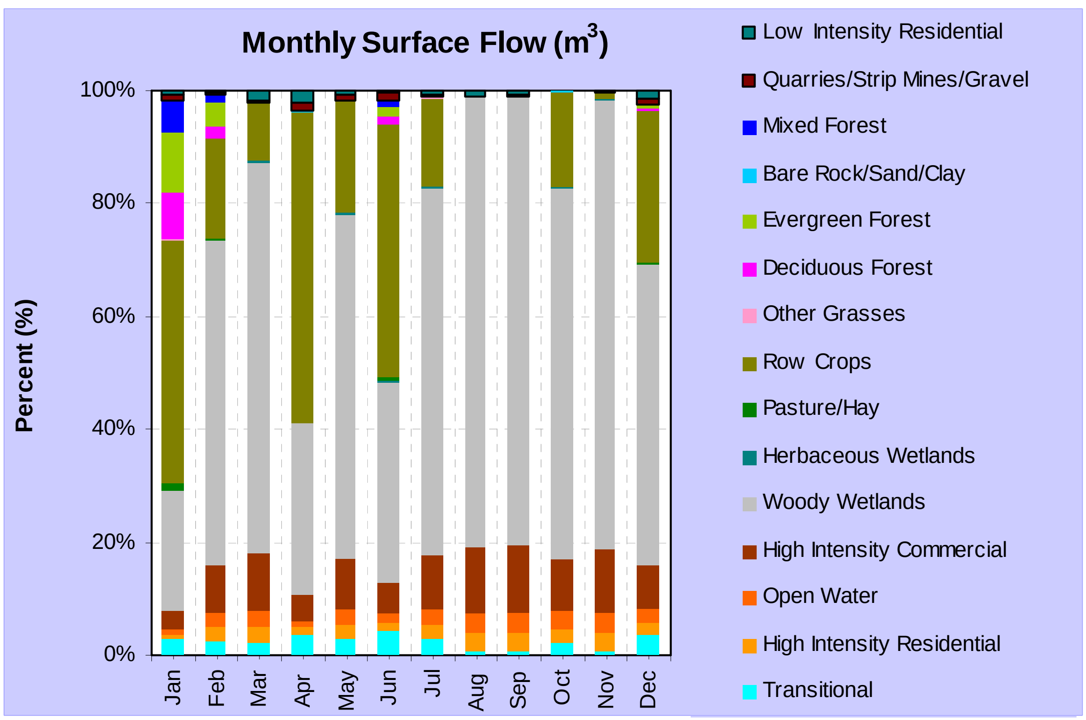


Figure 3.57. Monthly sediment load by land use at an assessment point.

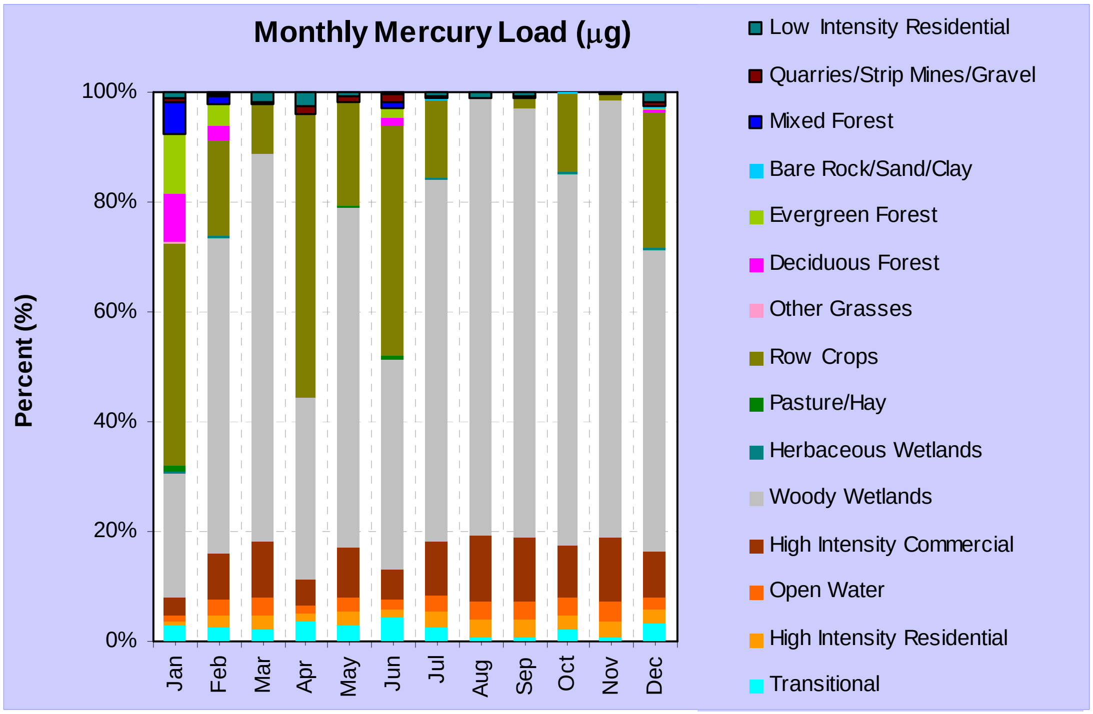


Figure 3.58. Monthly mercury load by land use at an assessment point.

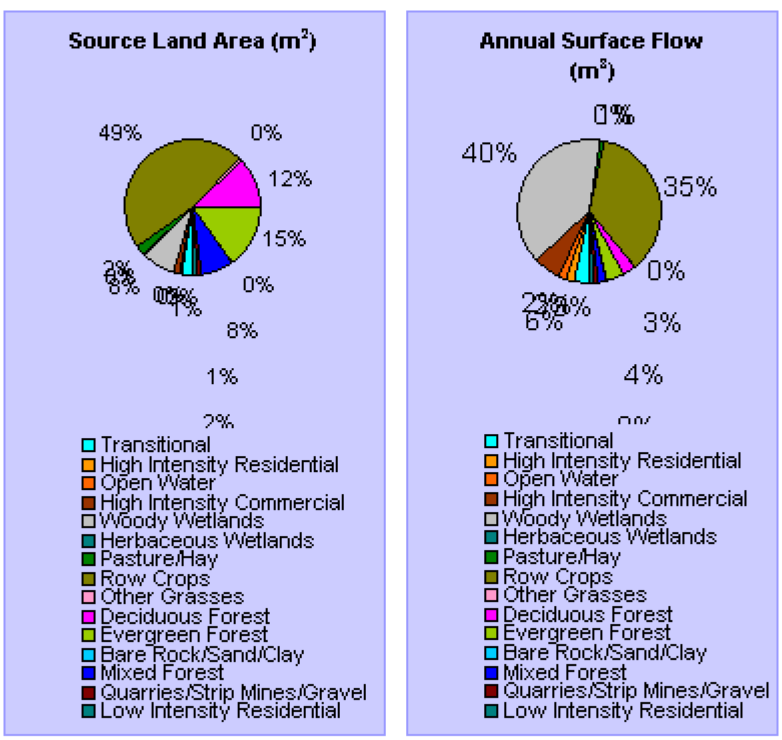


Figure 3.59. Yearly runoff by land use at an assesspoint point.

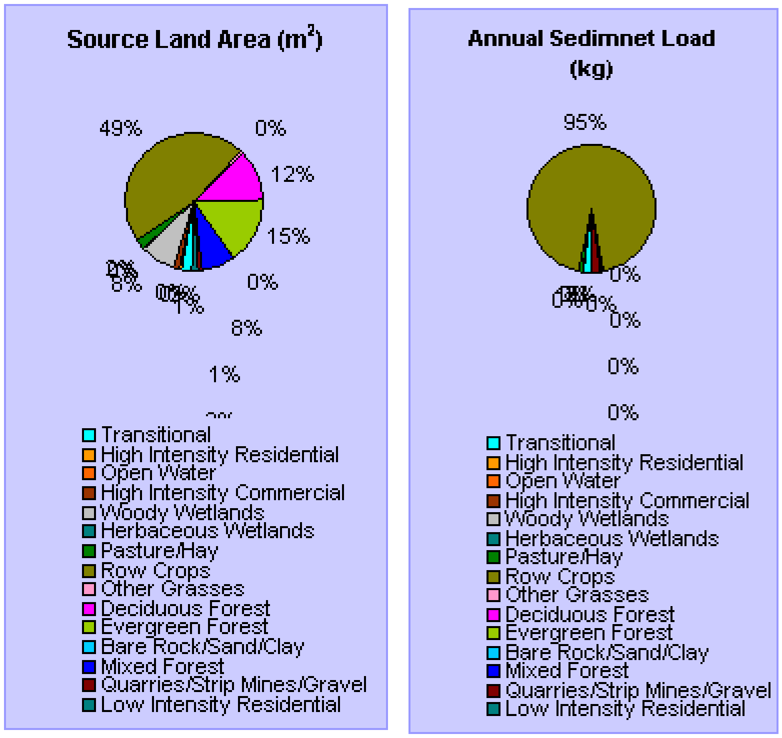


Figure 3.60. Yearly sediment load by land use at an assesspoint point.

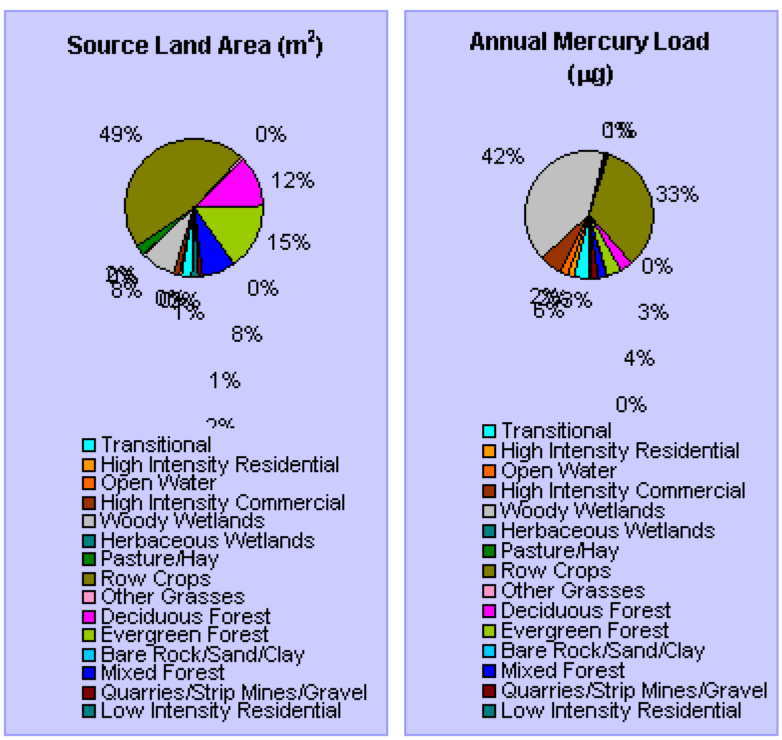


Figure 3.61. Yearly mercury load by land use at an assesspoint point.

3.13 Link External Models

The GBMM 2.0 provides links to two external models: WASP 7.x and WhAEM2000.

Click the **Optional: Link External Models from** the GBMM interface bar, you can see two options:

- Create WASP Link Files
- Create WhAEM Link Files

Depending on the simulation options you select earlier (Section 3.3), the above two options may or may not be enabled.

Create WASP Link Files

If **Create WASP Link Files** submenu is enabled, you click it and a window (Figure 3.62) is displayed for you to specify the current project path that contains GBMM simulations results saved for linking WASP model (in the WASPLINK folder).

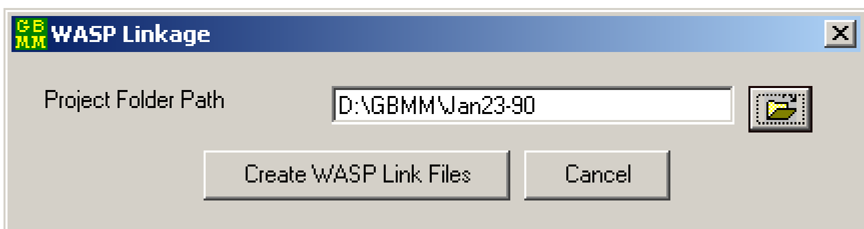


Figure 3.62. WASP linkage window.

Click **Create WASP Link Files** in the WASP Linkage window, and the GBMM interface converts the simulation results to WASP input files, e.g., BOUND.txt, FLOW.txt, LOAD.txt, NETWORK.WNF, and SEGMENT.txt in the WASPLINK folder. The GBMM interface displays a message (Figure 3.63) upon the completion of creating the link files.

Figure 3.63. Message displayed after WASP linkage files are created.

Create WhAEM Link Files

If **Create WhAEM Link Files** submenu is enabled, you click it and a WhAEM Linkage window (Figure 3.64) is displayed for you to specify the current project path that contains GBMM simulations results saved for linking WhAEM model (in the WhAEMLINK folder). You need to specify the appropriate spatial projection and an UTM zone for your study area. Click **US Zones** to display a map (Figure 3.65) and find your UTM zone. To export stream elevation data for WhAEM, you must provide a sampling distance (in meters) for GBMM to trace the elevation data along all the streams in the study area. The sampling distance must be large than the DEM resolution used in the project.

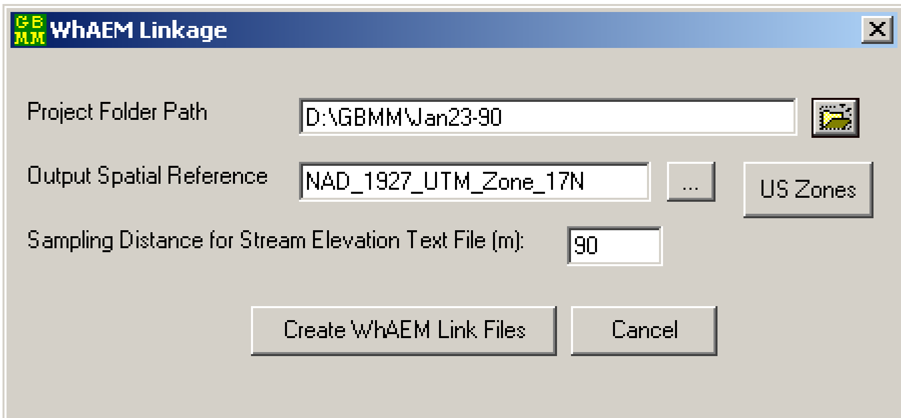


Figure 3.64. WhAEM Linkage window.

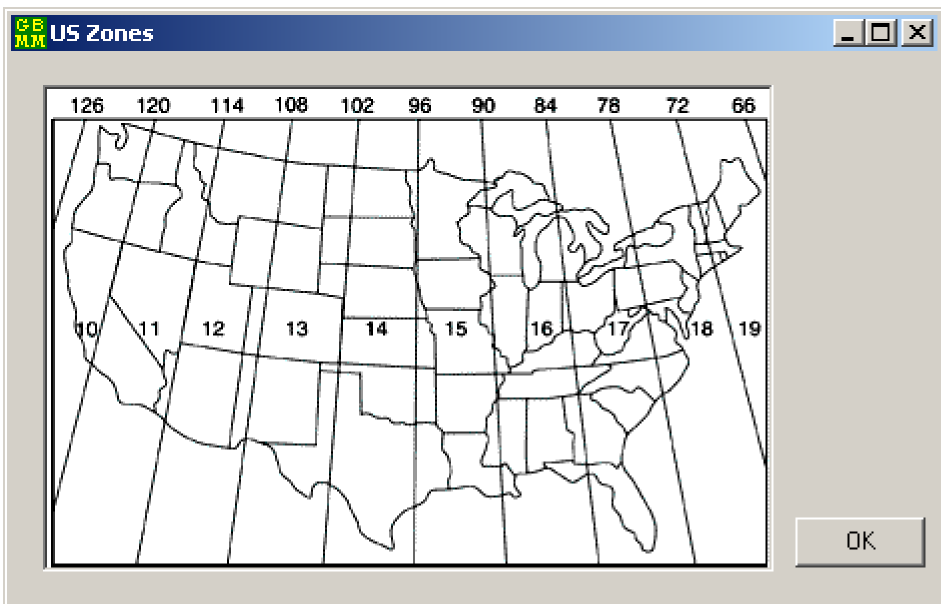


Figure 3.64. An UTM zone map for conterminous USA.

Click **Create WhAEM Link Files** in the WhAEM Linkage window, and the GBMM interface converts the simulation results to WhAEM input files, e.g., Elev.tx and Recharge*.tif (geo-referenced TIFF) in the WhAEMLINK folder. The GBMM interface displays the following message upon the completion of creating the link files:

Created geo-referenced tif and stream elevation files in [your project]\WhAEMLINK folder.

3.14 Link GBMM to WCS

The GBMM can import three data layers from WCS (see Section 3.15): (1) a WCS soil moisture grid, (2) a WCS soil mercury concentration grid, and (3) WCS watershed outlets.

It is assumed that you have built both WCS and GBMM projects for the same study area using the same datasets and same projection (See Table 2.1). In GBMM, you need to perform the first two steps in the main menu (see Sections 3.3 and 3.4) before importing WCS data layers.

- To import WCS soil moisture grid, click **Define Input** > **Hydrology/Hydraulic Simulation Input.** In the first tab of Hydrology and Hydraulic Input window (Figure 3.65), select the second option for importing the initial soil moisture content. Use the navigation button to find and load the WCS soil moisture grid.

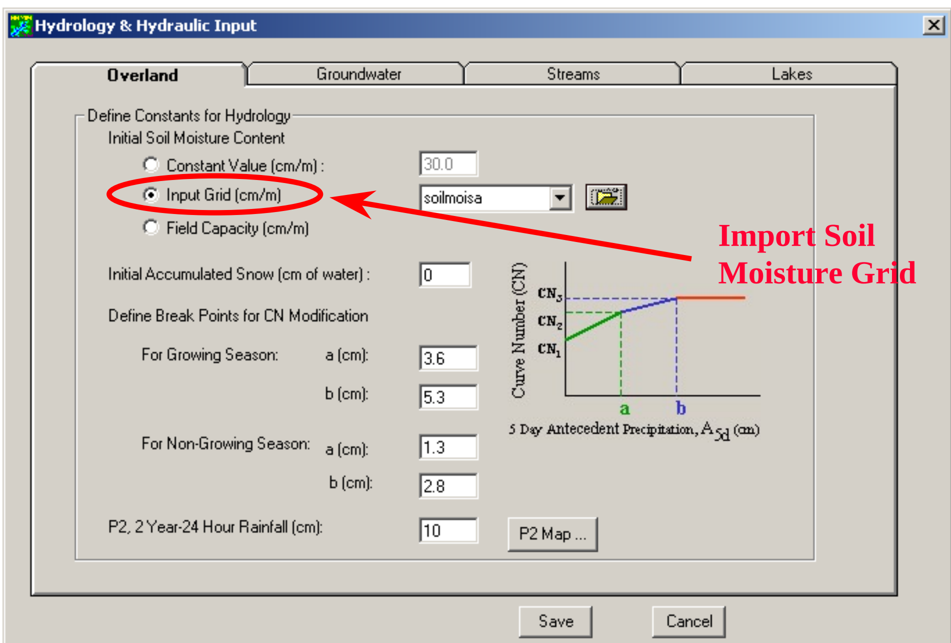


Figure 3.65. Import WCS soil moisture grid.

- To import WCS soil mercury concentration grid, click **Define Input** > **Mercury Simulation Input.** In the first tab of Mercury Input window (Figure 3.66), select the second option for importing the initial soil mercury concentration. Use the navigation button to find and load the WCS soil mercury concentration grid.
- Perform the **Process Input Grid** step and then import WCS watershed outlets. To import WCS watershed outlets, use the **Add Data** button to add the WCS outlets as a point theme and name it as "assesspoints". Click the **Delineate Watershed** menu to delineate watersheds on the basis of WCS outlets (Figure 67).

Once you have the three WCS layers imported in GBMM project and delineate the watersheds on the basis of WCS outlets, you can continue to work on the steps of **Create GBMM Input File** (see Section 3.10) and **Run GBMM model** (see Section 3.11). Upon the completion of simulation, the GBMM exports three data layers for linking WCS: (1) Soilwater.txt (grid in text) in MERCURYOUT folder, (2) SoilMercury.txt (grid in text) in MERCURYOUT folder, and (3) subwateshed shape files in the DATA folder of your current project. To convert grids in text format to the WCS format, you need to use the **Convert ASCII to Grid** tool (Section 3.16) in the GBMM Interface toolbar.

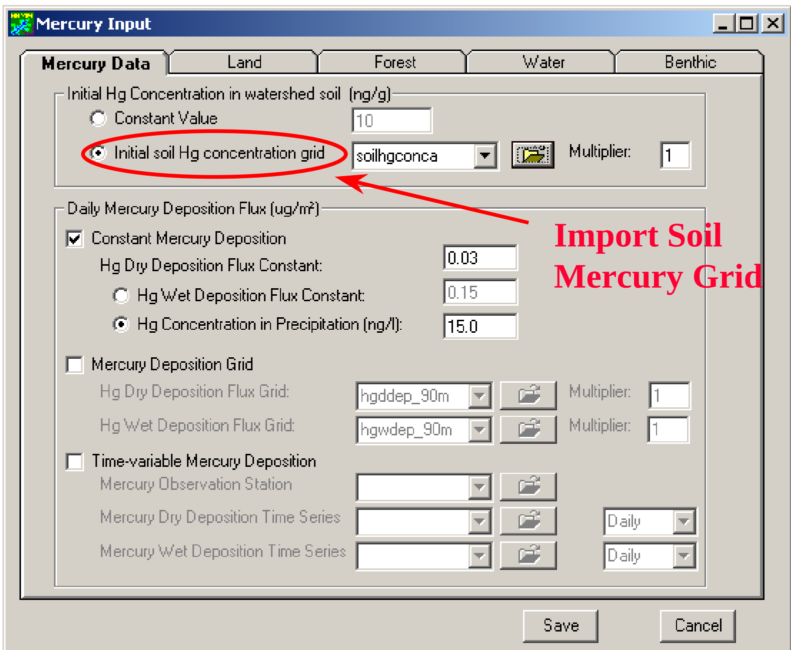


Figure 3.66. Import WCS soil mercury concentration grid.

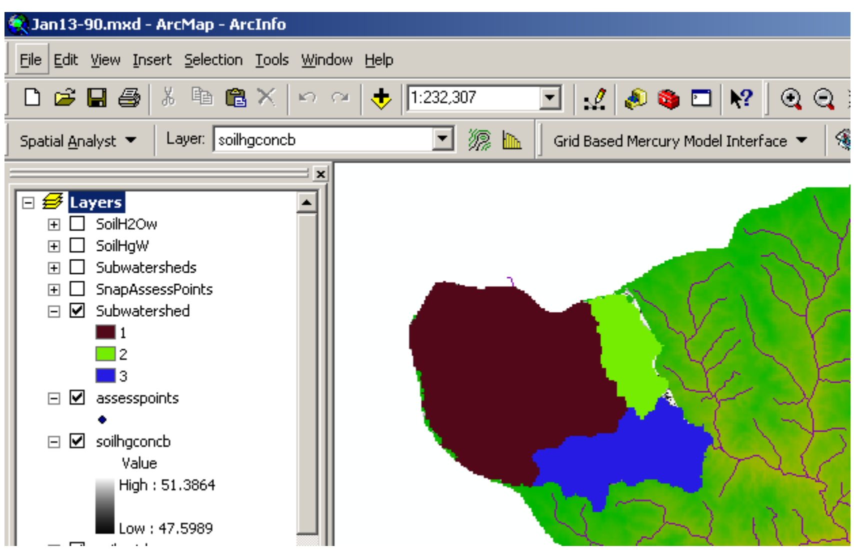


Figure 3.67. An example of subwatersheds delineated on the basis of imported WCS outlets.

3.15 Link WCS to GBMM

The WCS MLM (see Section 1.1) can import three data layers from GBMM: (1) a GBMM soil moisture grid, (2) a GBMM soil mercury concentration grid, and (3) a GBMM watershed boundary.

It is assumed that you have built both WCS and GBMM projects for the same study area using the same datasets and same projection (See Table 2.1). In WCS interface, you need to load and turn on the WCS MLM extension first. (*An updated WCS MLM extension, wcs_mercury23.avx is distributed in GBMM installation package. After installation, WCS MLM extension is installed in the GBMM\ETC folder with two sample mercury deposition time series files. You need to copy the WCS extension file to the WCS\etc folder so that the WCS interface can load the extension.*)

- To import the subwatesheds shape file (in GBMM\[your project]\DATA folder), use the WCS **Add Theme** button to add GBMM subwatersheds shape files to the WCS interface (Figure 3.68)

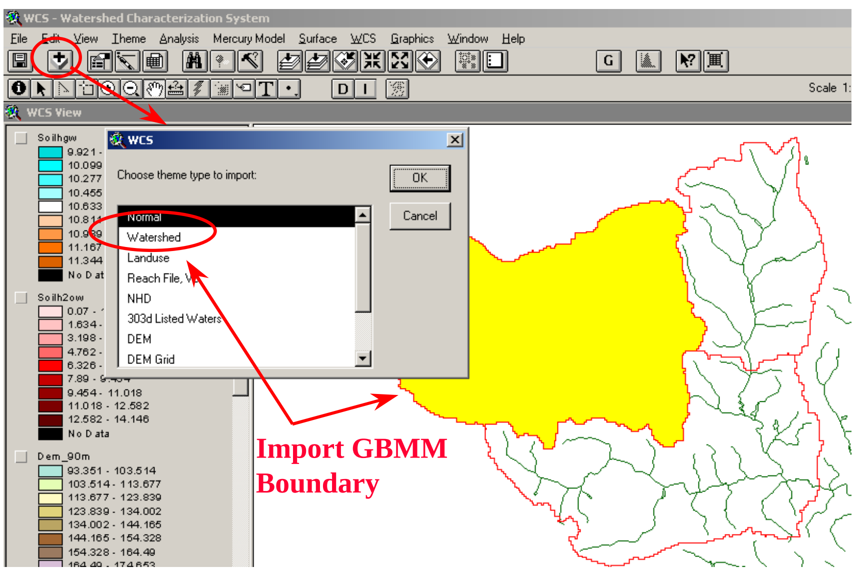


Figure 3.67. Import GBMM watershed boundary to WCS.

- In the WCS MLM's **Calculate Hydrology** step, you can import GBMM soil moisture grid. In the Calculate Hydrology window (Figure 3.68), select the **Use Existing Soil Moisture Content Grid** option and navigate to a folder with the soil moisture grid, e.g., GBMM\[your project]\MERCURYOUT folder, and load the grid (must be converted from original ASCII file, see Section 3.16).
- To import GBMM soil mercury concentration grid, you can use the option in the WCS MLM's **Calculate Mercury Concentration and Load** step. In the Calculate Mercury Concentration and Load window (Figure 3.69), select the **User Supplied Grid** in the Base Soil Mercury Concentration section. Navigate to a folder with the soil mercury concentration grid, e.g., GBMM\[your

project]\MERCURYOUT folder, and load the grid (must be converted from the original ASCII file, see section 3.16).

Once you have imported the three GBMM data layers, you can use WCS's simple algorithm (annual average calculation) to estimate soil mercury concentration for a long time period.

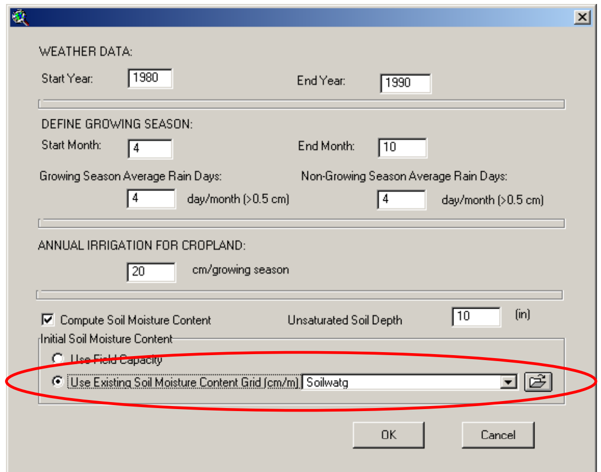


Figure 3.68. WCS MLM's Calculate Hydrology interface.

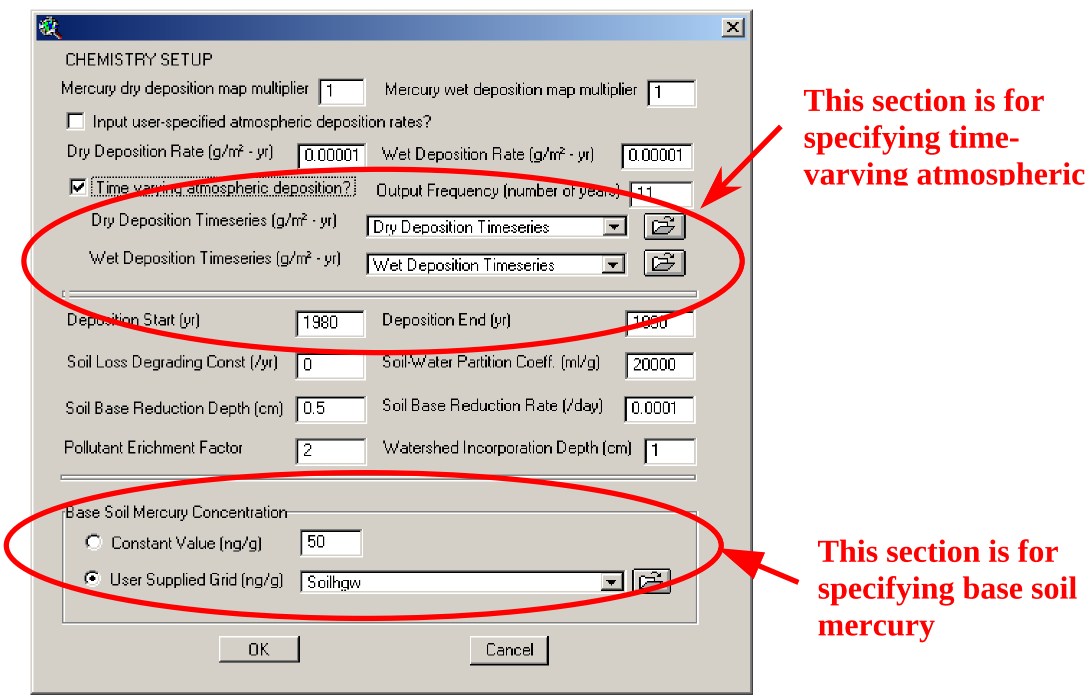


Figure 3.69. WCS MLM's Calculate Mercury Concentration and Load interface. This interface can be used to specify the base soil mercury concentration as a constant value or as an imported concentration grid. This interface also shows a section to specify mercury atmospheric deposition input. Annual wet and dry deposition rates can be supplied in two dbf tables respectively (see Appendix E).

Upon the completion of calculations in WCS, you can export three data layers for linking GBMM:

- To export watershed outlets, you can click the **Export Outlets for GBMM** menu from the WCS MLM interface (Figure 70). (Watershed outlets can be created using the WCS manual delineation tool or the automatic delineation tool.) When WCS starts to export the outlets theme, it asks you to specify a spatial projection and projection parameters. If you use the default WCS projection, you can accept the parameter values in Figure 71. The default name for watershed outlets exported to GBMM is "assesspoints" (see Section 3.14).

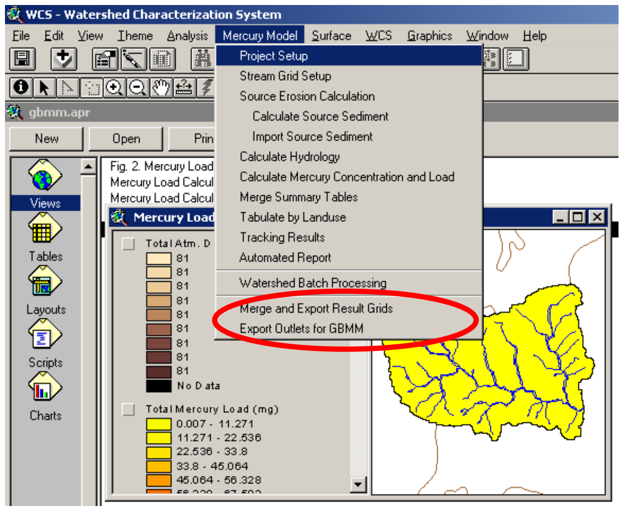
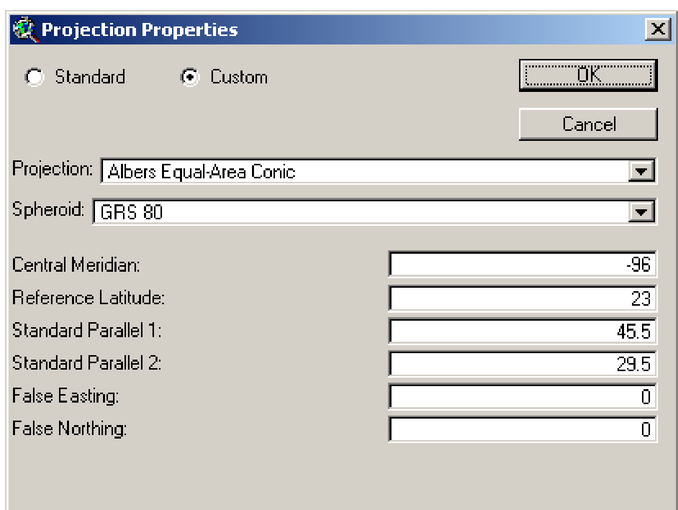


Figure 70. WCS MLM interface menu. **Export Outlets for GBMM** and **Merge and**



Export Results Grids are two menus for exporting data to link GBMM.

Figure 71. The default spatial projection for exporting WCS outlets and grids to GBMM.

- To export soil moisture grid, click the **Merge and Export Results Grids** from the WCS interface menu (Figure 70) and a Merge Output Grid dialog box (Figure 72) asks you to select a soil moisture grid to export. If you have soil moisture grids for multiple subwatersheds in your WCS projects, WCS MLM will merge the grids from all the subwatersheds and then export the merged grid to GBMM. You need to specify a folder and give a name to the merged grid.

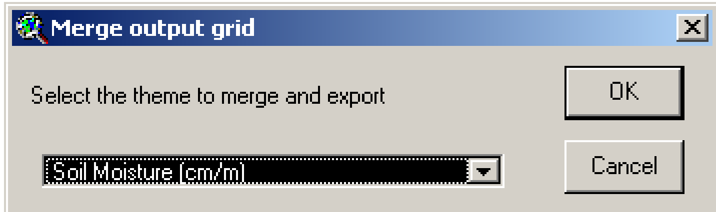


Figure 72. Dialog box for merging and exporting soil moisture grids to GBMM.

- To export soil mercury concentration grid, click the **Merge and Export Results Grids** from the WCS interface menu (Figure 70) and a Merge Output Grid dialog box (Figure 73) asks you to select a soil mercury concentration grid to export. If you have soil mercury grids for multiple subwatersheds in your WCS projects, WCS MLM will merge the grids from all the subwatersheds and then export the merged grid to GBMM. You need to specify a folder and give a name to the merged grid.

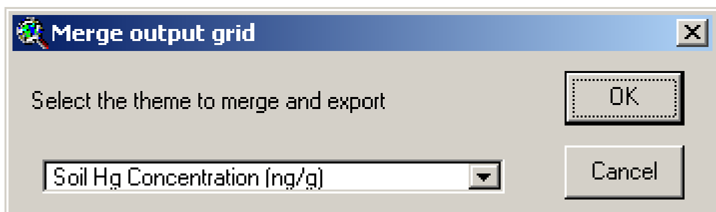


Figure 73. Dialog box for merging and exporting soil mercury concentration grids to GBMM.

To import the WCS grids and outlets to GBMM, see Section 3.14.

3.16 Convert Ascii to Grid

GBMM C++ module can only export result grids in text format (ASCII format). To convert ASCII grid to the ArcGIS (or ArcView) binary format, you can use the **Convert ASCII to Grid** tool from the GBMM toolbar. Once ASCII files are converted to binary grid format, you can load them into the WCS or the GBMM GIS interface easily and quickly.

After you complete running the GBMM C++ simulation module, for example, two text grids are written in the MERCURYOUT folder of your project: SoilMercury.txt and Soilwater.txt.

- To convert these files, click the  tool button.
- In the Convert ASCII to Raster window (Figure 74), navigate to the MERCURYOUT or other folders to load the ASCII text file.
- Specify the output folder and make sure that the output grid name has less than 8 characters (to ensure the stability of ArcGIS applications).

- Click the **Convert** button and start the converting process.
- Upon the completion of the conversion, a message is displayed as shown in Figure 75.

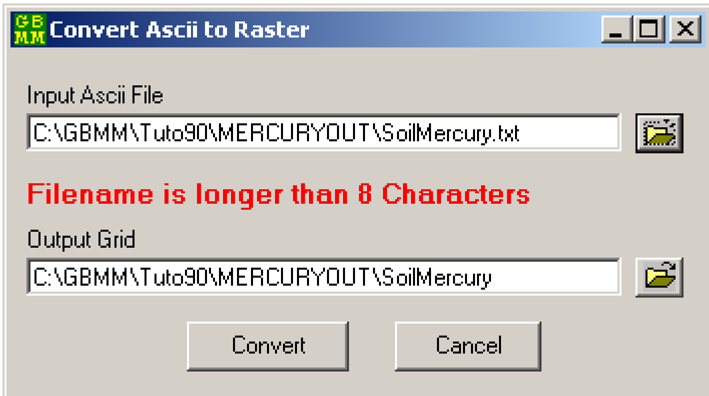


Figure 74. The Interface to convert grid files: ASCII text format to ArcGIS binary format.

Figure 75. The message shown after converting grid files from ASCII to ArcGIS binary format.

4. Model Calibration Case Study

The case study is to demonstrate the capabilities and application of GBMM 2.0.

4.1 Case Study Area

The Brier Creek watershed (HUC 03060108) is selected as the case study area. As shown in Figure 4.1, the Brier Creek watershed is located on the east side of Georgia, and drains to the Savannah River, which flows along the South Carolina-Georgia border. The total area of the watershed is 856 square miles. Based on the 1992 Multi-Resolution Land Characteristics (MRLC) data, the dominant land uses are forest (46.7%) and agricultural land (32.2%). The transitional and residential areas take approximately 8.3% of the total watershed area, and wetlands occupy 11.5%. The detailed land use distribution is listed in Table 4.1, and Figure 4.2 presents the land use map of the Brier Creek watershed.

Table 4.1. The land use distribution in the Brier Creek watershed (1992 MRLC)

Land Use/Cover	**Area (sq. mile)**	**Area % of Total**
Open Water	4.0	0.5
Low Intensity Residential	4.6	0.5
High Intensity Residential	0.9	0.1
High Intensity Commercial	2.5	0.3
Bare Rock/Sand/Clay	0.7	0.1
Quarries/Strip Mines/Gravel Pits	4.1	0.5
Transitional	63.4	7.4
Evergreen Forest	206.3	24.1
Deciduous Forest	114.5	13.4
Mixed Forest	79.5	9.3
Other Grasses	0.6	0.1
Pasture/Hay	22.7	2.6
Row Crops	253.2	29.6
Woody Wetland	96.3	11.2
Herbaceous Wetlands	3.0	0.3
Total	**856.3**	**100.0**

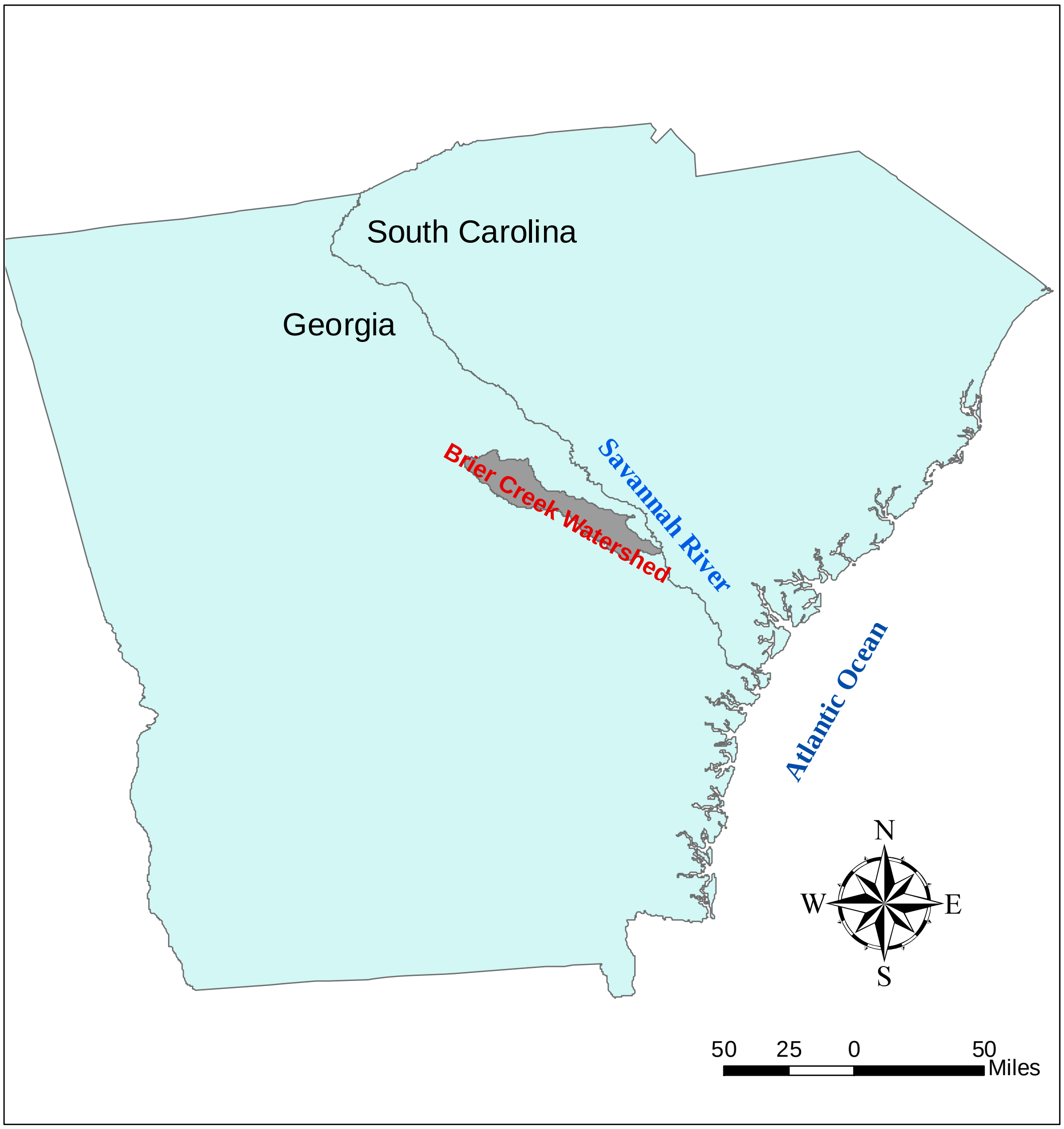


Figure 4.1. Location of the Brier Creek watershed

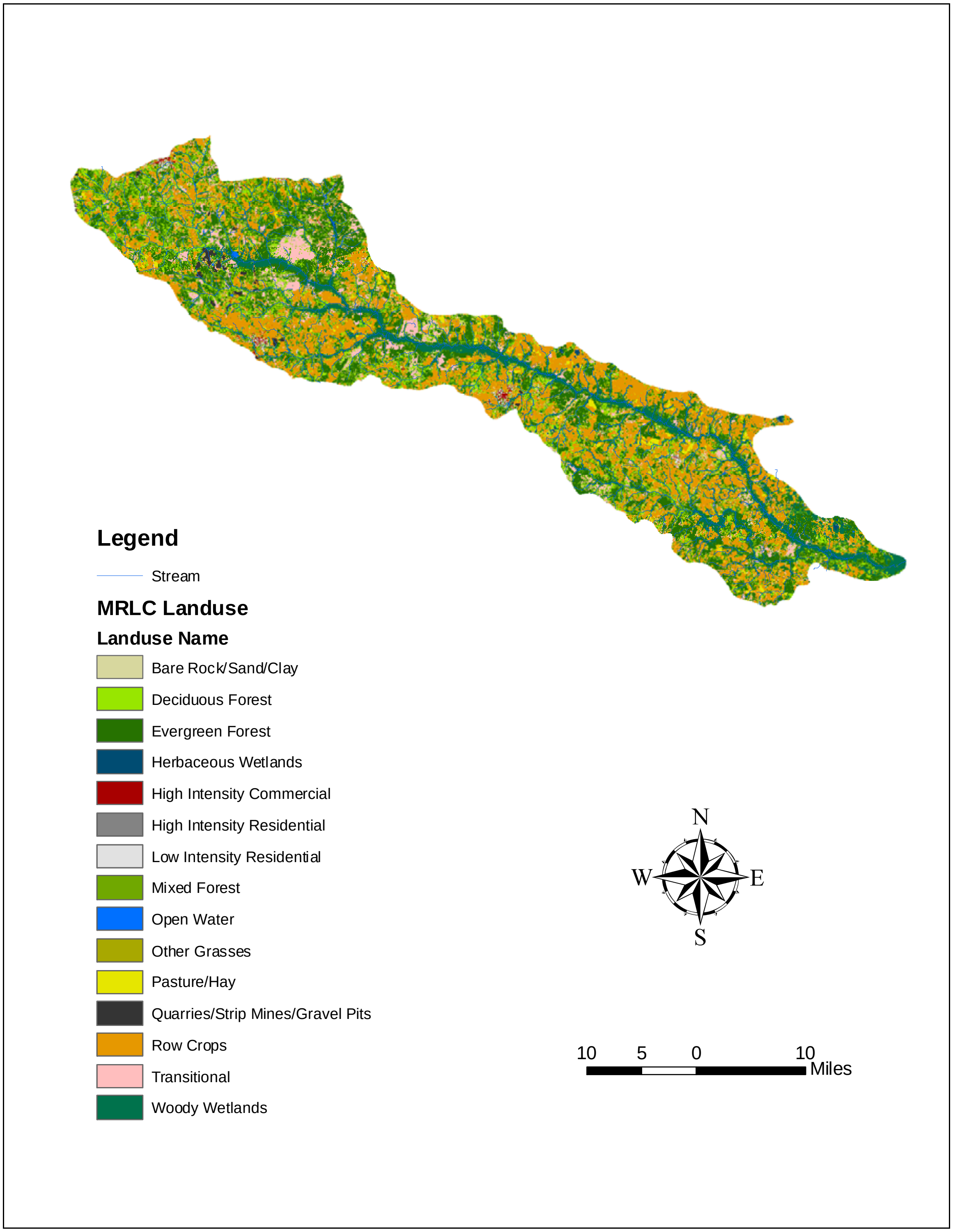


Figure 4.2. The Brier Creek watershed land use map

4.2 Data Collection

4.2.1 GIS Data

The following GIS data are collected and used in the Brier Creek case study.

- Land use: 90-meter resolution 1992 MRLC grid (see Section 2.4.1).
- DEM: 90-meter resolution USGS DEM grid (see Section 2.4.1).
- Soil: STATSGO (see Section 2.4.1).
- Stream and lake coverage: medium resolution National Hydrography Dataset (see Section 2.4.3)
- Climate stations: A point layer was created using the climate station long/lat information. Table 4.2 lists the station name, elevation, record period, and data coverage percentage for each station used in this case study.

Table 4.2. Climate Stations in or near the Brier Creek watershed

Station ID	Station Name	Elevation (ft)	Record Period (Coverage %)	
			Precipitation	Daily Temperature
090311	APPLING 2 NW	370	01/01/1961-12/31/2004 (99%)	01/19/1961-12/31/2004 (99%)
090495	AUGUSTA BUSH FIELD AP	132	07/01/1948-12/31/2004 (100%)	07/01/1948-12/31/2004 (100%)
095314	LOUISVILLE 1 E	322	07/01/1948-12/31/2004 (99%)	07/01/1948-12/31/2004 (99%)
098517	SYLVANIA 2 SSE	250	08/01/1948-12/31/2004 (23%)	06/01/1992-12/31/2002 (79%)
099141	WARRENTON	490	01/01/1930-12/31/2004 (99%)	01/01/1930-12/31/2002 (99%)
099194	WAYNESBORO 2 S	270	08/01/1948-12/31/2004 (91%)	08/01/1948-12/31/2002 (88%)

4.2.2 Other Data

<u>Climate Data</u>

Six NCDC climate stations in or near the Brier Creek watershed were selected. Figure 4.3 shows the station locations.

For each station, the daily precipitation, daily minimum and maximum temperature data were first extracted from the NCDC data CD, and then processed using MetADAPT to generate the required climate data file to run GBMM 2.0 (see Appendix B).

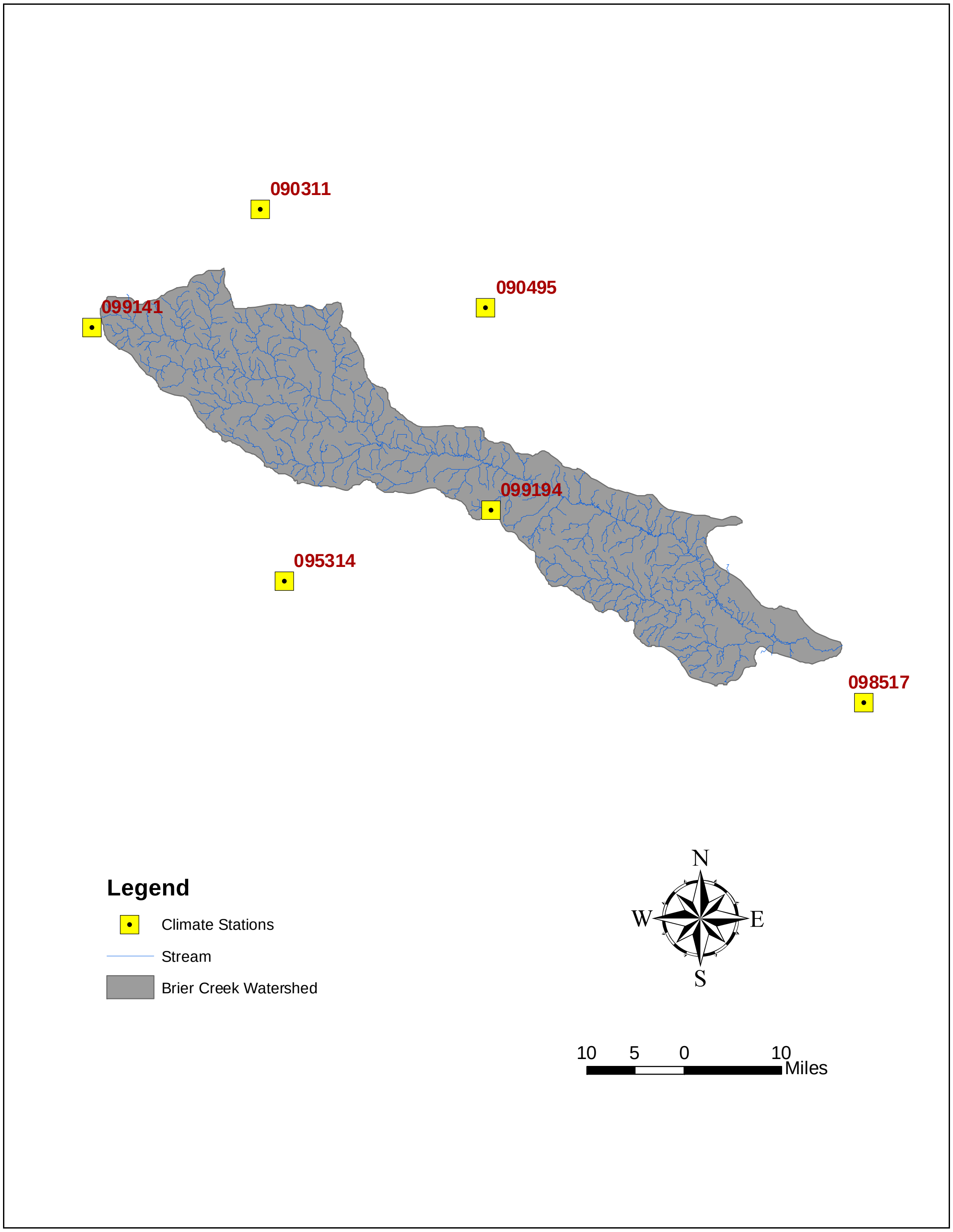


Figure 4.3. Climate stations in or near the Brier Creek watershed.

Mercury Deposition (Dry and Wet)

Figure 4.4 shows the locations of the Mercury Deposition Network (MDN, http://nadp.sws.uiuc.edu/mdn) stations near the Brier Creek watershed. The MDN, currently has over 35 sites, was formed in 1995 to collect weekly samples of precipitation, which are analyzed by Frontier Geosciences for total mercury. The objective of the MDN is to develop a national database of weekly concentrations of total mercury in precipitation and the seasonal and annual flux of total mercury in wet deposition. The data from four stations (i.e., SC03, SC05, SC19, and GA22) are retrieved and used in this case study. Table 4.3 lists the station ID, name, elevation, and monitoring starting and ending dates.

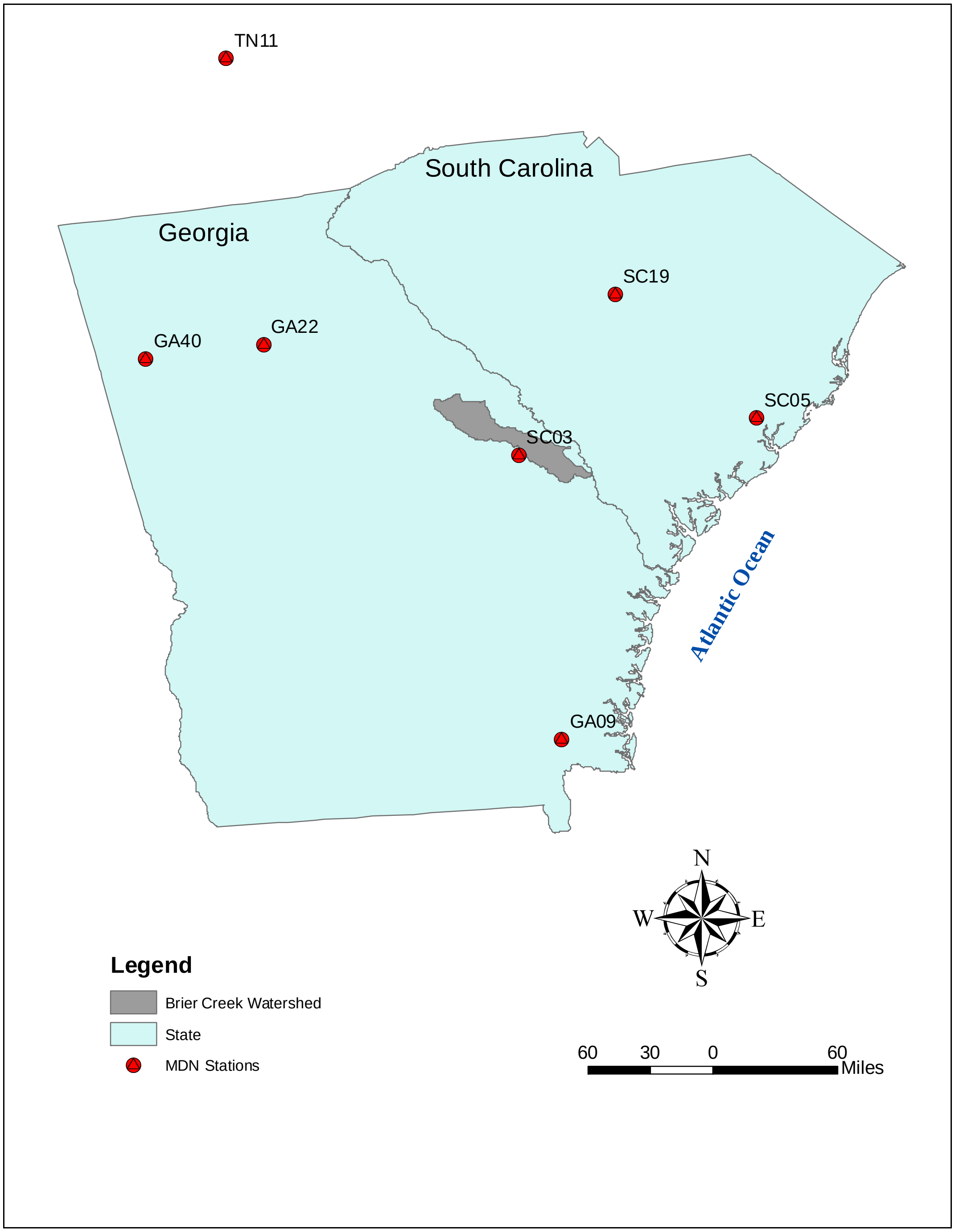


Figure 4.4. Mercury Deposition Network (MDN) stations near the Brier Creek watershed.

Table 4.3. The Mercury Deposition Network stations near the Brier Creek watershed

Station ID	Station Name	Elevation (ft)	Start Date	End Date
GA22	Jefferson Street	265	6/11/2002	6/29/2004
SC03	Savannah River	90	1/29/2001	1/21/2003
SC05	Cape Romain National Wildlife Refuge	0	3/2/2004	
SC19	Congaree Swamp	145	3/5/1996	

Based on the MDN data, the average mercury concentration in precipitation is 14.7 ng/l, and the dry deposition rate is 0.033 ug/m^2/day.

Flow Data

Continuous daily flow data from three USGS stations are collected. Figure 4.4 shows the station locations in the Brier Creek watershed. Table 4.4 lists the station ID, name, and record period available for the three stations.

Table 4.4. USGS flow stations in the Brier Creek watershed

USGS Station ID	Station Name	From	To
02197600	Brushy Creek near Waynesboro, GA	5/29/1958	9/30/2004
02198000	Brier Creek at Millhaven, GA	4/14/1937	9/30/2004
02198100	Beaverdam Creek near Sardis, GA	6/7/1986	10/1/2004

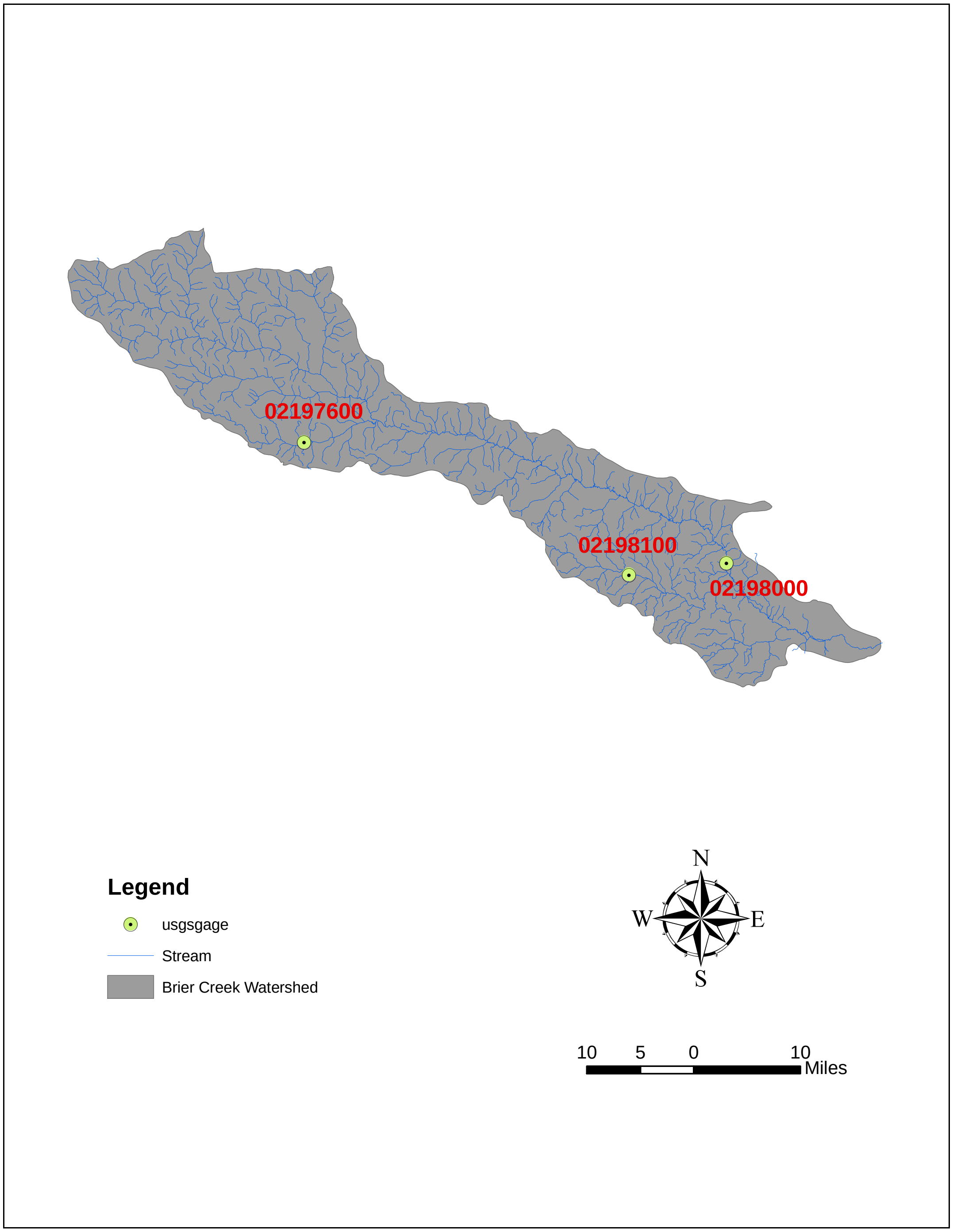


Figure 4.5. USGS flow stations in the Brier Creek watershed.

Available Mercury Monitoring Data

Based on the data collected by USEPA's Office of Research and Development during the summer of 2000, the average total mercury concentration in the Brier Creek watershed is 2.15 ng/l, the methylmercury concentration is 0.11 ng/l, and the fraction of methylmercury in water was about 5 percent (Payne, 2001).

Another sampling study was performed by USEPA Region 4 in June 2003. Water column and sediment samples were taken from the main stem of the Brier Creek (USEPA Region 4, 2004). The sampling locations are shown in Figure 4.6. The sampled water mercury concentration and sediment soil mercury concentration data are listed in Table 4.5.

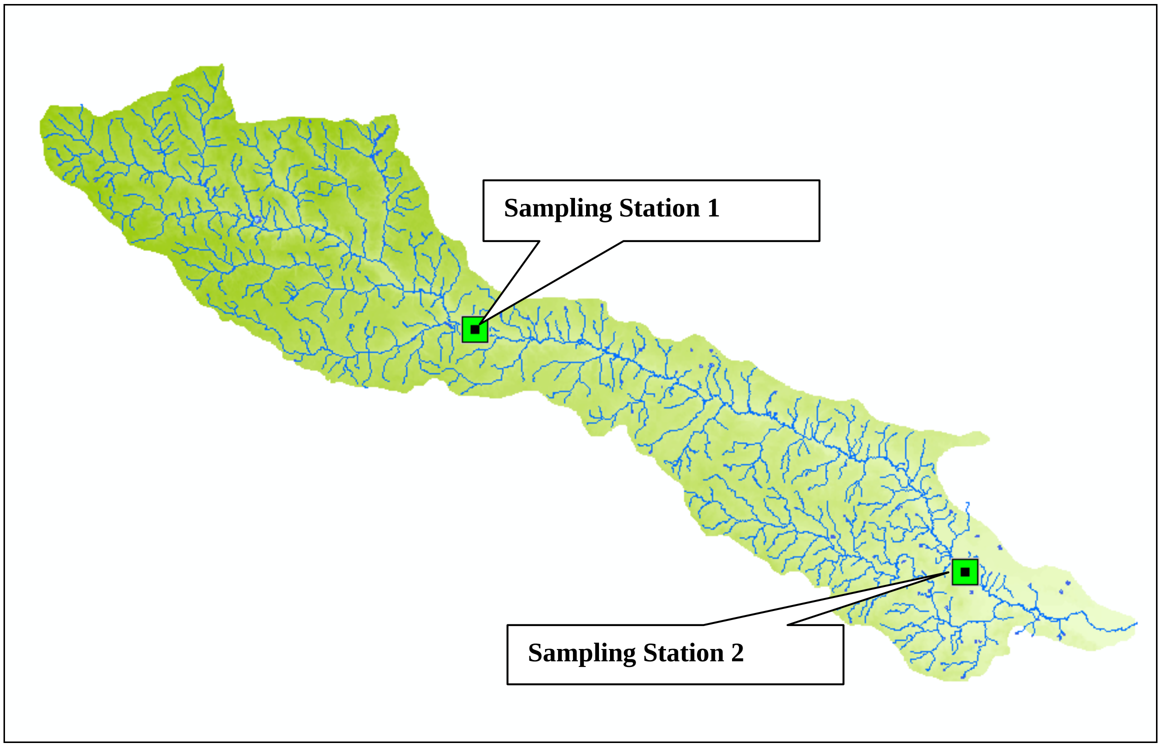


Figure 4.6. Mercury sampling locations in the Brier Creek watershed.

Table 4.5. The Brier Creek mercury monitoring data (June 2003).

Station	**Water Column Hg Conc. (ng/l)**			**Sediment/Soil Hg Conc. (ng/g)**	
	Total Hg	**Methyl-Hg**	**% Methyl-Hg**	**Sediment**	**Surface Soil**
Station 1	8.3	0.73	9%	37	130
Station 2	6.0	1.40	23%	6.4	75

<u>Groundwater Mercury Concentration</u>

No information is available on groundwater mercury concentration in the Brier Creek watershed. The default value of 0.00001 ng/l was used in the case study.

4.3 Model Setup and Calibration

Using the GIS data described in section 4.2.1 and following the step-by-step instructions described in Section 3, eleven sub-watersheds are delineated, and the assessments points are placed at the outlets of lakes that have surface area larger than 120,000 square meters, the locations of USGS flow gages, and the locations of water quality monitoring stations. The subwatershed layout is shown in Figure 4.7.

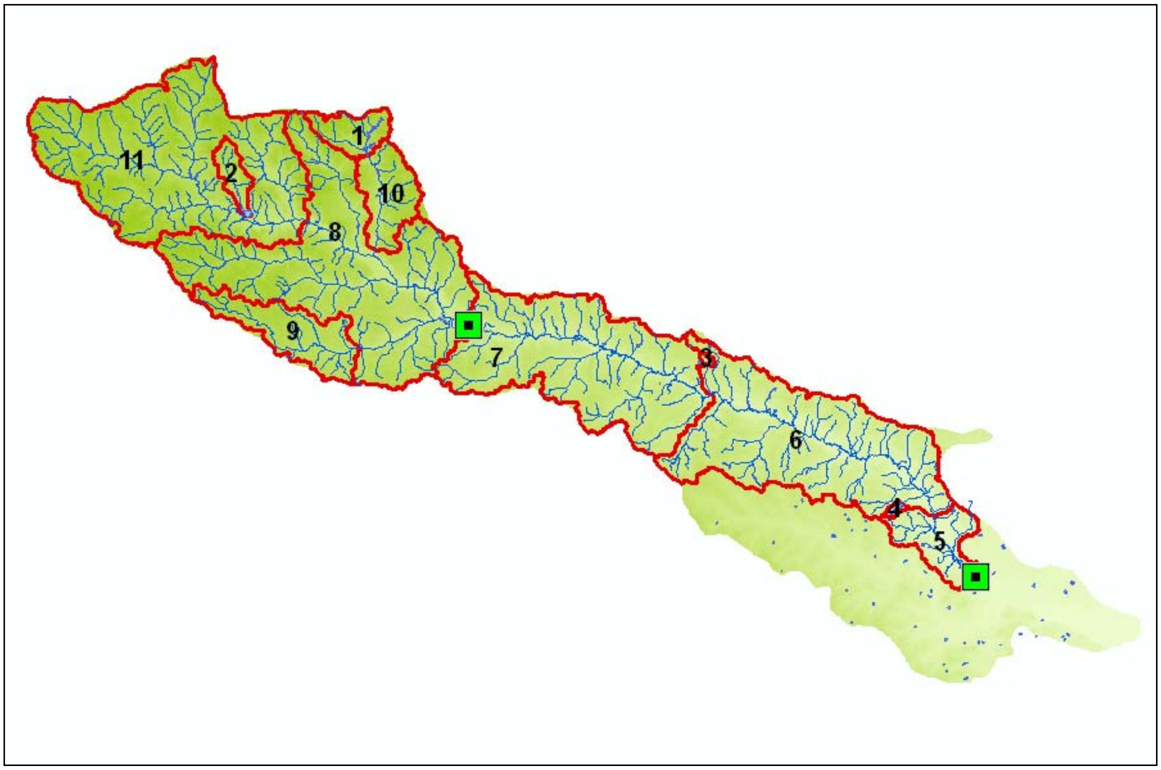


Figure 4.7. Subwatershed delineation of the Brier Creek watershed in GBMM.

4.3.1 Model Hydrology Calibration

The daily stream flow data collected at the USGS gage 02198000 (Figure 4.5) was used in the hydrology calibration. The hydrology calibration was carried out in two steps. The first step is to obtain a good match of the overall simulated flow volume with the observed value. The overall hydrologic/flow balance is sensitive to groundwater deep seepage coefficient, unsaturated zone depth, soil depth to bedrock (shallow groundwater layer depth), and the CN modification breakpoint values. Using a groundwater deep seepage coefficient of 0.025 (1/day), unsaturated zone depth of 1 meter, soil depth to bedrock of 1.5 meter, and CN modification five day precipitation parameter a=1.5, b=7 for growing season and a=1.0, b=5 for non-growing season, the simulated overall annual average flow volume at the outlet of subwatershed 6 (i.e., location of USGS gage 02198000), based on a five year (1999-2003) simulation, is 344.8 million cubic meter, which matches very well with the observed value of 348.5 million cubic meter (Figure 4.8). Figure 4.9 shows the water balance of the surface and unsaturated soil layer. It illustrates that, of the water leaving the surface and unsaturated soil layer, 58 percent is lost due to evapotransporation, 22 percent becomes runoff, and the rest 20 percent percolates into groundwater layer.

The second step is to calibrate the hydrograph (peak flow rate), which is sensitive to groundwater recession coefficient, unsaturated zone depth, soil depth to bedrock, and most important: the calculated flow travel time. In this case study, Manning's coefficient *n* was used to dictate the travel time. Figure 4.10 shows the simulated flow time series comparing to the observed flow data at the USGS gage 02198000 for the time period of 10/1/2002 – 9/30/2003. The simulated flow time series compares reasonably well with the observed values, especially considering the uncertainty of precipitation data for a large watershed like the Brier Creek watershed.

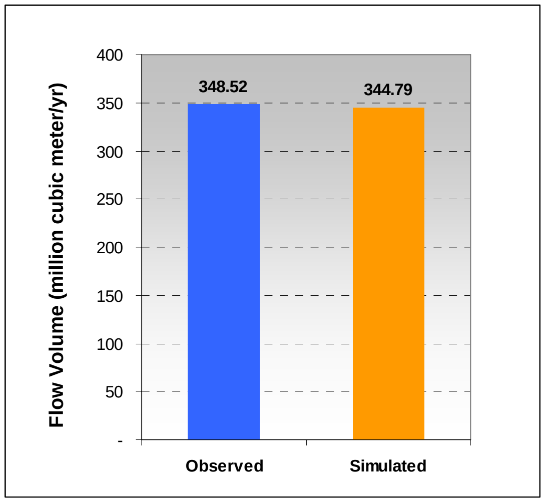


Figure 4.8. Simulated and observed annual average flow volume at the outlet of subwatershed 6 (i.e., USGS gage 02198000).

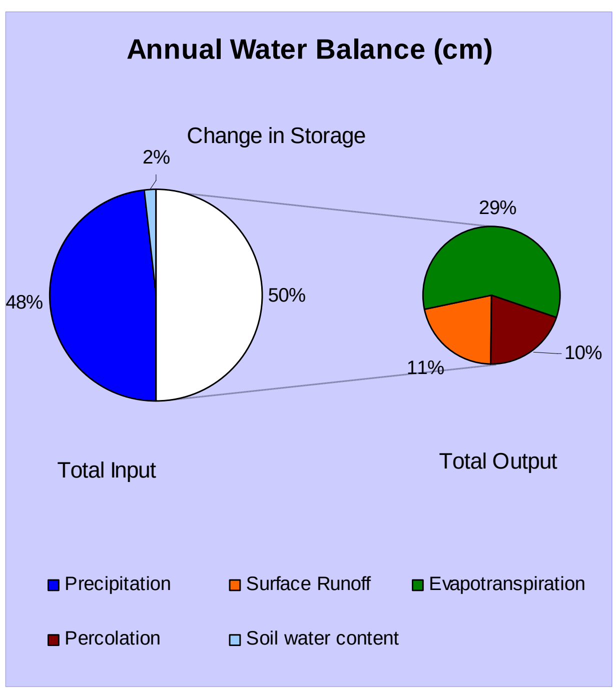


Figure 4.9. The annual water balance of the surface and unsaturated soil layer.

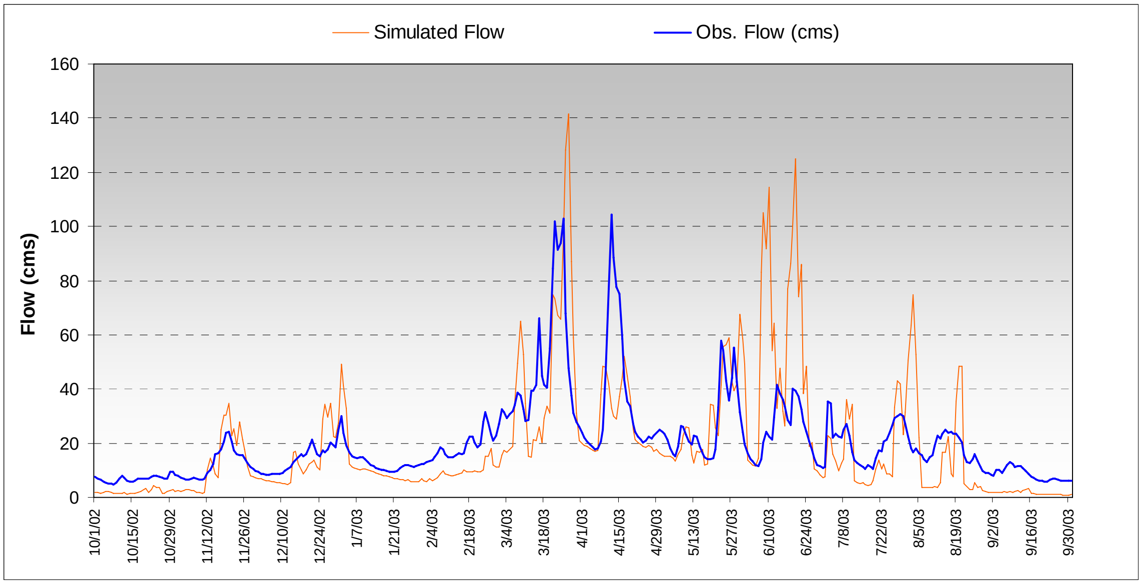


Figure 4.10. Simulated and observed stream flow time series for the hydrologic year 10/1/2002-9/30/2003 at USGS gage 02198000.

4.3.2 Sediment Calibration

Limited sediment concentration data were found for Brier Creek watershed, the sediment database available from the USGS website listed the daily values of suspended sediment concentration for the period of 1/10/1963 – 9/30/1964. The average observed sediment concentration is 22 mg/l.

The simulated average sediment concentration for Brier Creek at USGS Gage 02198000 is 26 mg/l (simulation period of 1/1/1999 – 12/31/2003) using the value of 1.0 for the sediment delivery calibration coefficient (α) and value of 0.003 for sediment delivery routing coefficient (β).

4.3.3 Mercury Calibration

For mercury simulation, the parameters specified for the case study are:

- Atmosphere dry deposition rate: 0.033 ug/m^2/day
- Mercury concentration in precipitation: 14.7 ng/l
- Initial soil mercury concentration: 100 ng/g

For all the other parameters, default values are used. Table 4.6 lists the simulated annual average total and methylmercury concentrations for the Region 4 sampling station 1 (outlet of the subwatershed 8, Figure 4.6 and Figure 4.7) and station 2 (outlet of the subwatershed 5) for the simulated time period of year 1999-2003. The simulated values compare well with the observed data collected in years 2000 and 2003 (see Available Mercury Monitoring Data in Section 4.2.2).

Table 4.6. Simulated annual average total and methylmercury concentrations for the Region 4 sampling station 1 (outlet of subwatershed 8) and station 2 (outlet of subwatershed 5).

	Station 1 (subwatershed 8)		**Station 2 (subwatershed 5)**	
Year	**Total Hg (ng/l)**	**Methyl-Hg (ng/l)**	**Total Hg (ng/l)**	**Methyl-Hg (ng/l)**
1999	4.1	0.26	2.7	0.17
2000	3.8	0.24	2.2	0.14
2001	3.2	0.2	2.2	0.14
2002	4.4	0.28	2.8	0.18
2003	3.8	0.24	2.4	0.15
Average	3.9	0.24	2.5	0.16

4.4 Conclusions

This case study demonstrates that input files for GBMM 2.0 can be collected from many public data sources. The model can be calibrated reasonably well to match the observed flow, sediment, and mercury concentration data. Once the hydrology and sediment is calibrated, the mercury simulation results are surprisingly good comparing to the limited observed data, requiring only the minimum changes of the default parameter values in the mercury simulation module.

5. References

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——. 1993b. The Water Quality Analysis Simulation Program, WASP5. Part B: The WASP5 input dataset. U.S. Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory, Athens, Georgia.

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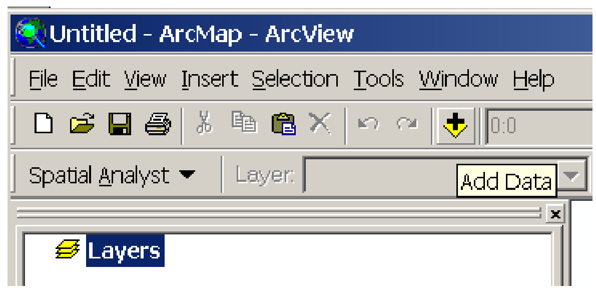
Appendix A. Basic ArcGIS Operation Guide

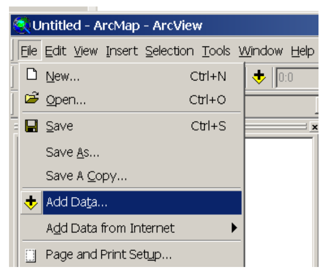
A.1 How to Add a Raster/Vector Layer or a Data Table to the Map

Choose Add Data button 

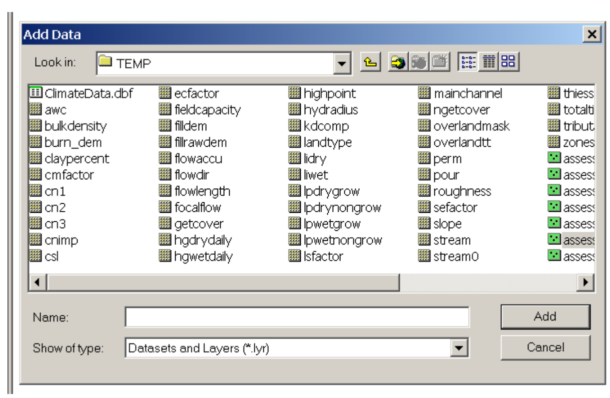


Or

Choose from the menu option > File > Add Data…



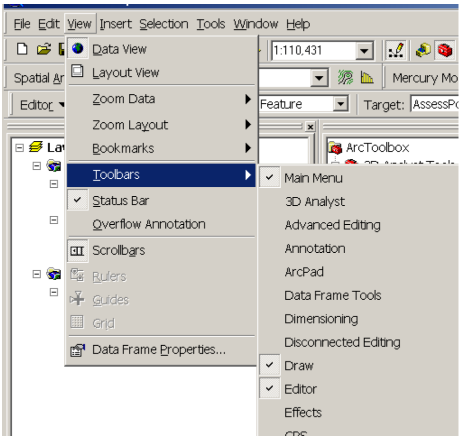
Navigate to the file location. Click on the Add button after you choose a shape file or feature class or raster file or a data table. The selected layer is added to the map. Check or uncheck the raster/vector layers in the Layers panel to make them visible or invisible in the map window.



For more information about adding Layers, open ArcGIS Desktop Help by clicking on Help menu or by pressing F1. Choose Index tab on the left panel.

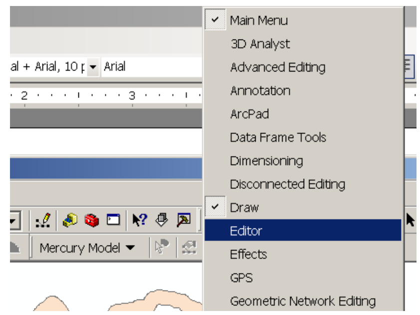
Suggested Keywords: Layers, adding to maps
Rasters, adding to maps
Data, adding to maps

A.2 Editing Table: How to Edit Value in a Table

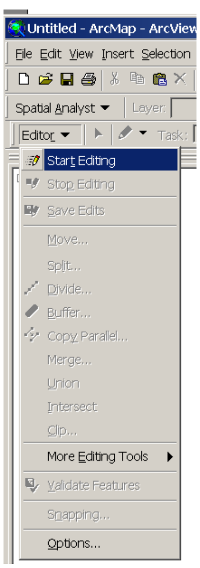


Choose View (Menu) >Toolbars >Editor

Or



Right click on the menu or tool bar to reveal a list of toolbars that can be activated. Click "Editor"

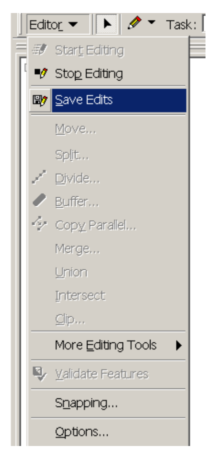


Click the dropdown arrow from the "Editor" toolbar. Choose "Start Editing"

To edit a raster or vector layer, select the desired layer from the layers panel, right click and choose "Open attribute table" from the menu list.

To edit a data table from the map, choose "Source" tab from the bottom of the layers panel. Click on the desired data table and right click to get a list of menu options. Choose "Open" option.

Choose the desired table column and record. Modify the values.



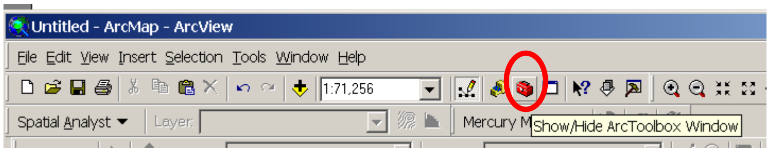
After modifying all the desired fields and records, choose "Save Edits" option from the "Editor" menu. Periodically using "Save Edits" is a good practice. To terminate editing session, choose "Stop Editing" from Editor toolbar menu.

For more information about editing tables, open ArcGIS Desktop Help by clicking on Help menu or by pressing F1. Choose Index tab on the left panel.

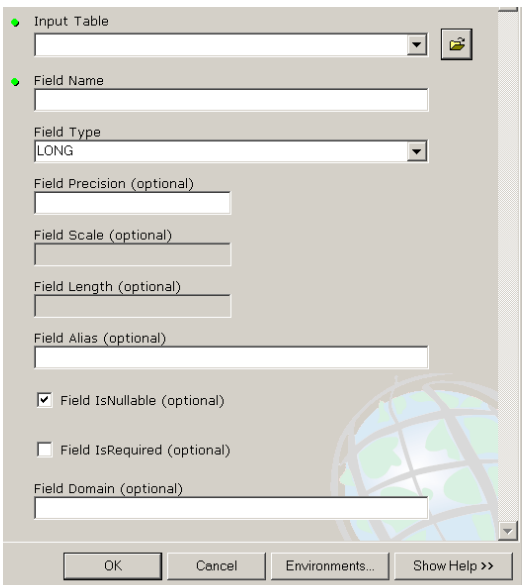
Suggested Keywords: editing, attributes

A.3 Editing Table: How to Add a New Column (Field) to a Table

Click on the ArcToolbox  button.



Choose Data Management Tools > Fields> Add Field. Double Click "Add Field"



Select the Data Table or layer to which you will add a field in the Input Table field. Add a Field Name and Field Type. Specify the optional field properties according to the needs. Click **OK** to create a new field.

Tip: To add values to the new field, follow "Editing Table: How to Edit Value in a Table"

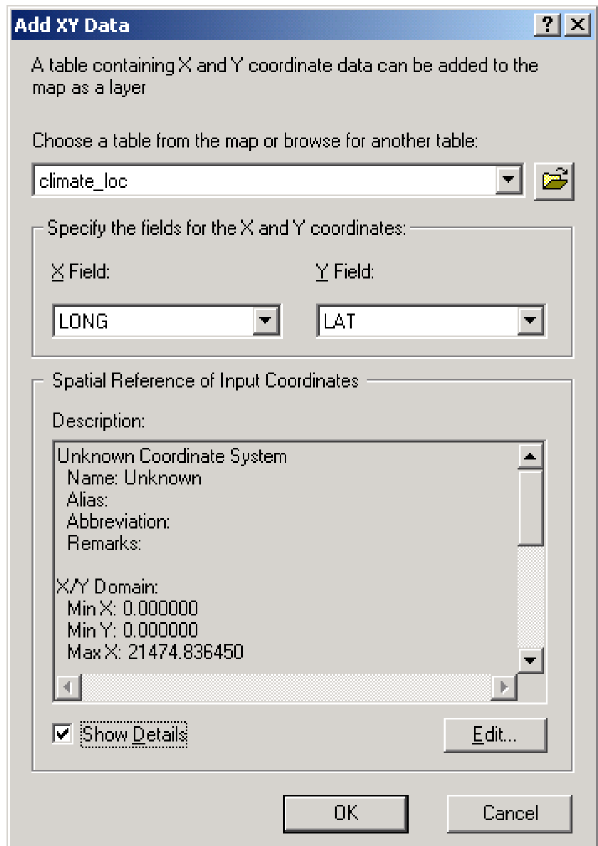
For more information about adding fields to a table, open ArcGIS Desktop Help by clicking on Help menu or by pressing F1. Choose Index tab on the left panel.

Suggested Keywords: Add Field

A.4 How to Add X,Y Coordinate Data to a Map

In addition to data sources, such as a shapefile, you can also add tabular data that contains geographic locations in the form of x,y coordinates to your map window.

X,y coordinates describe discrete locations on the earth's surface such as the location of weather stations or the points where soil samples were collected. You can easily collect x,y coordinate data using a global positioning system (GPS) device and make a table in a simple text format (two data columns contain x,y coordinates).



To add a table of x,y coordinates to your map, the table must contain two fields: one for the x-coordinate and one for the y-coordinate. The values in the fields may represent any coordinate system and units such as latitude and longitude or meters. The fields must be numeric, otherwise they will not be listed.

Below are steps to add a table with x,y coordinates to a map:

1. Click the Tools menu and click Add XY Data.

2. Click the table dropdown arrow and click a table that contains x,y coordinate data. If the table is not on the map, click the Browse button to access it from disk.

3. Click the X Field dropdown arrow and select the field containing x-coordinate values.

4. Click the Y Field dropdown arrow and select the field containing y-coordinate values.

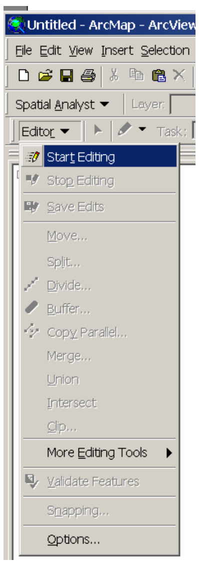
5. Click Edit to define the coordinate system and units represented in the x and y fields.

The x,y coordinates will be automatically transformed to match the coordinate system of the data frame.

6. Click OK.

Tip
To add x,y data, your coordinates need to be in the projected units or decimal degrees.

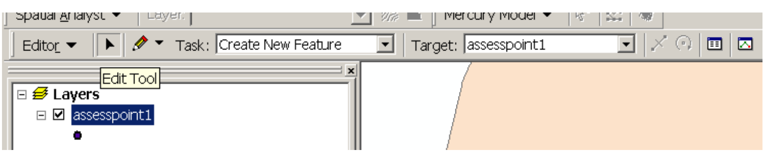
A.5 How to Delete Points or Move Their Locations Using ArcEditor



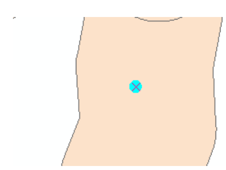
Right click on the main menu or tool bar to reveal a list of toolbars that can be activated. Click "Editor"

Click Editor option from the "Editor" toolbar. Choose "Start Editing"

Choose the layer to be edited in the Target.



Choose "Edit Tool" from Editor Toolbar menu



Moving a feature: Click on the desired feature, and it will be highlighted. Drag and release the feature to the desired location.

Deleting a feature: Click on the feature to select after activating the "Edit Tool". Hit Delete Key to delete the selected feature.

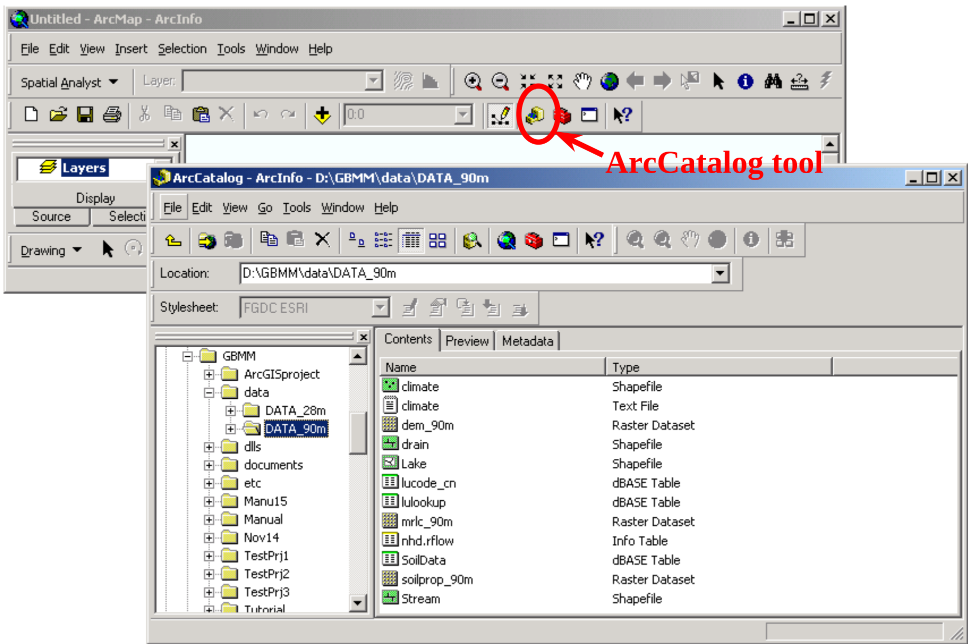
Choose "Save Edits" option from the "Editor" menu. Periodically using "Save Edits" is a good practice while you are editing many features. To terminate editing session, choose "Stop Editing" from Editor Toolbar menu.

For more information about editing point features, open ArcGIS Desktop Help by clicking on Help menu or by pressing F1. Choose Index tab on the left panel.

Suggested Keywords: features, moving features, deleting features

A.6 How to Manage Raster Files: Use ArcCatalog for Raster File Manipulation

Always use ArcCatalog to do raster file manipulations like copying, moving, or deleting instead of attempting to do it from Windows explorer. Each raster consists several closely connected files. To ensure the integrity of raster files, always use ArcCatalog for all raster file operations.



For more information about manipulate raster files, open ArcGIS Desktop Help by clicking on Help menu or by pressing F1. Choose Index tab on the left panel.

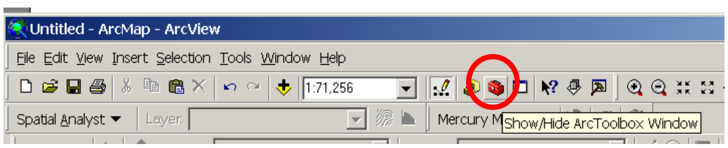
Suggested Keywords: rasters (copy and delete) and ArcCatalog (data)

A.7 Projection: How to Project a Shapefile or a Raster

NOTE: It is very important to maintain all the rasters and shapefiles used in GBMM in the same projection and coordinate System. For detailed understanding on concept of projection read on the suggested keywords at the end of this section.

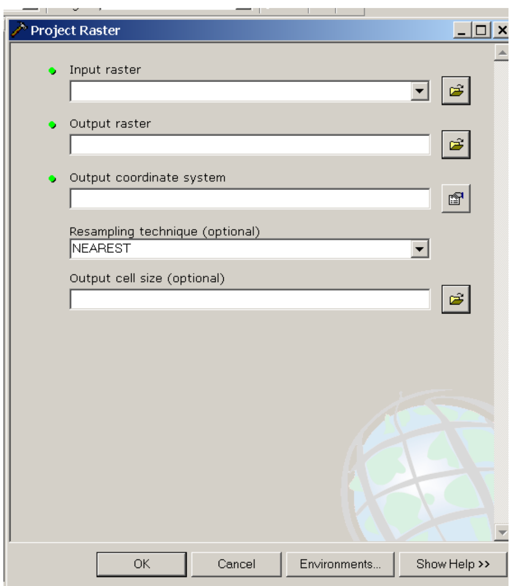
Project Raster: This function projects a raster dataset into a new spatial reference using a single polynomial fit to compute the adjustment between coordinate systems. For the target coordinate systems, you are able to choose a preexisting spatial reference, import it from another dataset, or create a new one.

Click on the ArcToolbox button to start the ArcToolbox.



In the ArcToolbox window, choose Data Management Tools > Projections and Transformations > Raster > Project Raster. Double click on "Project Raster"

In the Project Raster dialog, you need to input a source raster in the "Input raster" box. ArcToolbox will give a default name to the output raster. Click on the button next to the

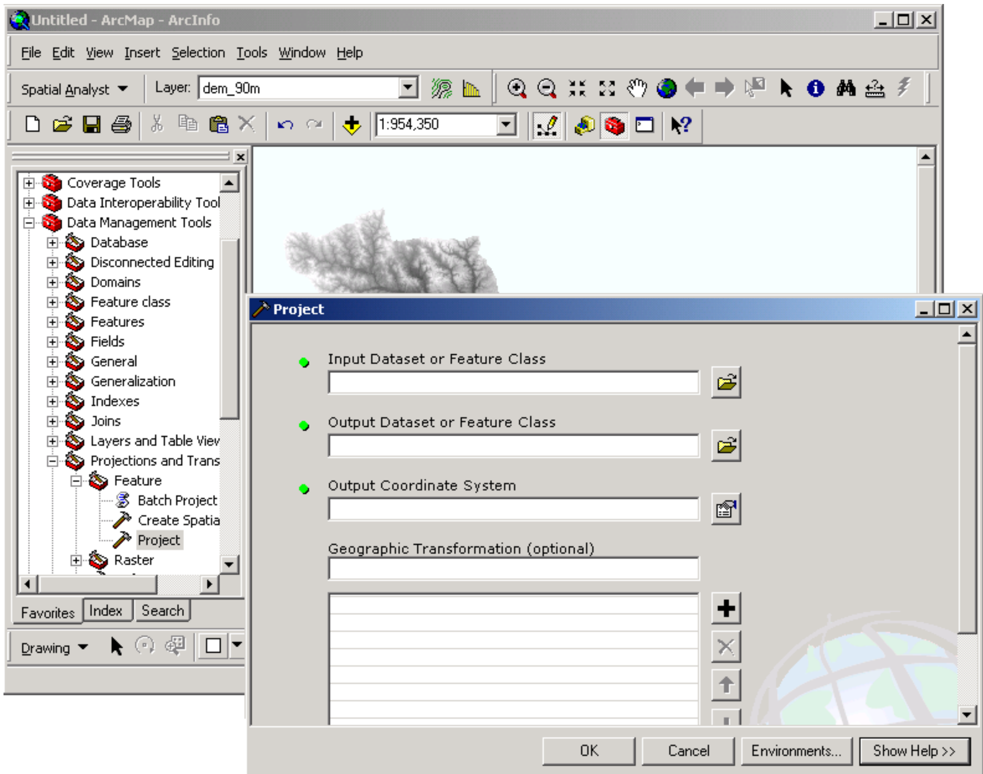


"Output coordinate system", and a new dialog will prompt you to select, import, or create a target coordinate system.

You can also set optional resampling technique and the output cell size for the output raster in the Project Raster dialog. Click on the OK button, and the ArcToolbox will project the input raster to the output raster using your specified coordinate system.

Project Shapefile (Feature Class): This function projects a shapefile from its current coordinate system to a new user-specified coordinate system.

Click on the ArcToolBox button to start ArcToolbox. In ArcToobox, select Data Management Tools > Projections and Transformations > Feature > Project.



The ArcToolbox will display a Project dialog. You need to (1) input a shapefile to be projected, (3) modify the default output file name suggested by the system, and (3) specify the target coordinate system. You can also optionally define the geographic transformation parameters for converting datum of the selected coordinate system.

Click on the OK button, and the ArcToolbox will project the input shapefile to the output sahpefile using your specified coordinate system.

Define Projection: This function helps you to define the coordinate system of a raster or shapefile, when the coordinate system (or projection parameters) of a raster or shapefile is not defined (unknown) or missing.

To define the projection information (or coordinate system) of a raster or shapefile, choose ArcToolbox > Data Management Tools > Projections and Transformations >Define Projection.

For more information about projecting map layers, open ArcGIS Desktop Help by clicking on Help menu or by pressing F1. Choose Index tab on the left panel.

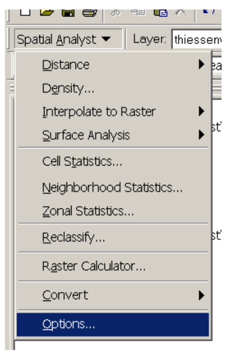
Suggested Keywords: projections, defining; projections, coordinate systems; projections, choosing; projections, rasters; and projections, supported map.

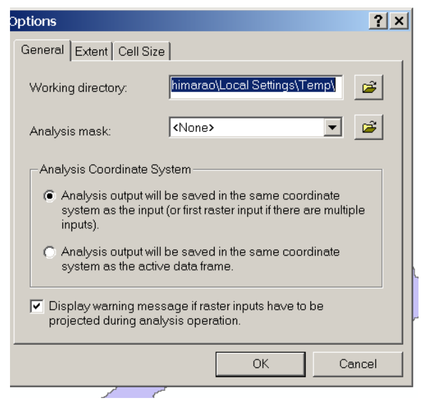
A.8 How to Perform Raster Calculations Using Raster Calculator

The Raster Calculator provides you a powerful tool for performing multiple tasks. You can perform mathematical calculations using operators and functions, set up selection queries, or type in Map Algebra syntax. Inputs can be raster datasets or raster layers, coverages, shapefiles, tables, constants, and numbers.

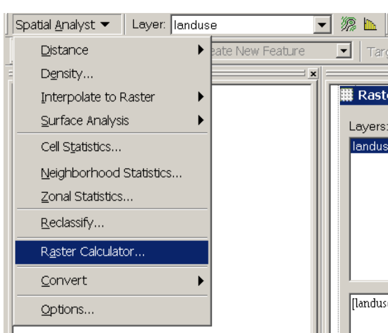
Performing raster calculations requires the availability of "Spatial Analyst" extension. If the "Spatial Analyst" toolbar is not activated yet, click on View > Toolbars or right click on the main menu bar to select (activate) the "Spatial Analyst" extension.

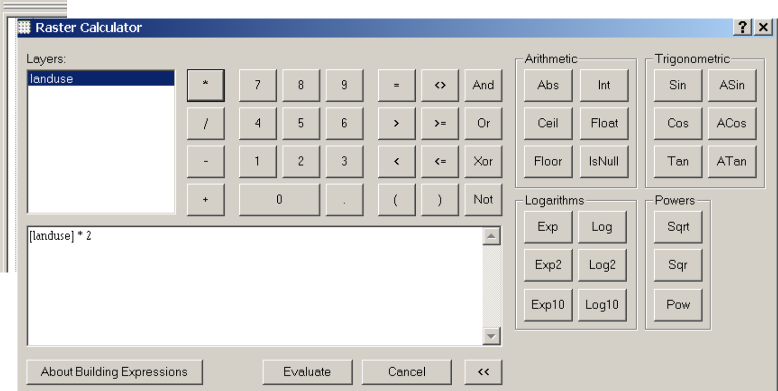
Prior to performing any raster calculations, choose Spatial Analyst >Options… to set the working directory (General tab), analysis extent (Extent tab) and cell size (Cell Size tab) has to be set.





To start the Raster Calculator, select Spatial Analyst > Raster Calculator…





To build an expression in the expression builder box, select an available raster layer from the Layers box. In the above figure, the landuse raster is available. You can double-click the landuse raster to add it to the Expression box (below the Layers box). Type “*2” after the [landuse] layer name, which implies that all the cell values of landuse raster will be multiplied by 2. Click on “Evaluate” button and the raster calculator will generate a new raster based on the expression. The new raster will be added to the ArcMap main window. For more tips on building expressions, click on “About Building Expressions” button.

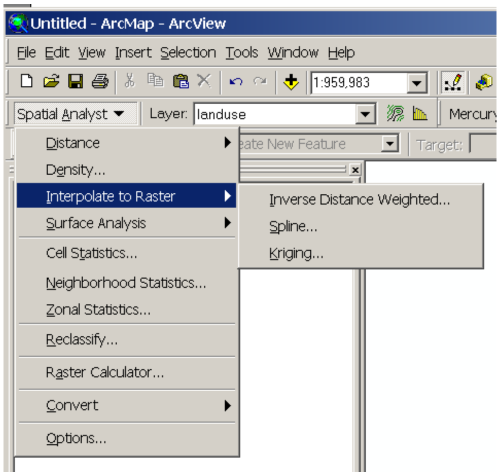
For more information about Raster Calculator, open ArcGIS Desktop Help by clicking on Help menu or by pressing F1. Choose Index tab on the left panel.

Suggested Keywords: Map Algebra, Raster Calculator.

In the ArcGIS Desktop Help window, choose the Search tab on the left panel. Search the following phrase including the quotes: "Using the Raster Calculator"

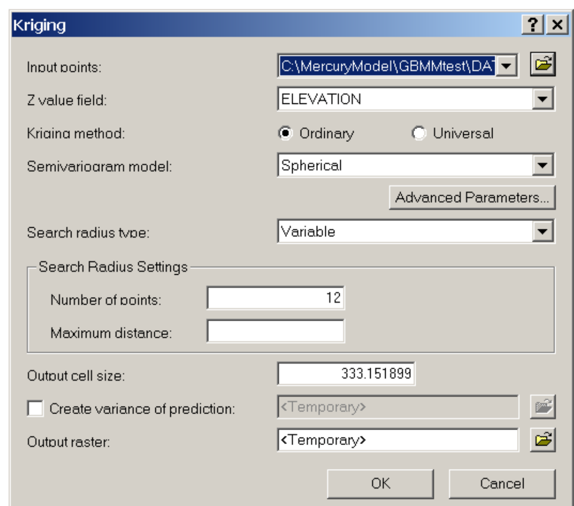
A.9 How to Create Raster (Grid Map) from Points

This operation requires “Spatial Analyst” extension of ArcGIS. If the “Spatial Analyst” toolbar is not activated yet, click on View > Toolbars or right click on the main menu bar to select (activate) the “Spatial Analyst” extension.



Click on the Spatial Analyst dropdown menu, select “Interpolate to Raster”. Spatial Analyst extension has three types of surface interpolations from points–Inverse Distance Weighted, Spline, and Kriging. Kriging is the most popular form of converting point information into a raster.

As an example, Kriging method is illustrated here.



Choose the “Input points” by selecting a desired point shapefile.

Select a field to be used for interpolation. Modify other parameters as applicable to the situation.

Clicking OK button will initiate the interpolation of the point shapefile into a raster.

For more information about interpolating points to surface, open ArcGIS Desktop Help by clicking on Help menu or by pressing F1. Choose Index tab on the left panel.

Suggested Keywords: interpolating

Tip: To evaluate the most appropriate algorithm for converting a point shapefile into raster, read the details of all three methods documented in ArcGIS online help.

Appendix B. How to Use MetADAPT to Generate Climate Data Files for GBMM

This appendix provides a step-by-step guidance on how to use MetADAPT, which stands for Meteorological Data Analysis and Preparation Tool.

Step 1. Export the climate data (daily precipitation, daily max temperature, and daily min temperature) file for selected climate stations from the EarthInfo (http://www.earthinfo.com) data CD (NCDC Summary of the Day). The exported data file should have a ".crd" file extension. Put the exported data in \GBMM\ETC\ folder.

Step 2. Navigate to \GBMM\ETC\ folder, and open the spreadsheet MetAdapt.xls.

Step 3. Click on "Summary of Day – NCDC (CR/LF)" button of MetADAPT to navigate to the data folder (\GBMM\ETC\) and open the exported climate data file (*.crd) (Figure B.1). MetADAPT extracts and outputs daily precipitation, daily max temperature, and daily min temperature and creates *.pre, *.tmx, and *.tmn files for each station in the exported file.

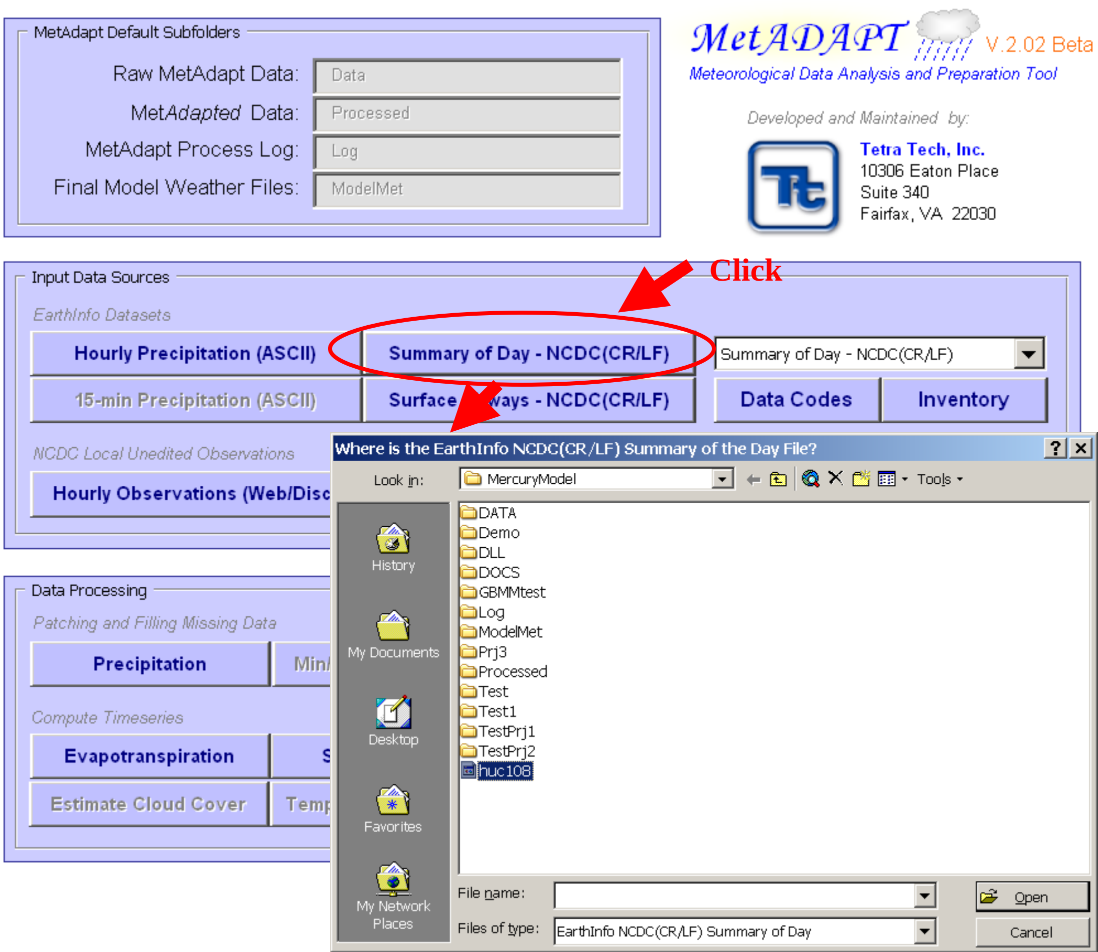


Figure B.1. Click on "Summary of Day – NCDC (CR/LF)" button on the MetADAPT interface to extract data from an exported climate data file

.

Step 4. Click on “Grid Model” button in the “Export Weather Data for Model Application” section (Figure B.2) to open the data processing worksheet.

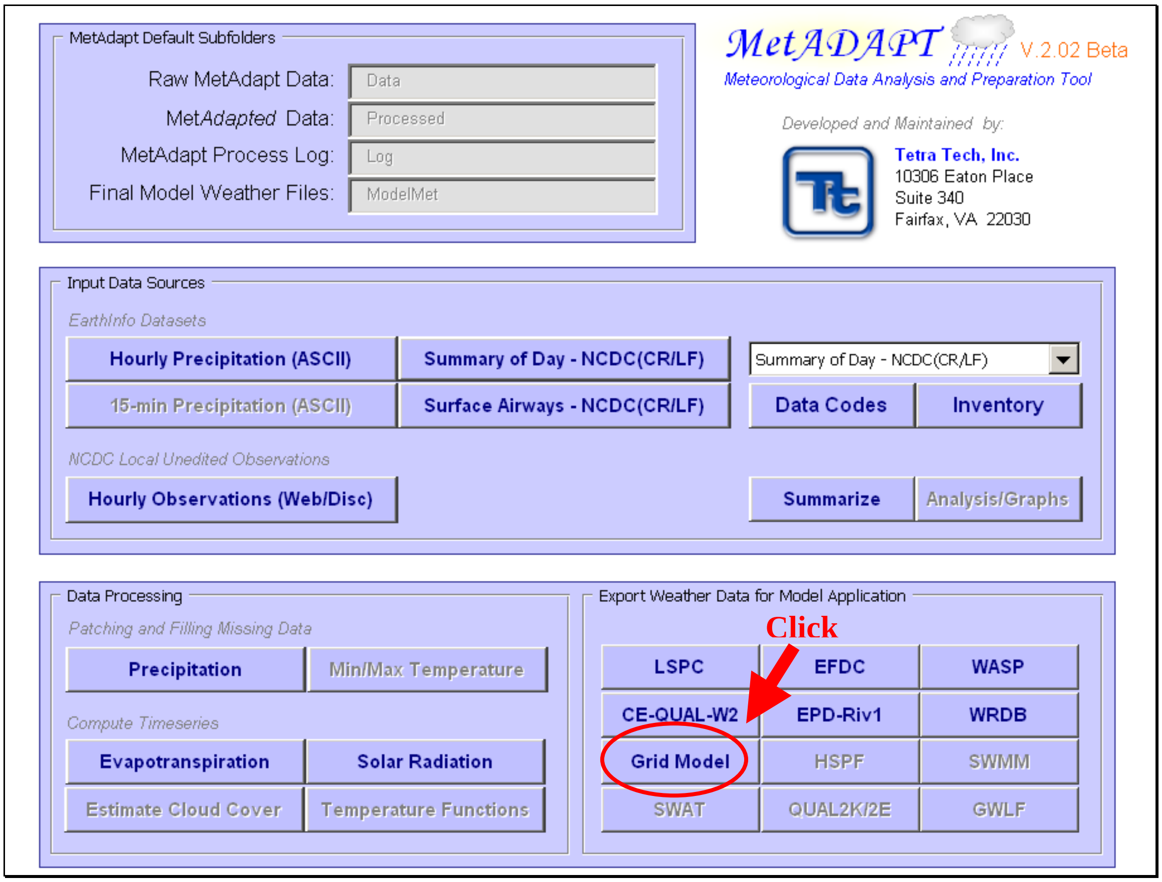


Figure B.2. Click on “Grid Model” button on the MetADAPT interface to process data for models.

Step 5. Clear all the existing data from the active worksheet using the “Clear ALL Data” button (Figure B.3). Then click on “Add New Group” button to load daily precipitation, daily max temperature, and daily min temperature files by climate stations. To load climate data, simply navigate to “\GBMM\ETC” folder and selected a file (e.g., *.pre) for a desired climate station (Figure B.4), and all the other related climate files (e.g., *.tmx and *.tmn) will be automatically loaded as the same group. A group is a file collection of daily precipitation, daily max temperature, and daily min temperature for a selected climate station.

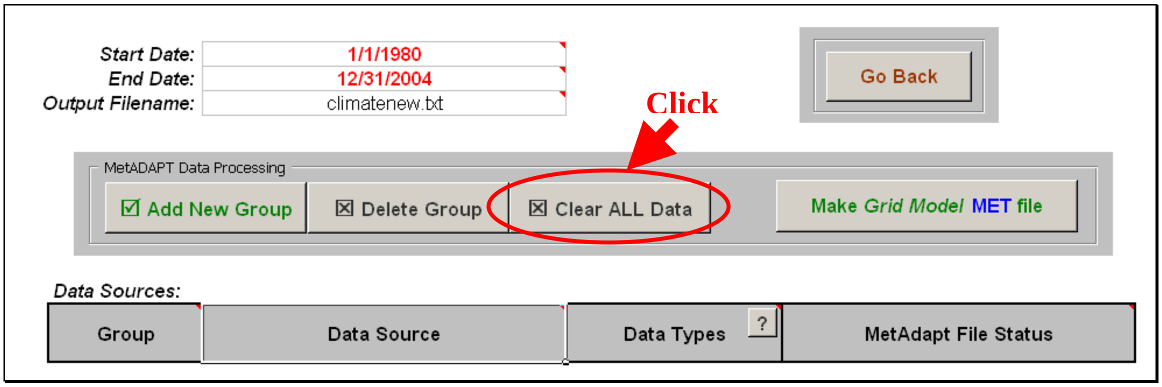


Figure B.3. Clear the data in the active worksheet.

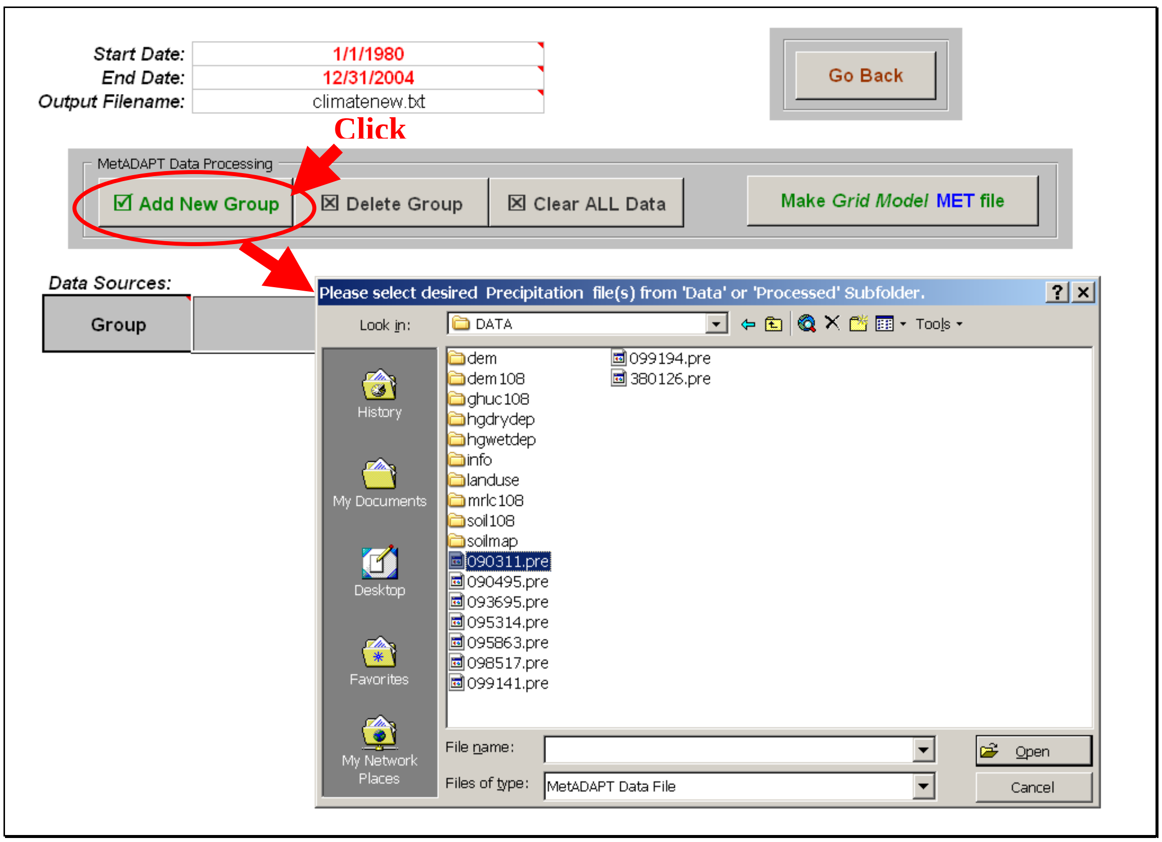


Figure B.4. Add data as new groups by stations.

Step 6. Enter the desired "Start Date", "End Date", and "Output File Name" in the active worksheet, and then click on "Make Grid Model MET file" button (Figure B.5) to create climate text file in a standard format required for the Grid Based Mercury Model version 2.0. The newly created climate text file is located in folder "\GBMM\ETC\ModelMet\GridModel\".

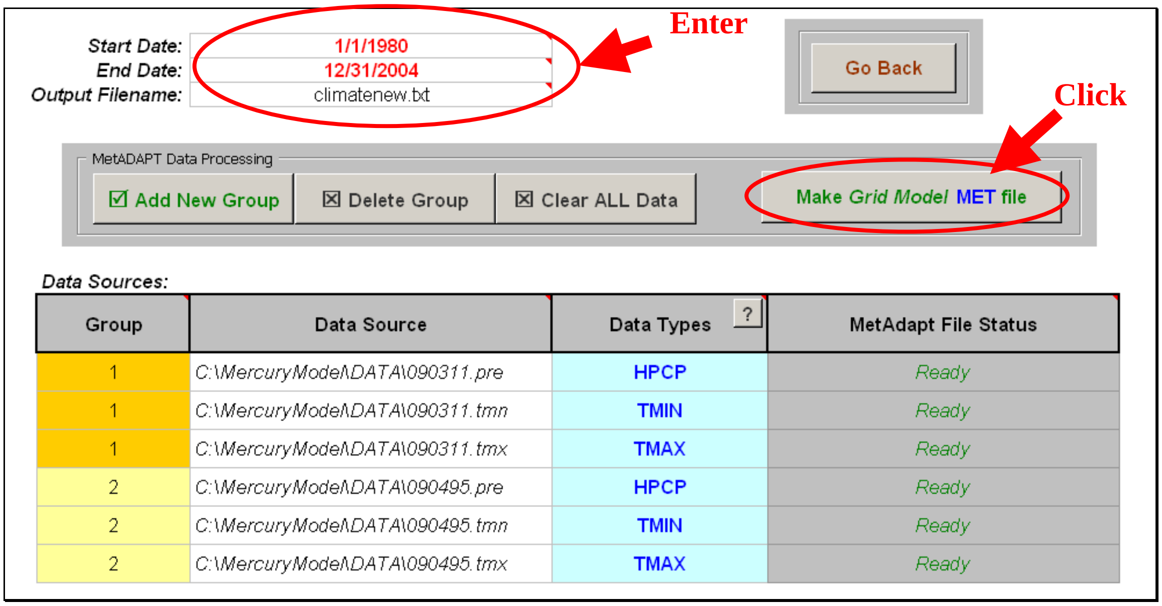


Figure B.5. Enter “Start Date”, “End Date”, “Output File Name”, and create climate text file.

Step 7. The newly created climate text file may be copied or moved to “\GBMM\DATA” folder.

Appendix C. Sample Input File

Below is the list of input cards used for the GBMM C++ simulation module:

C100 simulation control card (required)
C110 model simulation time period card (required)
C120 data time period card (required)
C130 time series file path and name card (required)
C140 input/output folder path card (required)
C150 hydrology input grids (ascii format) card (required)
C160 sediment input grids (ascii format) card (required for sediment run)
C170 mercury input grids (ascii format) card (required for mercury run)
C200 watershed controls card (required)
C210 subwatershed information card (required)
C220 land use information card (required)
C230 soil properties information card (required)
C240 climate station information card (required)
C250 mercury station information card (optional)
C260 point source information card (optional)
C270 lake information card (optional)
C280 lake-climate station fraction card (optional)
C290 routing network card (required)
C300 watershed hydrology parameters card (required)
C310 lake hydrology parameters card (optional)
C320 watershed sediment parameters card (required for sediment run)
C330 lake sediment parameters card (optional)
C340 air deposition mercury parameters card (required for mercury run)
C350 watershed mercury parameters card (required for mercury run)
C360 forest mercury parameters card (required for mercury run)
C370 lake mercury parameters card (optional)
C380 benthic mercury parameters card (optional)

```
c----------------------------------------------------------------------------------------------------
c   GBMM  - Grid Based Mercury Model, C++ Version 2.0
c
c   Designed for:
c      U.S. EPA, National Exposure Research Laboratory
c      Ecosystems Research Division
c      960 College Station Rd.
c      Athens, GA 30605
c
c   Developed and maintained by:
c      Tetra   Tech, Inc.
c      10306 Eaton Place, Suite 340
c      Fairfax, VA 22030
c      Phone: (703) 385 6000
```

```
c------------------------------------------------------------------------------------------------------
c GBMM INPUT FILE
c This input file was created at 01:27:26pm on 10/01/2005
c------------------------------------------------------------------------------------------------------
c100 simulation control
c
c    hydrofg     if = 1 run hydrology module
c    sedfg       if = 1 run sediment module
c    mercuryfg   if = 1 run mercury module
c    waspfg      if = 1 run model with wasp linkage
c    whaemfg     if = 1 run model with whaem linkage
c
c    hydrofg  sedfg   mercuryfg  waspfg  whaemfg
       1       1         1        0       0
c------------------------------------------------------------------------------------------------------
c110 model simulation time period
c
c    simstart    model start date
c    simend      model end date
c    startmon    growing season start month
c    endmon      growing season end month
c    delt        time step in days (fixed = 1)
c
c    simstart    simend        startmon    endmon    delt
    1/1/1980    12/31/1981      4           8         1
c------------------------------------------------------------------------------------------------------
c120 data time period
c
c    ******data time period should be within simulation time period in card 110******
c    ******data time period should be minimum one year if simulation time period is
greater than or equal to one year******
c    ******data time period should be equal to simulation time period if simulation time
period is less than one year******
c
c    dataindex   data index to distinguish the data type
c              if = 1  climate data
c              if = 2  mercury dry deposition data
c              if = 3  mercury wet deposition data
c    datastart   data start date
c    dataend     data end date
c
c    dataindex   datastart   dataend
    1           1/1/1980    12/31/1981
c------------------------------------------------------------------------------------------------------
c130 time series file path and name
c
```

```
c    fileindex   file index to distinguish the data type
c              if = 1  climate file (month/day/year, station_ID, precipitation_cm, average
temperature_C)
c              if = 2  dry deposition mercury file (month/day/year, station_ID, dry deposition
rate_ug/m2)
c              if = 3  wet deposition mercury file (month/day/year, station_ID, wet
deposition rate_ug/m2)
c              if = 4  point source file (month/day/year, station_ID, flow rate_m3/s, sediment
load_kg, mercury load_ug)
c    filepath    time series file path
c
c    fileindex   filepath
    1          climate.txt
c-----------------------------------------------------------------------------------------------------
c140 input/output folder path
c
c    pathindex   folder path index to distinguish the folder type
c              if = 1   input data folder path
c              if = 2   output result folder path
c    folderpath  folder path (directory)
c
c    pathindex   folderpath
    1          c:\GBMM\INPUT
    2          c:\GBMM\OUTPUT
c-----------------------------------------------------------------------------------------------------
c150 hydrology input grids (ascii format)
c
c    gridindex   grid index to distinguish the grid type
c              if = 101  thiessen grid for climate stations (INTEGER GRID)
c              if = 102  landuse grid i.e. MRLC (INTEGER GRID)
c              if = 103  soil properties grid (INTEGER GRID)
c              if = 104  subwatershed grid (INTEGER GRID)
c              if = 105  curve number pervious land grid (REAL GRID)
c              if = 106  curve number impervious land grid (REAL GRID)
c              if = 107  total travel time grid (REAL GRID)
c              if = 108  stream travel time grid (REAL GRID)
c              if = 109  soil water grid, optional (REAL GRID)
c              if = 110  length of flow path for overland cells to the streams of study area
(REAL GRID)
c              if = 111  average roughness along the flow path for overland cells (REAL
GRID)
c              if = 112  average slope along the flow path for overland cells (REAL GRID)
c    gridtype    grid type (integer or real)
c              if = 1    integer grid
c              if = 2    real grid
c    gridfile    grid file name
```

```
c
c    gridindex   gridtype   gridfile
     101         1          thiessenwtr.asc
     102         1          landuse.asc
     103         1          soilprop.asc
     104         1          subwatershed.asc
     105         2          cnper.asc
     106         2          cnimp.asc
     107         2          totaltime.asc
     108         2          streamtime.asc
c-----------------------------------------------------------------------------------------------------
```
c160 sediment input grids (ascii format)
```
c
c    gridindex   grid index to distinguish the grid type
c              if = 201  slope length and gradient grid (LS factor) for MUSLE equation
(REAL GRID)
c    gridtype    grid type (integer or real)
c              if = 1    integer grid
c              if = 2    real grid
c    gridfile    grid file name
c
c    gridindex   gridtype   gridfile
     201         2          lsfactor.asc
c-----------------------------------------------------------------------------------------------------
```
c170 mercury input grids (ascii format)
```
c
c    gridindex   grid index to distinguish the grid type
c              if = 301  forest litter decomposition rate grid (REAL GRID)
c              if = 302  thiessen grid for mercury stations, optional (INTEGER GRID)
c              if = 303  mercury dry deposition grid, optional (REAL GRID)
c              if = 304  mercury wet deposition grid, optional (REAL GRID)
c              if = 305  soil mercury conc grid, optional (REAL GRID)
c    gridtype    grid type (integer or real)
c              if = 1    integer grid
c              if = 2    real grid
c    gridfile    grid file name
c
c    gridindex   gridtype   gridfile
     301         2          kdcomp.asc
c-----------------------------------------------------------------------------------------------------
```
c200 watershed controls
```
c
c    nsws      number of subwatersheds in study area
c    nlu       number of land uses in study area
c    nsl       number of soil types in study area
c    ncls      number of climate data stations in study area
```

```
c    nhgs      number of mercury data stations in study area
c    npts      number of point sources in study area
c    nlks      number of lakes in study area
c
c    nsws   nlu    nsl   ncls   nhgs   npts   nlks
     9     15     7     2      0      0      1
c-----------------------------------------------------------------------------------------------------
c210 subwatershed information
c
c    swsindex  subwatershed index (serial number)
c    swsid     subwatershed id (grid value)
c    swsarea   subwatershed area (m2)
c
c    swsindex  swsid     swsarea
     1         1         18354600.0
     2         2         35097300.0
     3         3         286731900.0
     4         4         144787500.0
     5         5         5629500.0
     6         6         195355800.0
     7         7         88014600.0
     8         8         160242300.0
     9         9         76569300.0
c-----------------------------------------------------------------------------------------------------
c220 landuse information
c
c    luindex   landuse index (seriel number)
c    luid      landuse id (grid value)
c    lutype    landuse type
c              0  for water body
c              1  for pervious land
c              2  for impervious land
c              3  for forest land
c    growvcf   growing season vegetation cover factor (0-1)
c    ngrowvcf  nongrowing season vegetation cover factor (0-1)
c    cfact     crop management factor (0-1)
c    pfact     practice factor (0-1)
c    luname    landuse name
c
c    luindex   luid   lutype   growvcf   ngrowvcf  cfact    pfact    luname
     1         11     0        1.0       1.0       0.0      0.0      Open Water
     2         21     2        0.8       0.5       0.003    1.0      Low Intensity Residential
     3         22     2        0.5       0.5       0.005    1.0      Medium Intensity Residential
     4         23     2        0.15      0.15      0.003    1.0      High Intensity Commercial
     5         31     1        0.3       0.3       0.0      1.0      Bare Rock/Sand/Clay
     6         32     1        0.0       0.3       0.75     1.0      Quarries/Strip Mines/Gravel Pits
```

```
    7      33     1      0.3     0.3     0.02     1.0      Transitional
    8      41     3      1.0     0.3     0.0001   1.0      Deciduous Forest
    9      42     3      1.0     1.0     0.0001   1.0      Evergreen Forest
    10     43     3      1.0     0.65    0.0001   1.0      Mixed Forest
    11     81     1      1.0     1.0     0.003    1.0      Pasture/Hay
    12     82     1      1.0     0.3     0.12     1.0      Row Crops
    13     85     1      1.0     1.0     0.003    1.0      Small Grains
    14     91     0      1.0     1.0     0.011    1.0      Woody Wetlands
    15     92     0      1.0     1.0     0.003    1.0      Herbaceous Wetlands
c---------------------------------------------------------------------------------------------------------
c230 soil properties information
c
c   slindex   soil properties index (seriel number)
c   slid      soil type (grid value)
c   awc       plant available water content (cm/m)
c   bd        soil bulk density (g/cm3)
c   clayfr    fraction of clay content in soil
c   perm      soil permeability rate (cm/hr)
c   kfact     soil erodibility factor (0-1)
c
c   slindex   slid    awc     bd       clayfr    perm     kfact
    1         1860    14.0    1.389    0.4265    0.3909   0.27
    2         1873    10.0    1.529    0.1150    1.9427   0.15
    3         1875     9.0    1.548    0.1390    1.7194   0.14
    4         1881    12.0    1.510    0.2270    1.0884   0.16
    5         1884    10.0    1.533    0.1290    1.5910   0.13
    6         1885    11.0    1.526    0.2180    1.1876   0.13
    7         1886    11.0    1.457    0.0930    1.9894   0.12
c---------------------------------------------------------------------------------------------------------
c240 climate station information
c
c   clsindex  climate station index (seriel number)
c   clsid     climate station id (grid value)
c   clsname   climate station name (station_id)
c   clslat    climate station latitude (degree)
c
c   clsindex  clsid   clsname   clslat
    1         2       090311    33.0125
    2         4       090495    33.406667
c---------------------------------------------------------------------------------------------------------
c250 mercury station information
c
c   hgsindex  mercury station index (seriel number)
c   hgsid     mercury station id (grid value)
c   hgsname   mercury station name (station_id)
c
```

```
c    hgsindex  hgsid    hgsname
c-----------------------------------------------------------------------------------------------------
c260 point source information
c
c    psindex  point source index (seriel number)
c    swsid    subwatershed id (grid value)
c    psname   point source name (permit)
c    psttime  point source travel time to outlet (hr)
c
c    psindex  swsid    psname    psttime
c-----------------------------------------------------------------------------------------------------
c270 lake information
c
c    lkindex  lake index (seriel number)
c    lkid     lake id (grid value)
c    swsid    subwatershed id corresponding to the lake (grid value)
c    lkarea   lake surface area (m2)
c    lkdepth  lake bakfull depth (m)
c    lkidepth lake initial water depth (m)
c    lkised   lake initial sediment concentration (mg/l)
c    lkihg    lake initial mercury concentration (ng/l)
c    lkihgb   lake initial benthic mercury concentration (ng/g)
c
c    lkindex  lkid   swsid   lkarea     lkdepth   lkidepth   lkised   lkihg        lkihgb
     1        34     1       469800.00  0.500     0.500      0.000    0.000001000  0.000021400
c-----------------------------------------------------------------------------------------------------
c280 lake-climatestation fraction
c
c    index    sequence number
c    lkid     lake id (grid value)
c    clsid    climate station id (grid value)
c    frac     fraction contribution of the climate station to the lake, (0-1)
c
c    index    lkid    clsid   frac
     1        34      4       1.0
c-----------------------------------------------------------------------------------------------------
c290 routing network
c
c    from       swsid (outlet)
c    to         swsid (outlet)
c    traveltime travel time from outlet to outlet (hr)
c
c    from    to    traveltime
     3       6     1.712515235
     1       6     1.675037742
     7       5     1.010087132
```

```
    6     5    0.98242861
    5     9    0.971968055
    4     9    0.863741636
    9     2    0.382582515
    8     2    0.353152961
    2     0    0.0
c-----------------------------------------------------------------------------------------------------
```
c300 watershed hydrology parameters

```
c
c   swfg      soil water flag
c             if = 1  constant value
c             if = 2  input grid
c             if = 3  field capacity
c   swater    initial soil water if swfg = 1 otherwise 0 (cm/m)
c   isnow     initial snow on land (cm of water)
c   grow_a    5day precipitation parameter a for growing season (cm)
c   grow_b    5day precipitation parameter b for growing season (cm)
c   ngrow_a   5day precipitation parameter a for non growing season (cm)
c   ngrow_b   5day precipitation parameter b for non growing season (cm)
c   usdepth   unsaturated soil depth (m)
c   brdepth   soil depth to bed rock (m)
c   gwater    initial shallow ground water (cm/m)
c   gr        groundwater recession coefficient (/day)
c   sr        groundwater seepage coefficient (/day)
c   gwrp      average groundwater recharge period (days)
c
c   swfg   swater  isnow   grow_a   grow_b  ngrow_a   ngrow_b   usdepth   brdepth
gwater   gr    sr    gwrp
    3     0.0     0.0    3.6     5.3    1.3      2.8      1.0      1.5      50.0    0.1   0.0   31
c-----------------------------------------------------------------------------------------------------
```
c310 lake hydrology parameters

```
c
c   ks        lake infiltration rate (cm/hr)
c   evap_c    evaporation coefficient used to compute AET from lake (AET = evap_c *
PET)
c   orif_h    orifice depth to bed (m)
c   orif_d    orifice diameter (m)
c   orif_c    orifice coefficient of discharge
c   weir_l    length of the weir crest (m)
c   weir_c    weir coefficient of discharge
c
c   ks      evap_c   orif_h  orif_d  orif_c   weir_l    weir_c
    0.01    0.1      0.0     0.0     0.6      300.0     1.84
c-----------------------------------------------------------------------------------------------------
```
c320 watershed sediment parameters

```
c
```

```
c    psed_init    initial sediment on pervious land (kg/ha)
c    ised_init    initial sediment on impervious land (kg/ha)
c    ised_acc     sediment accumulation rate on impervious land (kg/ha/day)
c    ised_depl    sediment depletion rate constant on impervious land (/day)
c    sed_cap      sediment yield capacity on land (kg/ha)
c    rain_alph    fraction of daily rainfall that occurs during the time of concentration
c    sdr_alph     calibration coefficient for computing sediment delivery ratio
c    sdr_beta     routing coefficient for computing sediment delivery ratio
c
c    psed_init   ised_init  ised_acc   ised_depl   sed_cap    rain_alph   sdr_alph    sdr_beta
     0.0         0.0        0.05       0.12        30.0       0.5         1.0         3.0
c-----------------------------------------------------------------------------------------------------
c330 lake sediment parameters
c
c    tss_eq    equilibrium concentration of suspended solids in the water (mg/l)
c    sett_k    settling constant rate (/day)
c    tss_clay  fraction of clay in the inflow sediment
c    tss_silt  fraction of silt in the inflow sediment
c    tss_sand  fraction of sand in the inflow sediment
c
c    tss_eq   sett_k   tss_clay   tss_silt    tss_sand
     0.4      0.184    0.3        0.6         0.1
c-----------------------------------------------------------------------------------------------------
c340 air deposition mercury parameters
c
c    adfg      air deposition mercury flag
c              if = 1  constant value
c              if = 2  input grid
c              if = 3  time series
c
c    "if adfg = 1"
c    adfg      air deposition mercury flag
c    dd_f      daily dry deposition mercury flux (µg/m2/day)
c    wdfg      wet deposition mercury flag
c              if = 1  daily wet deposition mercury flux (µg/m2/day)
c              if = 2  daily precipitation mercury concentration (ng/l)
c    wd_v      daily wet deposition mercury based on wdfg
c
c    adfg   dd_f  wdfg   wd_v
c
c    "if adfg = 2"
c    adfg      air deposition mercury flag
c    dd_m      daily dry deposition mercury grid multiplier
c    wd_m      daily wet deposition mercury grid multiplier
c
c    adfg   dd_m  wd_m
```

```
c
c   "if adfg = 3"
c   adfg     air deposition mercury flag
c   dd_d     dry deposition mercury time series (ug/m2/day)
c            if = 1  daily data
c            if = 2  monthly data
c   wd_d     wet deposition mercury time series (ug/m2/day)
c            if = 1  daily data
c            if = 2  monthly data
c
c   adfg   dd_d  wd_d
c
c   adfg   dd_f    wdfg   wd_v
   1     0.001   1     0.002
c-----------------------------------------------------------------------------------------------------
```
c350 watershed mercury parameters

```
c
c   shgfg     soil mercury flag
c            if = 1  initial soil mercury concentration (ng/g)
c            if = 2  initial soil mercury grid multiplier
c   smercury  value based on shgfg
c   gwmercury initial ground water mercury concentration (ng/l)
c   zd       watershed soil mixing depth (cm)
c   zr       soil reduction depth (cm)
c   kds      soil water partition coefficient (ml/g)
c   krs      soil base reduction rate (per day)
c   ef       pollutant enrichment factor
c   rd       bedrock density (g/cm3)
c   kcw      chemical weathering rate constant (µm/day)
c   crock    concentration of mercury in bedrock (ng/g)
c   kd       mercury decay rate in channel (per hr)
c   fmehg    fraction of methylmercury in total mercury
c
c   shgfg   smercury  gwmercury   zd    zr    kds    krs    ef    rd    kcw     crock    kd
fmehg
   1      0.03570      0.0000214   1.0   0.5    58000.  0.0001  2.0    2.6   0.0004   0.06
0.0017   0.06
c-----------------------------------------------------------------------------------------------------
```
c360 forest mercury parameters

```
c
c   aaet   actual annual evapotranspiration (cm/year)
c   fint   interception fraction
c   fadh   adhering fraction
c   lit    initial amount of litter (g/m2)
c   bcf    air-plant bio-concentration factor
c   ca     air mercury concentration (ng/g)
```

```
c
c    aaet   fint   fadh   lit     bcf       ca
    30.0   0.47   0.6    40.0   18000.0   0.00155
c----------------------------------------------------------------------------------------------------
c370 lake mercury parameters
c
c    alpha_w   net reduction loss factor in the water column
c    beta_w    net methylation loss factor in the water column
c    kwr       water body mercury reduction rate constant (per day)
c    kwm       water body mercury methylation rate constant (per day)
c    vsb       biomass settling velocity in the water column (m/day)
c    vrs       sediment resuspension velocity (m/day)
c    kdsw      sediment/water partition coefficient in the water column
c    kbio      biomass/water partition coefficient in the water column
c    cbio      biomass concentration in the water column (mg/l)
c    pd        soil particle density (g/cm3)
c
c    alpha_w   beta_w  kwr     kwm     vsb    vrs      kdsw     kbio     cbio    pd
    1.0      0.4     0.0075   0.001   0.20   0.00001   100000    200000    0.70    2.65
c----------------------------------------------------------------------------------------------------
c380 benthic mercury parameters
c
c    alpha_b   net reduction loss factor in the benthic sediments
c    beta_b    net methylation loss factor in the benthic sediments
c    kbr       benthic sediment mercury reduction rate constant (per day)
c    kbm       benthic sediment mercury methylation rate constant (per day)
c    por_bs    porosity of the benthic sediment bed
c    vbur      burial velocity (m/day)
c    zb        depth of the benthic sediment bed (m)
c    kdbs      bed sediment/sediment pore water partition coefficient
c    cbs       solids concentration in the benthic sediments (g/m3)
c    esw       pore water diffusion coefficient (m2/sec)
c
c    alpha_b   beta_b  kbr       kbm     por_bs   vbur         zb     kdbs    cbs     esw
    1.0      0.4     0.000001   0.0001  0.65     0.00000035    0.02    50000.  75000.
0.000000005
c----------------------------------------------------------------------------------------------------
```

Appendix D. GBMM Equations and Algorithms

This appendix describes the algorithms and equations used for the GBMM system.

D.1 Hydrology

D.1.1 Pervious Land

Water Balance

Daily water balance for the unsaturated zone can be described as

$$S_w = S_{w_o} + P_{tot} - R_o - ET - P_c \qquad \text{for } (S_w \geq WP) \text{ ....Equation D.1}$$

where

S_w = available water in the unsaturated soil zone (cm)
S_{wo} = initial water in the unsaturated soil zone (cm)
P_{tot} = total available input water at the surface (cm)
R_o = surface runoff (cm)
ET = actual evapotranspiration (cm)
P_c = percolation, water moved from unsaturated to saturated groundwater (cm)
WP = water content at wilting point (cm)

Total Available Water

Total available water (P_{tot}) at the surface is the sum of rainfall and snowmelt for the day.

$$P_{tot} = R_n + M_s \qquad \text{for wet day ....Equation D.2}$$

where

P_{tot} = total available input water at the surface (cm)
R_n = rainfall (cm)
M_s = snowmelt (cm of water)

Rainfall R_n (cm) and snowmelt M_s (cm of water) are estimated from the precipitation and temperature data. Precipitation is assumed to be rain when the daily mean air temperature T_{av} (^oC) is above 0 and snowfall otherwise. Snowmelt water is computed by a degree-day equation (Haith, 1985):

$$M_s = 0.45 * T_{av} \qquad \text{for } (T_{av} > 0) \text{ ....Equation D.3}$$

where

M_s = snowmelt (cm of water)
T_{av} = daily average air temperature (^oC)

Runoff

The Curve Number Equation (USDA-NRCS, 1972) developed by the Natural Resources Conservation Service (NRCS) is used to calculate daily surface runoff (R_o) as

$$R_o = \frac{(P_{tot} - 0.2 * D_s)^2}{(P_{tot} + 0.8 * D_s)} \quad \text{for } (P_{tot} > 0) \text{ ....Equation D.4}$$

where

R_o = surface runoff (cm)
P_{tot} = total available input water at the surface (cm)
D_s = detention storage (cm)

The detention storage is estimated from the curve number as

$$D_s = \frac{2540}{CN} - 25.4 \text{ ....Equation D.5}$$

where

D_s = detention storage (cm)
CN = curve number

Curve Number Modification

Curve numbers are selected as functions of antecedent moisture as described by Haith (1985) and are shown in Figure D.1. Curve numbers for antecedent moisture conditions 1 (driest), 2 (standard average), and 3 (wettest) are CN_1, CN_2, and CN_3.

$$CN_1 = \frac{CN_2}{(2.334 - 0.01334 * CN_2)} \text{ ....Equation D.6}$$

$$CN_3 = \frac{CN_2}{(0.4036 + 0.0059 * CN_2)} \text{ ....Equation D.7}$$

The curve number (CN2) for selected vegetation-soil combinations can be found in Haith et al. (1992), and a CN2 raster grid can be generated by combining the land use and soil hydrologic group themes.

The actual curve number, CN, is selected as a linear function of A_{5d}, the 5-day antecedent precipitation (cm), as shown in Figure D.1.

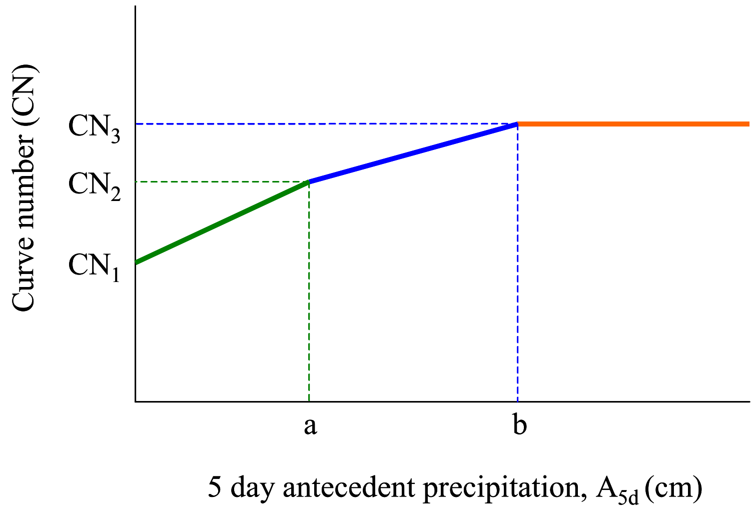


Figure D.1. Curve number selection as a function of antecedent moisture.

$$A_{5d} = \sum_{n=t-5}^{t-1} \left(P_{tot,n}\right) \quad \text{.......... Equation D.8}$$

Recommended values (Ogrosky and Mockus, 1964) for the break points in Figure D.1 for the non-growing and growing seasons are as follows:

For non-growing season: $a = 1.3$ $b = 2.8$

For growing season: $a = 3.6$ $b = 5.3$

For snowmelt conditions, it is assumed that the wettest antecedent moisture conditions prevail and hence regardless of A_{5d}, $CN = CN_3$ when $M_s > 0$.

$$CN = CN_3 \qquad \text{for } (M_s > 0) \quad \text{.......... Equation D.9}$$

$$CN = A_{5d} * \frac{(CN_2 - CN_1)}{a} + CN_1 \qquad \text{for } (A_{5d} < a) \quad \text{.......... Equation D.10}$$

$$CN = (A_{5d} - a) * \frac{(CN_3 - CN_2)}{(b - a)} + CN_2 \qquad \text{for } (a \le A_{5d} \le b) \quad \text{.......... Equation D.11}$$

$$CN = CN_3 \qquad \text{for } (A_{5d} > b) \quad \text{.......... Equation D.12}$$

Evapotranspiration

Daily potential evapotranspiration (PET) is calculated as given by Hamon (1961):

$$PET = 0.021 * H^2 * e_t / (T_{av} + 273) \qquad \text{for } (T_{av} > 0) \text{ ....Equation D.13}$$

where

PET = potential evapotranspiration (cm)
H = daylight hours per day
e_t = saturated vapor pressure (millibars)
T_{av} = average daily air temperature (°C)

Daylight hours per day are calculated as

$$H = 7.63942 * \left[ATAN\left(\frac{-X}{\sqrt{-X * X + 1}} \right) + 2 * ATAN(1) \right] \text{ ....Equation D.14}$$

$$X = 0.43481 * TAN\left[Lat * 0.017453\right] * COS\left[0.0172 * (day + 9)\right] \text{.............Equation D.15}$$

where

H = daylight hours per day
Lat = latitude in decimal degree
day = day of the year

Saturated vapor pressure is approximated as in Bosen (1960):

$$e_t = 33.8639 * [(0.00738 * T_{av} + 0.8072)^8 - 0.000019 * (1.8 * T_{av} + 48) + 0.001316] \text{ ....Equation D.16}$$

where

e_t = saturated vapor pressure (millibars)
T_{av} = average daily air temperature (°C)

Actual evapotranspiration can be calculated as

$$ET = \min(PET * VCF, S_w + P_{tot} - R_o - WP) \text{ ....Equation D.17}$$

where

ET = actual evapotranspiration (cm)
PET = potential evapotranspiration (cm)
VCF = vegetation cover factor (from land use and cover coefficients for both the growing and non-growing seasons)
S_w = available water in the unsaturated soil zone (cm)
P_{tot} = total available input water at the surface (cm)
R_o = surface runoff (cm)
WP = water content at the wilting point (cm)

Percolation

For each time step, percolation (P_c) is estimated if the soil water content exceeds the field capacity water content.

$$S_{w_{excess}} = S_w + P_{tot} - R_o - ET - FC \qquad \text{for } \left(S_{w_{excess}} > 0\right) \text{ ....Equation D.18}$$

where

$S_{w_{excess}}$ = drainable excess available water in unsaturated soil zone (cm)

S_w = available water in unsaturated soil zone (cm)

P_{tot} = total available input water at the surface (cm)

R_o = surface runoff (cm)

ET = actual evapotranspiration (cm)

FC = water content at field capacity (cm)

The mean permeability rate grid (k) was determined using data from the STATSGO Comp and Layer tables (Earth System Science Center at The Pennsylvania State University Web Site, 2004). Daily percolation is calculated as

$$P_c = k * 24 \qquad \text{for } (P_c < S_{w_{excess}}) \text{ ....Equation D.19}$$

$$P_c = S_{w_{excess}} \qquad \text{for } (P_c \geq S_{w_{excess}}) \text{ ....Equation D.20}$$

where

P_c = percolation, water moved from unsaturated to saturated zone (cm/day)

k = soil permeability rate (cm/hr)

Field capacity is the sum of the wilting point and the plant-available water capacity.

$$FC = WP + \left(AWC * d_{unsat}\right) \text{ ....Equation D.21}$$

where

FC = water content at field capacity (cm)

WP = water content at wilting point (cm)

AWC = available water capacity in unsaturated soil (cm/m)

d_{unsat} = unsaturated soil depth (m)

Wilting point is calculated based on the Soil and Water Assessment Tool (Neitsch et al., 2002).

$$WP = 0.4 * m_c * BD * d_{unsat} \text{ ....Equation D.22}$$

where

WP = water content at wilting point (cm)
mc = percent clay content in soil layer (%)
BD = bulk density of the soil (g/cm^3)
d_{unsat} = unsaturated soil depth (m)

D.1.2 Impervious Land: Curve Number Modification

Curve number modification algorithms are chosen from the SWAT user's manual (Neitsch et al., 2002). Urban areas can be differentiated into two groups: the area that is hydraulically connected to the drainage system and the area that is not directly connected. As an example, assume there is a house surrounded by a yard where runoff from the roof flows into the yard and is able to infiltrate into the soil. The rooftop is impervious, but it is not hydraulically connected to the drainage system. In contrast, a parking lot whose runoff enters a storm water drain is hydraulically connected. Table D.1 lists typical values for impervious and directly connected impervious fractions in different urban land types.

Table D.1. Range and average impervious fractions for different urban land types

Urban Land Type	Average total impervious	Range total impervious	Average directly connected impervious	Range directly connected impervious
Residential-High Density (> 8 unit/acre or unit/2.5 ha)	0.60	0.44–0.82	0.44	0.32–0.60
Residential-Medium Density (1 – 4 unit/acre or unit/2.5 ha)	0.38	0.23–0.46	0.30	0.18–0.36
Residential-Med/Low Density (> 0.5 – 1 unit/acre or unit/2.5 ha)	0.20	0.14–0.26	0.17	0.12–0.22
Residential-Low Density (< 0.5 unit/acre or unit/2.5 ha)	0.12	0.07–0.18	0.10	0.06–0.14
Commercial	0.67	0.48–0.99	0.62	0.44–0.92
Industrial	0.84	0.63–0.99	0.79	0.59–0.93
Transportation	0.98	0.88–1.00	0.95	0.85–1.00
Institutional	0.51	0.33–0.84	0.47	0.30–0.77

Source: Neitsch et al., 2002.

In urban areas, surface runoff is calculated separately for the directly connected impervious area and the disconnected impervious/pervious area. For directly connected impervious areas, a curve number of 98 is always used. For disconnected impervious/pervious areas, a composite curve number is calculated and used in the surface runoff calculations. The equations used to calculate the composite curve number for disconnected impervious/pervious areas are as follows (USDA-NRCS, 1986):

$$CN = \frac{CN_2 * \left[1 - imp_{tot} + \frac{imp_{dcon}}{2}\right] + 98 * \left[\frac{imp_{dcon}}{2}\right]}{\left[1 - imp_{con}\right]} \quad \text{for } \left(imp_{tot} \le 0.30\right)$$

....Equation D.23

$$CN = \frac{CN_2 * \left[1 - imp_{tot}\right] + 98 * imp_{dcon}}{\left[1 - imp_{con}\right]} \quad \text{for } \left(imp_{tot} > 0.30\right)$$ Equation D.24

where

CN = composite curve number
CN_2 = pervious curve number
imp_{tot} = fraction of the grid area that is impervious (both directly connected and disconnected)
imp_{con} = fraction of the grid area that is impervious and hydraulically connected to the drainage system
imp_{dcon} = fraction of the grid area that is impervious but not hydraulically connected to the drainage system

D.1.3 Shallow Groundwater

Water Balance

Shallow groundwater daily balance is computed as

$$G_w = G_{wo} + P_c - G_o - S_p$$ ....Equation D.25

where

G_w = shallow groundwater at the end of the time step (cm)
G_{wo} = shallow groundwater at the start of the time step (cm)
P_c = percolation rate (cm/day)
G_o = shallow groundwater outflow (cm/day)
S_p = seepage to deep aquifer (cm/day)

Shallow Groundwater Outflow

Shallow groundwater outflow is computed based on a simple groundwater recession coefficient and can be written as

$$G_o = g_r * G_w$$ ....Equation D.26

where

G_o = shallow groundwater outflow (cm/day)
g_r = groundwater recession coefficient (per day)
G_w = shallow groundwater storage (cm)

The groundwater recession coefficient can be derived from observed stream flow during the flow recession period.

$$g_r = \frac{\ln(F_2) - \ln(F_1)}{t_2 - t_1} \quad \text{..........Equation D.27}$$

where

F_2 = stream flow at time t_2 (m^3/day)
F_1 = stream flow at time t_1 (m^3/day)
t_2 = time for stream flow F_2 (per day)
t_1 = time for stream flow F_1 (per day)

Seepage to Deep Aquifer

Seepage to deep aquifer is computed based on a simple groundwater seepage coefficient and can be written as

$$S_p = s_r * G_w \quad \text{..........Equation D.28}$$

where

S_p = seepage to deep aquifer (cm/day)
s_r = groundwater seepage coefficient (per day)
G_w = shallow groundwater storage (cm)

D.1.4 Lake/Wetland/Reservoir

Water Balance

The water balance equation for a water body is

$$V = V_i + V_{q_i} + V_{G_o} + V_{q_u} + V_{q_p} + V_{pcp} - V_{evp} - V_{sep} - V_{q_o} \quad \text{..........Equation D.29}$$

where

V = volume of water in the impoundment at the end of the day (m^3)
V_i = volume of water in the water body at the beginning of the day (m^3)
V_{qi} = volume of runoff water entering the water body (m^3)
V_{Go} = volume of groundwater entering the water body (m^3)
V_{qu} = volume of upstream water entering the water body (m^3)
V_{qp} = volume of point flow entering the water body (m^3)
V_{pcp} = volume of precipitation falling on the water body (m^3)
V_{evp} = volume of water removed by evaporation (m^3)
V_{sep} = volume of water lost by the seepage (m^3)
V_{qo} = volume of water leaving the water body (m^3)

Precipitaion

The volume of precipitation falling on the reservoir during a given day is calculated as

$$V_{pcp} = 10^{-3} * P_{day} * A_w \text{ ....Equation D.30}$$

where

V_{pcp} = volume of precipitation falling on the water body (m^3)
P_{day} = amount of precipitation falling on a given day (mm)
A_w = surface area of the water body (m^2)

Evaporation

The volume of water lost to evaporation on a given day is calculated as

$$V_{evp} = 10^{-2} * \eta * PET * A_w \text{ ....Equation D.31}$$

where

V_{evp} = volume of water removed by evaporation (m^3)
η = evaporation coefficient (0-1)
PET = potential evapotranspiration for a given day (cm)
A_w = surface area of the water body (m^2)

Seepage

The volume of water lost by seepage through the bottom of the reservoir on a given day is calculated as follows (Neitsch et al., 2002):

$$V_{sep} = 0.024 * K_{sat} * A_w \text{ ....Equation D.32}$$

where

V_{sep} = volume of water lost by seepage (m^3)
K_{sat} = effective saturated hydraulic conductivity of the reservoir bottom (mm/hr)
A_w = surface area of the water body (m^2)

Outflow

Outflow from a water body is computed in two parts, outflow through orifice and overflow over spillway weir, as shown in Figure D.2.

The equation for the orifice flow is

$$Q_o = C_o * A_o * \sqrt{2 * g * H} \text{ ....Equation D.33}$$

where

Q_o = outflow through orifice (m^3/s)
C_o = orifice coefficient of discharge
A_o = orifice cross-sectional area (m^2)
g = acceleration due to gravity (m/s^2)
H = depth of the water level above the orifice (m)

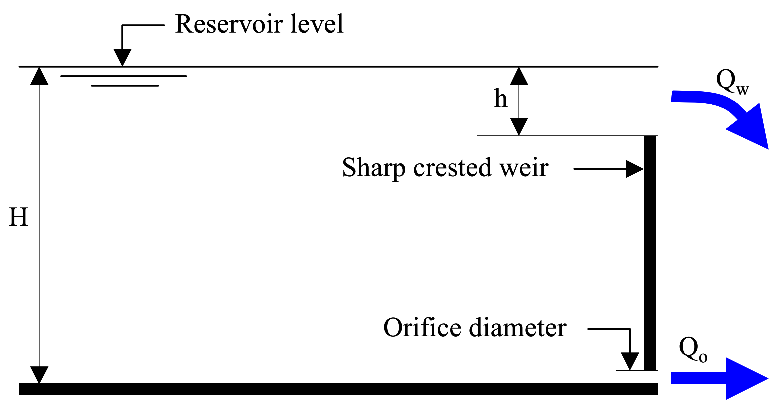


Figure D.2. Wetland/lake/reservoir weir and orifice outflow diagram.

Orifice cross-sectional area is computed as

$$A_o = \frac{\Pi}{4} * D^2 \quad \text{.......Equation D.34}$$

where

A_o = orifice cross-sectional area (m^2)
D = orifice diameter (m)
Π = 3.1428

Depth of the water level is computed as

$$H = \frac{V_i + V_{q_i} + V_{G_o} + V_{q_u} + V_{q_p} + V_{pcp} - V_{evp} - V_{sep}}{A_w} \quad \text{.......Equation D.35}$$

where

H = water depth of the water body (m)
V_i = volume of water in the water body at the beginning of the day (m^3)
V_{qi} = volume of watershed water entering the water body (m^3)
V_{Go} = volume of groundwater entering the water body (m^3)
V_{qu} = volume of upstream water entering the water body (m^3)
V_{qp} = volume of point flow entering the water body (m^3)
V_{pcp} = volume of precipitation falling on the water body (m^3)
V_{evp} = volume of water removed by evaporation (m^3)

V_{sep} = volume of water lost by seepage (m^3)
A_w = surface area of the water body (m^2)

The equation for the sharp crested weir overflow is

$$Q_w = C_w * L_w * h^{3/2} \quad \text{for } (h > 0) \text{ ....Equation D.36}$$

where
Q_w = outflow over the sharp crested weir (m^3/s)
C_w = weir coefficient of discharge
L_w = length of the weir crest (m)
h = depth of the water above the weir crest (m)

Depth of water above the weir crest is calculated as

$$h = H - D_w \text{ ....Equation D.37}$$

where
h = depth of the water above the weir crest (m)
H = depth of the water level (m)
D_w = depth of the water body (m)

Total outflow from the water body is calculated as

$$q_o = Q_o + Q_w \text{ ....Equation D.38}$$

where
q_o = water discharge from the water body (m^3/s)
Q_o = outflow through the orifice (m^3/s)
Q_w = outflow over the sharp crested weir (m^3/s)

The volume of outflow from the water body is then calculated as

$$V_{q_o} = 86400 * q_o \text{ ....Equation D.39}$$

where
V_{q_o} = volume of water leaving the water body (m^3/day)
q_o = water discharge from the water body (m^3/s)

D.1.5 Point Source Discharge

Point coverage for point flow is used to create a point flow grid. Point flow time series are added to the corresponding cells in the point flow grid. Point discharges are routed through the precalculated travel time along the predefined flow paths (see section D.1.6).

D.1.6 Flow Routing

Flow Travel Time

Flow Travel time is the time water takes to travel from one location to another in a watershed. Water moves through a watershed as sheet flow, shallow concentrated flow, open channel flow, or some combination of these. *Urban Hydrology for Small Watersheds* (USDA-NRCS, 1986) is used for computing travel time overland and in channels.

- *Overland Flow Travel Time*

$$T_{ov} = \frac{0.0289 * (n * L)^{0.8}}{P_2^{0.5} * S^{0.4}} \quad \text{Equation D.40}$$

where

T_{ov} = overland flow travel time (hr)
n = Manning's roughness coefficient
L = flow length (m)
P_2 = 2-year, 24-hour rainfall (cm)
S = land slope (m/m)

- *Channel Flow Travel Time*

$$T_{ch} = \frac{L}{3600 * V} \quad \text{Equation D.41}$$

where

T_{ch} = stream flow travel time (hr)
L = flow length (m)
V = flow velocity (m/sec)

Velocity in a channel is calculated by Manning's equation.

$$V = \frac{1}{n} R^{2/3} * S^{1/2} \quad \text{Equation D.42}$$

where

V = flow velocity (m/sec)
n = Manning's roughness coefficient
R = hydraulic radius (m)
S = channel slope (m/m)

Total flow travel time from each cell to the outlet is computed as

$$T_{tot} = T_{ov} + T_{ch} \quad \text{.......... Equation D.43}$$

where

T_{tot} = total flow travel time (hr)
T_{ov} = overland flow travel time (hr)
T_{ch} = stream flow travel time (hr)

Hydraulic radius is calculated based on the regression equations developed for the specific geographic regions. The shape of the channel can be trapezoidal or rectangular based on the user-defined side slopes of the channel.

Hydraulic radius is computed as

$$R = \frac{A_x}{P} \quad \text{.......... Equation D.44}$$

where

R = hydraulic radius of the channel (m)
A_x = channel cross-sectional area (m^2)
P = channel wetted parameter (m)

Channel cross-sectional area is computed as

$$A_x = D * \left[W + \frac{D}{2}\left(\frac{1}{S_1} + \frac{1}{S_2}\right)\right] \quad \text{.......... Equation D.45}$$

where

A_x = channel cross-sectional area (m^2)
D = channel depth (m)
W = channel width (m)
S_1 = channel left slope (m)
S_2 = channel right slope (m)

Average channel depth is computed based on the geographic region and drainage area (Rosgen, 1996):

$$D = \alpha_D * A_d^{\beta_D} \quad \text{.......... Equation D.46}$$

where

D = channel depth (m)
α_D = regression coefficient for channel depth (see Table D.2)
A_d = drainage area (km^2)
β_D = regression coefficient for channel depth (see Table D.2)

Average channel width is computed based on geographic region and drainage area (Rosgen, 1996):

$$W = \alpha_w * A_d^{\beta_w} \text{ .... Equation D.47}$$

where

W = channel width (m)
α_w = regression coefficient for channel depth (see Table D.2)
A_d = drainage area (km^2)
β_w = regression coefficient for channel depth (see Table D.2)

Table D.2. Coefficients for channel depth and width for specific regions

Region	α_D	β_D	α_w	β_w
San Francisco Bay Region	0.378	0.2582	3.513	0.3692
Eastern United Sates	0.33	0.2964	2.933	0.3916
Upper Green River, Wyoming	0.3094	0.1923	1.579	0.3866
Upper Salmon River, Idaho	0.1593	0.2625	1.4968	0.4562

Source: Rosgen, 1996.

Channel wetted parameter is computed as

$$P = W + D * \left[\sqrt{1 + \left(\frac{1}{S_1}\right)^2} + \sqrt{1 + \left(\frac{1}{S_2}\right)^2} \right] \text{ .... Equation D.48}$$

where

P = channel wetted parameter (m)
W = channel width (m)
D = channel depth (m)
S_1 = channel left slope (m)
S_2 = channel right slope (m)

Digital Elevation Model

A digital elevation model (DEM) is a raster representation of a continuous surface. Some extreme data in DEMs are usually classified as either sinks or peaks. A *sink* is an area surrounded by higher elevation values and is also referred to as a depression or pit. Sinks should be removed before attempting to derive any surface information.

DEM data layer is one of the most important layers that determine flow direction, flow accumulation, flow length, and slope. DEM-related flow functions are critical for hydrological and pollutant routing in GBMM.

Flow Direction

One of the keys to deriving hydrologic characteristics about a surface is the ability to determine the direction of flow from every cell in the grid. This is done with the Flow Direction command in ArcGIS. There are eight valid output directions, relating to the eight adjacent cells into which flow could travel as shown in Figure D.3.

The distance is determined between cell centers. Therefore if the cell size is 1, the distance between two orthogonal cells is 1 and the distance between two diagonal cells is 1.414216, the square root of 2.

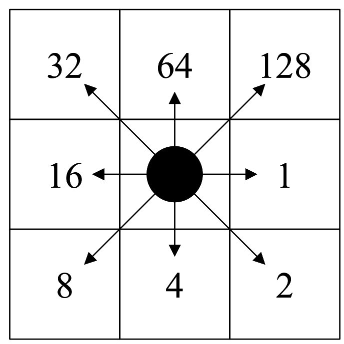


Figure D.3. Eight directions of flow for a DEM grid.

Flow Accumulation

The Flow Accumulation function can be used to calculate accumulated flow as the accumulated weight of all cells flowing into each downslope cell in the output grid. If no weight grid is provided, a weight of 1 is applied to each cell, and the value of cells in the output grid will be the number of cells that flow into each cell.

Because the sources of DEM data and the stream network features of the national hydrography dataset (NHD) are different, inconsistency between a DEM-derived stream network and an NHD stream network, (as shown in Figure D.4), has been noticed such as shifting of streams and their convergence points.

To minimize problems in stream network delineation and associated drainage area delineation, an algorithm was developed to modify the DEM grid by burning in the NHD stream network. Flow accumulation was computed based on the modified DEM. However, there were still some gaps due to the nature of the ArcGIS built-in algorithm for flow direction calculation. Therefore, a further step was carried out to fill out such gaps.

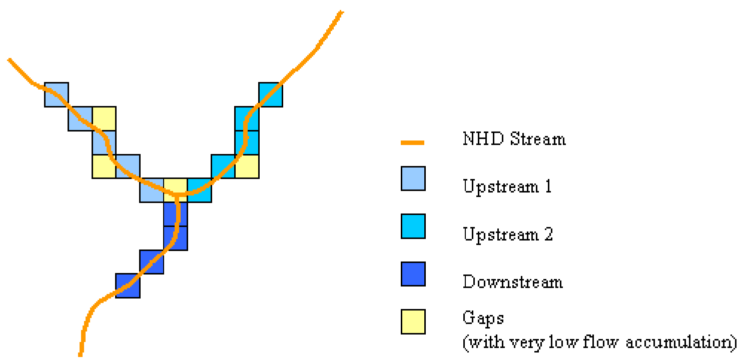


Figure D.4. Example showing the shifting of stream convergence points between a DEM-derived stream network and an NHD stream network.

Flow Length Algorithm

The Flow Length function calculates the distance along a flow path for each cell. This function uses the Flow Direction grid to compute a flow length for each cell along the flow path to the outlet. The steps involved in flow length calculation are shown in Figure D.5.

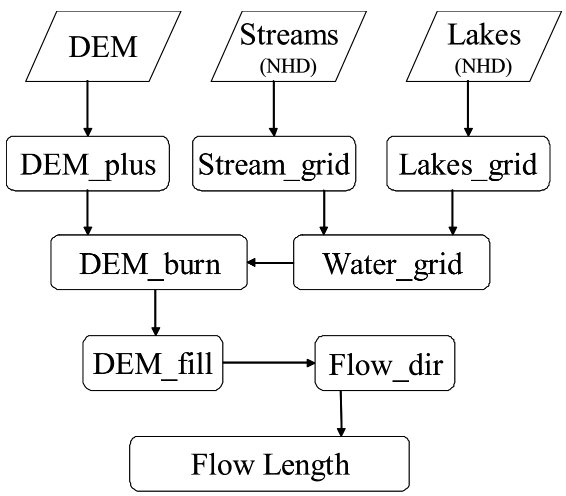


Figure D.5. Steps for deriving flow length from a DEM.

The flow length function has two arguments (input grids) – a Flow Direction grid and a Weight Factor grid.

Function: flowlength (<dir_grid>, <weight_grid>)

Arguments: <dir_grid> a grid indicating direction of flow
<weight_grid> a grid defining the impedance to move through each cell

The following two weighting masks are created with a unit value for overland cells and channel cells, and a zero value is assigned to the rest of the cells:

- overland cells mask
- channel cells mask

These masks are used as weighting grids along with the Flow Direction grid in the Flow Length function, which results in two output grids: flow length for overland cells (length to channel) and flow length for channel cells (length from channel cell to outlet).

Slope

GBMM uses DEM to compute the slope for each cell following the flow direction, which is different from the default slope function in ArcGIS (which computes the steepest slope rather than the slope along the flow direction). The flow direction-based slope further derives the following two grids using the overland and channel masks: average slope for overland cells (average slope to channel) and average slope for channel cells (average slope from channel cell to outlet).

Roughness Factor

A grid for Manning's coefficient can be generated from the land use coverage and a lookup table that defines a Manning's coefficient for each land use type. The average roughness factor is computed along the flow path for each cell using the *flowlength* function with the Manning grid as its weighting grid. The output grids are the average "n" for overland cells (average slope to channel) and the average "n" for channel cells (average slope from channel cell to outlet).

Hydraulic Radius

The channel hydraulic radius (R) grid can be calculated from user-defined channel width and depth or from the results of the regression equations discussed above (see section D.1.6). The average hydraulic radius is computed along the flow path for each channel cell using the *flowlength* function with the R grid as the weighting grid.

Rainfall

Rainfall (P_2) is defined as 24-hour-duration storm for a return period of 2 years rainfall events. A P_2 map of United States is shown in Figure D.6. A rainfall grid for the 2-year, 24-hour rainfall is created from your input constant value.

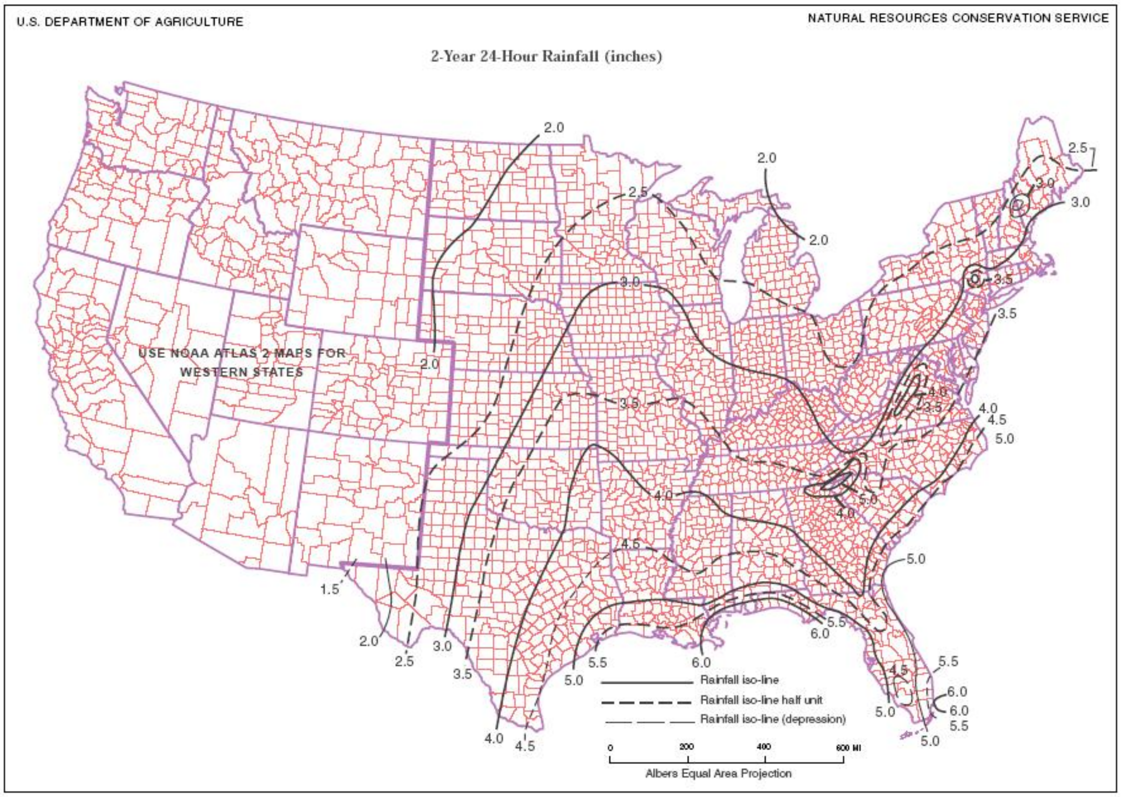


Figure D.6. 2-year, 24-hour rainfall map of United States.

D.1.7 Routing Algorithm

Overland Routing

Overland flow is routed through special runoff/water travel time zones. In this approach the watershed travel time grid is reclassified into several time zones based on the user-defined simulation time step. If the time step is daily, 1-day, 2-day, 3-day …, and n-day water travel zones to the outlet or outlets are defined as shown in Figure D.7.

Each day water moves from the n day zone to the (n-1) day zone, and the same procedure is repeated for each time step. Zonal sums for each simulation day are stored in arrays, and the daily hydrograph is calculated as shown in Table D.3.

Table D.3. Algorithm for calculating the hydrograph at the outlet

Day	Time Zone 1	Time Zone 2	Time Zone 3	Time Zone 4	Zone …
Day 1	Runoff 1	Runoff 2	Runoff 3	Runoff 4	Runoff…
Day 2		Runoff 1	Runoff 2	Runoff 3	Runoff …
Day…			Runoff 1	Runoff 2	Runoff …
…				…	…
Total (Time Series)	Sum (day1)	Sum (day2)	Sum (day3)	Sum (day4)	Sum (day…)

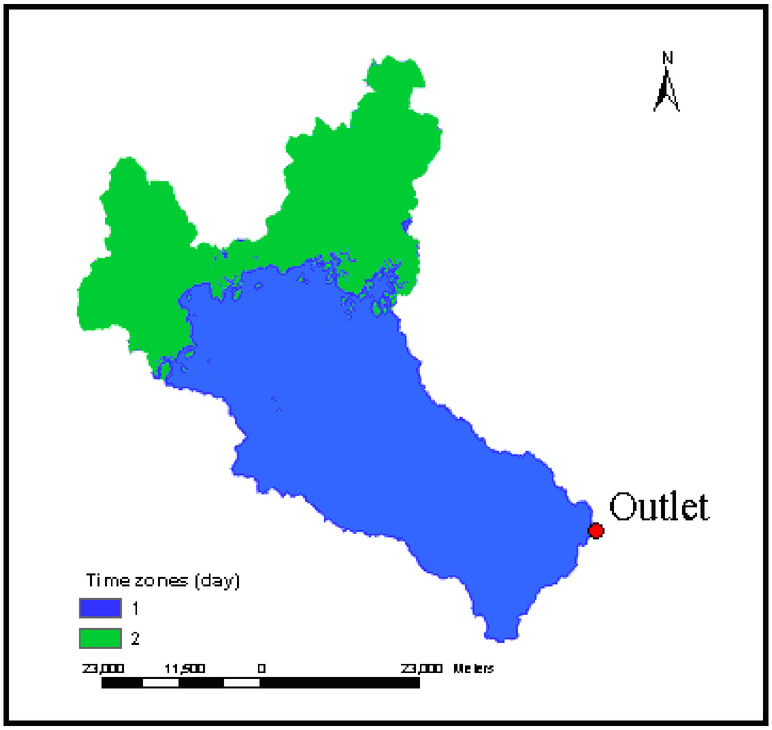


Figure D.7. Overland routing simulation time zones.

Channel Routing

Channel routing is performed based on the precalculated travel time along the flow paths for each channel cell. Channel cells are also classified into travel zones similar to those of overland routing. You can add “assessment points” along the stream channels, and the system automatically defines the lake/wetland outlets. Water is routed through the assessment points, lake/wetland, and watershed outlet, and daily hydrographs are automatically calculated and exported.

D.2 Sediment

D.2.1 Pervious Land

Sediment Yield

The Modified Universal Soil Loss Equation (MUSLE) is used for predicting the sediment yield (SY) at each cell assuming that each cell is a small watershed with homogenous land use and hydraulic characteristics. Comparing to the traditional USLE, MUSLE increases sediment yield prediction accuracy. It has been tested for a wide range of watersheds with areas ranging from 0.01 to 234 km^2 and slopes ranging from less than 1% to about 30% (Williams and Hann, 1978).

$$SY = 11.8 * (R_o * q_p)^{0.56} * K * C * P * LS \quad \text{Equation D.49}$$

where

SY = sediment yield per grid (tons/day)
R_o = runoff per cell (mm)
q_p = peak runoff rate per grid (m^3/s)
K = soil erodibility factor
C = crop management factor
P = erosion control practice factor
LS = slope length and gradient factor

Peak Runoff Rate

To apply MUSLE, the peak runoff rate (q_p) is calculated for each grid by using the modified rational approach (Neitsch et al., 2002). In this method, the peak runoff rate is determined using the fraction of daily rainfall that occurs during the time of concentration. The peak runoff rate is calculated by

$$q_p = \frac{\alpha_{tc} * R_o * A_c}{3.6 * t_{ov}} \quad \text{Equation D.50}$$

where

q_p = peak flow rate (m^3/s)
α_{tc} = fraction of daily rainfall that occurs during the time of concentration
R_o = runoff per cell (mm)
A_c = source grid area (km^2)
t_{ov} = overland travel time per cell (hr)

Slope Length and Gradient Factor

The slope length used in the slope length and gradient factor (LS) is calculated in one of two ways; the user can select either option.

1. *DEM-based slope length*

The LS factor calculation in GBMM is a direct translation of the Revised USLE LS factor AML (Arc Macro Language) code (Van Remortel et al., 2001) into VB scripts with ArcObjects. Some enhancements have been made to improve the performance by taking advantage of the availability of functions within the ArcObjects raster library (with the Spatial Analyst extension) to access and manipulate cell values in a grid with the row and column numbers. During the calculation of cumulative slope length, a flag raster with a value of 0 or 1 is introduced to indicate whether a cell needs further processing in subsequent iterations to eliminate redundant and unnecessary calculations. With the support of ArcObjects raster functions and the use of flag raster, the current LS factor module can finish the task of calculating the LS factor for a grid of around 2,000 x 2,000 cells in minutes. With AML code, the same calculation would take hours or even days.

2. *User-defined constant slope length*

The LS factor is calculated for each source grid as (Wischmeier and Smith, 1978)

$$LS = (0.045 * X_k)^b * (65.41 \sin^2\theta_k + 4.56 \sin\theta_k + 0.065) \quad \text{.....................Equation D.51}$$

$$\theta_k = \tan^{-1}\left(\frac{ps_k}{100}\right) \quad \text{...Equation D.52}$$

where

LS = slope length and gradient factor
X_k = user-defined slope length (m)
b = exponent coefficient
ps_k = percent slope (%)

The exponent coefficient (b) in Equation D51 is given by Wischmeier and Smith (1978):

$b = 0.5$ for $(ps_k \geq 5)$
$b = 0.4$ for $(3 < ps_k < 5)$
$b = 0.3$ for $(1 \leq ps_k \leq 3)$
$b = 0.2$ for $(ps_k < 1)$

Enhanced MUSLE Equation

The smallest watershed size for which the MUSLE has been tested is about 0.01 km^2 (Williams and Hann, 1978), which approximates a 100 m x 100 m grid area. To apply

MUSLE to a smaller grid cell, a grid size adjusting factor S_{adj} is introduced to the MUSLE equation. With the S_{adj} factor, the sediment yield calculated and summarized for several small grid areas will be equivalent to that calculated for the 100 m x 100 m grid area:

$$S_{adj} = 0.00221 * C_{sm}^{1.328} \quad \text{for } (C_{sm} \le 100 \text{ m}) \qquad \text{Equation D.53}$$

$$S_{adj} = 0.0 \quad \text{for } (C_{sm} > 100 \text{ m}) \qquad \text{Equation D.54}$$

where
S_{adj} = grid size adjusting factor
C_{sm} = cell resolution (m)

Multiplying S_{adj} with Equation D.49, the MUSLE equation is enhanced as

$$SY = 0.0261 * C_{sm}^{1.328} * (R_o * q_p)^{0.56} * K * C * P * LS \qquad \text{Equation D.55}$$

where
C_{sm} = cell resolution (≤ 100 m); if C_{sm} > 100 m, then SY should be calculated with the original MUSLE (Equation D.49)

Deriving MUSLE Grid Size Adjusting Factor

To derive the MUSLE grid size adjusting factor (S_{adj}), let C_{st} be the standard cell size (100 m x 100 m) and C_{sm} be the small cell size (< 100 m).

$$SY_{sm} = SY_{st} \Big/ \left(\frac{C_{st}}{C_{sm}}\right)^2 \qquad \text{Equation D.56}$$

where
SY_{sm} = sediment yield per small grid cell (tons/day)
SY_{st} = sediment yield per standard grid cell (tons/day)
C_{sm} = small grid cell (< 100 m)
C_{st} = standard grid cell (100 m)

Let F is the ratio of the small cell size to the standard cell size;

$$F = \frac{C_{st}}{C_{sm}} \qquad \text{Equation D.57}$$

Assuming cell size is the only variable in Equation D.49, the sediment yield for any cell size can be adjusted for standard cell size as

$$SY_{st} = \left(\frac{F^2}{F^{0.8}}\right)^{0.56} * SY \text{ ......} \quad \text{Equation D.58}$$

Substituting Equations D57 and D58 in Equation D.56 results in

$$SY_{sm} = \left(\frac{F^2}{F^{0.8}}\right)^{0.56} * SY \Big/ F^2 \text{ ......} \quad \text{Equation D.59}$$

$$SY_{sm} = \left(\frac{1}{C_{st}} * C_{sm}\right)^{1.328} * SY \text{ ......} \quad \text{Equation D.60}$$

where

$$S_{adj} = \left(\frac{1}{C_{st}} * C_{sm}\right)^{1.328} = 0.00221 * C_{sm}{}^{1.328} \text{ ......} \quad \text{Equation D.61}$$

D.2.2 Impervious Land: Sediment Load

The urban sediment load is based on accumulation of sediments during the dry period and wash-off during the wet period. The accumulation and washoff processes used in GBMM are similar to those used in both SWMM (Huber and Dickinson, 1988) and STORM (Hydrologic Engineering Center, 1977).

The rate of accumulation during the dry period is

$$\frac{dS}{dt} = S_{ac} - \beta * S \text{ ......} \quad \text{Equation D.62}$$

where

S = sediment accumulation for a grid (kg/ha)
S_{ac} = sediment accumulation rate (kg/ha/day)
β = depletion rate constant (per day)

By solving the above equation

$$S_t = \left[S_t^* * e^{-\beta * \Delta t} + \left[\frac{S_{ac}}{\beta}\right] * (1 - e^{-\beta * \Delta t})\right] * A_c * 10^{-7} \text{ ......} \quad \text{Equation D.63}$$

where

S_t = sediment accumulation at the end of the time step (tons/day)
S_t^* = available sediment load at the start of the time step (kg/ha)
S_{ac} = sediment accumulation rate (kg/ha/day)
β = depletion rate constant (per day)

A_c = grid area (m^2)
Δt = time step (day)

The wash-off per grid during the wet period is (Amy et al., 1974)

$$SY = (1 - e^{-1.81 * R_o * \Delta t}) * S_t \quad \text{.......... Equation D.64}$$

where
SY = sediment wash-off for the source grid (tons/day)
S_t = sediment load (accumulated load) for the source grid (tons/day)
R_o = runoff generated for the source grid (cm/day)
Δt = time step (day)

D.2.3 Sediment Delivery Ratio

There are many ways to estimate the sediment delivery ratio (SDR). For example, the U.S. Department of Agriculture (USDA) has published a handbook in which the SDR is simply related to drainage area (USDA-NRCS, 1972). The SDR, however, can be affected by a number of factors, including sediment texture source, distance to streams, channel density, basin area, slope, length, land use/land cover, and runoff rate.

In GBMM, the SDR, the fraction of the gross soil loss from overland cells that actually reaches the channel through shallow concentrated flow is estimated as a function of travel time (Ferro and Minacapilli, 1995; Ferro and Porto, 2000).

$$SDR = \alpha * e^{-\beta * T_{tot}} \quad \text{.......... Equation D.65}$$

where
SDR = sediment delivery ratio of a grid cell to the assessment point
α = calibration coefficient
β = routing coefficient
T_{tot} = total travel time (overland + channel) for the specific cell along the flow path to the outlet or assessment point (hr)

D.2.4 Sediment Load

The sediment yield at each grid is added to the leftover sediments from the previous day to determine the available sediments.

$$SY = SY + SY^* \qquad \text{for } (SY \leq SY_c) \quad \text{.......... Equation D.66}$$

where
SY = sediment yield for the source grid (tons)
SY^* = leftover sediment yield from the previous day (tons)
SY_c = sediment yield capacity per grid (tons)

The sediment load at any user-specified point or assessment point is computed by multiplying the sediment delivery ratio by the sediment generated at each grid, and then the contributions from the grid cells are summarized.

$$S_s = SY * SDR \quad \text{Equation D.67}$$

where
S_s = sediment load from each cell to the assessment point (tons/day)
SY = sediment generated at the source grid cell (tons/day)
SDR = sediment delivery ratio from each cell to a user-specified point

The leftover sediment at the end of the day for each grid cell is computed as

$$SY^* = SY - S_s \quad \text{Equation D.68}$$

where
SY^* = leftover sediment at the end of day (tons/day)
SY = sediment yield of the specific cell (tons/day)
S_s = sediment load from source cell to the user-specified point (tons/day)

D.2.5 Lake/Wetland/Reservoir

Mass Balance

When calculating sediment movement through a water body, it is assumed that the system is completely mixed. In a completely mixed system, as sediment enters the water body it is instantaneously distributed throughout the entire volume.

The mass balance equation for sediment in a water body is

$$S_w = S_i + S_{q_i} + S_{q_p} + S_{q_u} - S_{set} - S_{q_o} \quad \text{Equation D.69}$$

where
S_w = sediment load in the water body at the end of the time step (tons)
S_i = sediment load at the start of the time step (tons)
S_{qi} = sediment load entering through watershed inflow (tons)
S_{qp} = sediment point load entering through point sources (tons)
S_{qu} = sediment load entering through upstream inflow (tons)
S_{set} = sediment load removed by settling (tons)
S_{qo} = sediment load leaving through outflow (tons)

Settling

The amount of suspended solid settling that occurs in the water body on a given day is calculated as a function of concentration (Neitsch et al., 2002).

The initial suspended solid concentration is

$$C_i = 10^6 * \left[\frac{S_i + S_{q_i} + S_{qp} + S_{qu}}{V_i + V_{q_i} + V_{Go} + V_{pcp} + V_{qp} + V_{qu}} \right] \text{......................................Equation D.70}$$

where

C_i = initial concentration of suspended solids in the water (g/m^3)
S_i = sediment load at the start of the time step (tons)
S_{qi} = sediment load entering through watershed inflow (tons)
S_{qp} = sediment point load entering through point sources (tons)
S_{qu} = sediment load entering through upstream inflow (tons)
V_i = volume of water stored in the water body (m^3)
V_{qi} = volume of water entering the water body (m^3)
V_{Go} = volume of groundwater entering the water body (m^3)
V_{pcp} = volume of precipitation falling on the water body (m^3)
V_{qp} = volume of water entering through point sources to the water body (m^3)
V_{qu} = volume of water entering through upstream inflow to the water body (m^3)

Settling occurs only when the sediment concentration in the water body exceeds the equilibrium sediment concentration specified by the user, C_{eq}. The concentration of sediment in the water body at the end of the day is calculated as

$$C_{TSS} = (C_i - C_{eq}) * e^{-k_s * \Delta t * d_{50}} + C_{eq} \qquad \text{if } C_i > C_{eq} \text{ ....Equation D.71}$$

$$C_{TSS} = C_i \qquad \text{if } C_i \le C_{eq} \text{ ....Equation D.72}$$

where

C_{TSS} = final total suspended solids concentration in the water (g/m^3)
C_i = initial concentration of suspended solids in the water (g/m^3)
C_{eq} = equilibrium concentration of suspended solids in the water (g/m^3)
k_s = settling constant (per day)
Δt = time step (day)
d_{50} = median particle size of the inflow sediment (μm)

The median particle size of the inflow sediment is calculated based on SWAT algorithms (Neitsch et al., 2002):

$$d_{50} = \exp\left[0.41 * \frac{m_c}{100} + 2.71 * \frac{m_{silt}}{100} + 5.7 * \frac{m_s}{100} \right] \text{...................................Equation D.73}$$

where

d_{50} = median particle size of the inflow sediment (μm)
m_c = percent clay in the inflow sediment (%)
m_{silt} = percent silt in the inflow sediment (%)
m_s = percent sand in the inflow sediment (%)

The amount of sediment settling out of solution on a given day is then calculated as

$$S_{set} = 10^{-6} * (C_i - C_{TSS}) * V \text{ ....Equation D.74}$$

where

S_{set} = sediment load removed by settling (tons)
C_i = initial concentration of suspended solids in the water (g/m^3)
C_{TSS} = final total suspended solids concentration in the water (g/m^3)
V = total volume of water in the water body (m^3)

The total volume of water in the water body is the sum of all inflows and the initial volume of the lake at the start of the day:

$$V = V_i + V_{q_i} + V_{Go} + V_{pcp} + V_{qp} + V_{qu} \text{ ....Equation D.75}$$

where

V = total volume of water in the water body (m^3)
V_i = volume of water stored in the water body (m^3)
V_{qi} = volume of water entering in the water body (m^3)
V_{Go} = volume of groundwater entering the water body (m^3)
V_{pcp} = volume of precipitation falling on the water body (m^3)
V_{qp} = volume of water entering through point sources to water body (m^3)
V_{qu} = volume of water entering through upstream inflow to water body (m^3)

Sediment Outflow

The amount of sediment transported out of the water body on a given day is calculated as a function of the final concentration. The initial suspended solid concentration is

$$S_{q_o} = 10^{-6} * C_{TSS} * V_{q_o} \text{ ....Equation D.76}$$

where

S_{qo} = sediment load leaving through the outflow (tons)
C_{TSS} = final total suspended solids concentration in the water (g/m^3)
V_{qo} = volume of outflow from the water body (m^3)

D.2.6 Point Source Load

Point source coverage is used to create a point load grid. Time series data for each point source are added to the corresponding cells in the point grid at each time step. Point loads are routed through the predefined flow paths. Point time series data can be specified for flow, sediment, and mercury.

D.3 Mercury

For each grid in a watershed, the mercury module simulates mercury loading processes for various land categories; the module also simulates a simplified channel process. The overall structure of the module is shown in Figure D.8.

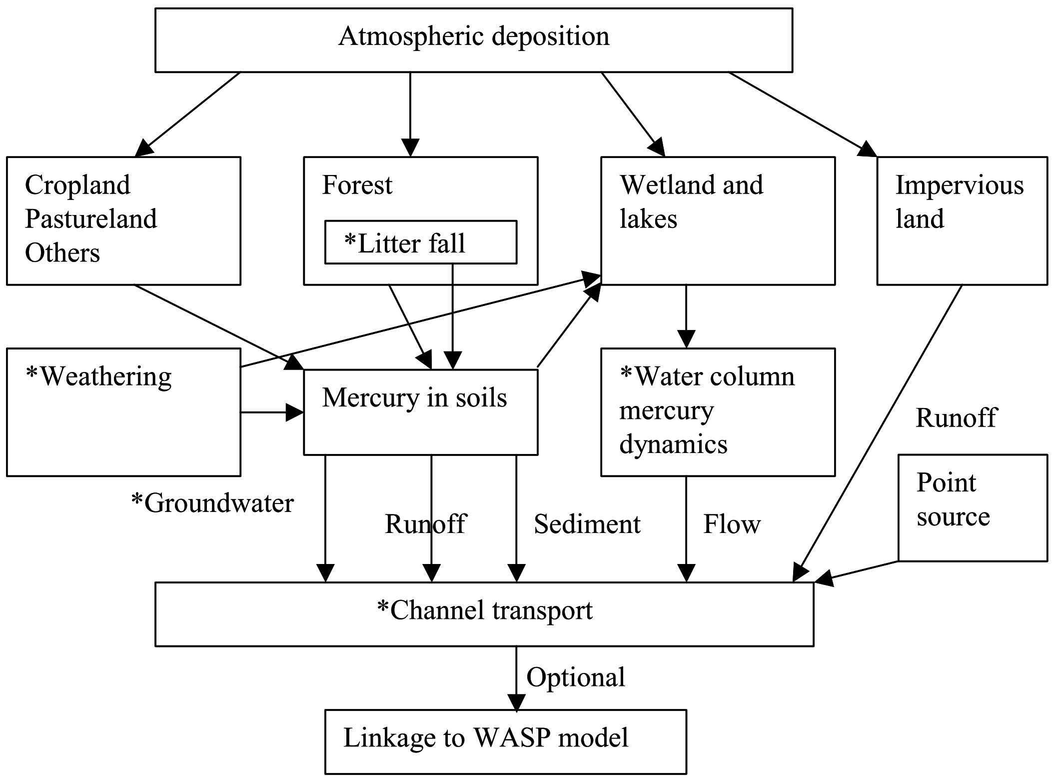


Figure D.8. Structure of the grid-based watershed mercury module.

New algorithms (*, not in the first generation of the WCS mercury model) were developed, including forest litter fall, wetland (lake) water column mercury dynamics, weathering and groundwater output, and channel transport.

The major computational steps for the mercury module are outlined below:

- Simple deposition equations are used to calculate the atmospheric load on various land categories. The amount of the total deposition that reaches the soil varies depending on the land use and vegetation cover.

- In addition to the direct atmospheric deposition load, a special module is developed to simulate the mercury load in the forest litter fall.

- Once the mercury reaches soils, the mercury transformation and loss in soil and the mercury load from watershed runoff and sediment are calculated based on IEM-2M algorithms (USEPA, 1997, 1998).

- A simple weathering module is developed to calculate the mercury output from shallow groundwater.

- The wetland module receives mercury input from atmospheric deposition, runoff, sediment, and groundwater; calculates the change in mercury concentration in the water column, including the burial and methylation processes; and exports the mercury load to tributaries or mainstem rivers.

- Mercury loss in channels is calculated as a first-order decay rate.

- In addition to the simple channel transport algorithm in GBMM, the mercury load from tributaries can be used as direct input for the WASP model to simulate the mercury dynamics in mainstem rivers.

- The mercury module is integrated with the hydrology and sediment modules.

The enhanced GBMM system uses the daily time step. The detailed algorithms used to calculate mercury load from watersheds are described in sections 2.3.1 through 2.3.9.

D.3.1 Pervious Land: Atmospheric Deposition Load

The atmospheric deposition load for the pervious land is calculated by multiplying the local deposition rate by the grid area:

$L_p = (1 - f_{veg}) * D * A_c$ for dry day ....Equation D.77

$L_p = (1 - f_{veg}) * W * A_c$ for wet day..Equation D.78

where

L_p = mercury deposition load on pervious land (µg/day)
f_{veg} = vegetation factor or the fraction of deposition that is intercepted, reemitted and absorbed by the vegetation. (For this implementation, $f_{veg} = 0$.)
D = daily dry deposition rate (µg/m^2/day)
W = daily wet deposition rate (µg/m^2/day)
A_c = grid area (m^2)

D.3.2 Impervious Land: Atmospheric Deposition Load

The atmospheric deposition load for impervious land is calculated by multiplying the local deposition rate by the grid area:

$$L_{Id} = D * A_c \quad \text{for dry day} \qquad \text{Equation D.79}$$

$$L_{Iw} = W * A_c \quad \text{for wet day} \qquad \text{Equation D.80}$$

where

L_{Id} = mercury dry deposition load on impervious land (μg/day)
L_{Iw} = mercury wet deposition load on impervious land (μg/day)
D = daily dry deposition rate (μg/m^2/day)
W = daily wet deposition rate (μg/m^2/day)
A_c = grid area (m^2)

D.3.3 Forestland

The forest mercury loading module includes these processes: atmospheric deposition on leaf surface, leaf mercury capture, leaf mercury accumulation, canopy litter fall, litter decomposition, and mercury release to soil.

Mosbaek et al. (1988) convincingly showed that for leafy, aboveground parts of plants, virtually the entire mercury uptake was from air. More recently, Rea et al. (2002) found that direct uptake of dissolved mercury from soil water accounted for only about 3 to14 percent of the mercury in forest litter fall. Based on measurements and modeled deposition velocities, they concluded that it is possible that all the mercury in foliage represents atmospheric mercury accumulated throughout the growing season. Fleck et al. (1999) also found that tree leaf mercury concentration was closely related to the growing season length.

Mercury in plant tissue can increase 10-fold from spring bud break (3.5 ng/g) to autumn litter fall (36 ng/g) (Rea et al., 2002). Mercury levels as high as 52.3 ng/g have been measured in “pristine” deciduous forest foliage (Lindberg, 1996), and from 20.0 to 65.5 ng/g in conifer species (Rasmussen, 1994).

Forest canopies in the northeast United States have foliage surface areas up to 10 times greater than the land area they cover, providing mercury concentrations in the through fall that average twice that of precipitation and annual mercury flux in litter fall that is greater than annual wet deposition (Rea et al., 1996). Leaf litter decomposes over a number of years, releasing the mercury for potential aqueous transport, most likely as organically bound complexes (e.g., humic acids). The association between total mercury concentration and the organic fraction of suspended sediment can be explained by the high affinity of divalent mercury for organic substances in forest soils.

The contribution of litter fall to the total mercury deposition in forests is significant (Rea et al., 2002; Schwesig and Matzner, 2000). According to Schwesig and Matzner (2001), 74 percent of total mercury deposited on a forest could reach the mineral soil. At the annual catchment scale, forested watersheds act as sinks for both methylmercury and total mercury (Schwesig, 2001). Less than 10 percent of total mercury input to a forested watershed was exported (Scherbatskoy et al., 1998).

Atmospheric Deposition Load

The atmospheric deposition load for forestland is calculated by multiplying the local deposition rate by the grid area.

$$L_f = (1 - f_{int}) * D * A_c \quad \text{for dry day........Equation D.81}$$

$$L_f = \left[\{(1 - f_{int} * f_{adh}) * W\} + \{f_{int} * (1 - f_{adh}) * D * Dy_{dry}\}\right] * A_c \quad \text{for wet day .Equation D.82}$$

where

L_f = mercury deposition load on forestland (μg/day)
D = daily dry deposition rate (μg/m^2/day)
W = daily wet deposition rate (μg/m^2/day)
f_{int} = interception fraction
f_{adh} = adhering fraction
Dy_{dry} = number of dry days before rainy day (days)
A_c = grid area (m^2)

The interception fraction is the fraction of the total deposition within a unit area that is initially intercepted by vegetation; the adhering fraction is the fraction of deposition that adheres to the plant; that is, it is not washed off (USEPA 1997).

Litter Decomposition Load

The litter decomposition load for forestland is calculated by multiplying the amount of decomposed litter by the leaf litter mercury concentration:

$$L_d = D_L * C_L * A_c \text{ ....Equation D.83}$$

where

L_d = litter decomposition mercury load on forestland (μg/day)
D_L = daily leaf litter decomposed (g/m^2/day)
C_L = leaf litter mercury concentration (μg/g)
A_c = grid area (m^2)

Daily leaf litter decomposition can be calculated as

$$D_L = K_{dcomp} * L_t \text{ ....Equation D.84}$$

where

D_L = daily leaf litter decomposed (g/m^2/day)
K_{dcomp} = litter decomposition rate (per day)
L_t = amount of litter (g/m^2)

The daily mass balance for litter is calculated as

$$L_t = L_{t0} + \left(P_{Ld} - K_{dcomp} * L_{t0}\right) * \Delta t \quad \text{Equation D.85}$$

where

L_t = amount of litter at the end of the day (g/m^2)
L_{t0} = amount of litter at the beginning of the day (g/m^2)
P_{Ld} = daily litter production (g/m^2/day)
Δt = time step (day)
K_{dcomp} = litter decomposition rate (per day)

Forest litter production and decomposition rates can be found in a more recent publication (Finzi et al., 2001):

K_{dcomp} = 0.0005 (per day) for evergreen pine forest
K_{dcomp} = 0.0019 (per day) for deciduous forest
K_{dcomp} = 0.0012 (per day) for mixed forest

The rate of litter decomposition was also shown to be related to evapotranspiration (ET) and to the lignin content of litter (Meentemeyer, 1978). Daily leaf litter production is assumed to be linear in relation to annual leaf litter production. It is calculated by dividing the annual litter production to the number of days for the specific year.

$$P_{Ld} = \frac{P_{Ly}}{d_y} \quad \text{Equation D.86}$$

where

P_{Ld} = daily litter production (g/m^2/day)
P_{Ly} = yearly litter production (g/m^2/year)
d_y = number of days per year (365 days)

Meentemeyer et al. (1982) demonstrated a strong positive relationship between the leaf and total plant litter production and the ET calculated by using a global climatic database. Annual leaf litter production is calculated as a linear function of actual annual ET (Meentemeyer et al., 1982):

$$P_{Ly} = 5.805 * ET - 78.55 \qquad \text{for } (ET \geq 25) \quad \text{Equation D.87}$$

$$P_{Ly} = 2.6 * ET \qquad \text{for } (ET < 25) \quad \text{Equation D.88}$$

where

P_{Ly} = yearly litter production (g/m^2/year)
ET = actual annual evapotranspiration (cm/year)

The mercury concentration in leaf litter can be estimated using the air-plant bio-concentration factor (BCF) (USEPA, 1997) or the average leaf mercury content for different types of plants:

$$C_L = 10^{-3} * C_A * BCF \quad \text{Equation D.89}$$

where

C_L = leaf litter mercury concentration (μg/g)
C_A = air mercury concentration (ng/g)
BCF = air-plant bio-concentration factor

D.3.4 Watershed Mercury Mass Balance

The core equations for mercury transformation in soils and loadings from the watersheds are based on the Indirect Exposure Model, version 2 (IEM-2M). IEM-2M was initially developed by EPA's Office of Research and Development for the dioxin exposure reassessment and was revised for the *Mercury Study, Report to Congress* (USEPA, 1997). Most of the equations are also documented in the *Methodology for Assessing Health Risks Associated with Multiple Pathways of Exposure to Combustor Emissions* (USEPA, 1998). IEM algorithms and parameters were modified and used in mercury studies by Lyon et al. (1997, 1998) and Tsiros and Ambrose (1998, 1999). IEM-2M produces point estimates of media concentrations, exposure, and risk from concentrations and deposition rates of air toxics. When combined with GIS modeling technology, IEM-2M can be modified to estimate mercury loading from different sources at the watershed scale, as done in the original WCS mercury loading model (Greenfield et al., 2002).

$$\frac{dC_s}{dt} = \frac{L}{V_s} - (Ks_r + Ks_L + Ks_{ro} + Ks_{se}) * C_s \quad \text{Equation D.90}$$

$$L = L_p \quad \text{for pervious land} \quad \text{Equation D.91}$$

$$L = L_f + L_d \quad \text{for forestland} \quad \text{Equation D.92}$$

$$V_s = 10^{-2} * A_c * z_d \quad \text{Equation D.93}$$

where

C_s = concentration of mercury in watershed soils (μg/m^3)
L = mercury deposition load (μg/day)
L_p = mercury deposition load on pervious land (μg/day)
L_f = mercury deposition load on forestland (μg/day)
L_d = litter decomposition mercury load on forestland (μg/day)
Ks_r = reduction rate constant (per day)
Ks_L = leaching loss constant (per day)
Ks_{ro} = runoff loss constant (per day)
Ks_{se} = erosion loss constant (per day)
V_s = watershed soil volume (m^3)

A_c = grid area (m^2)
z_d = watershed soil mixing depth (cm)

In the simplified procedure, the volatilization process between atmosphere and soil is assumed to be balanced and therefore ignored; the divalent-mercury is considered a dominant component.

Calculate Soil Volumetric Water Content

$$\theta_w = \frac{S_w}{100} \quad \text{.......... Equation D.94}$$

where
θ_w = soil volumetric water content per cell (cm/cm)
S_w = available water in unsaturated soil zone (cm/m)

Calculate Soil Mercury Water Fraction

$$f_{ws} = \frac{\theta_w}{\left(\theta_w + K_{ds} * BD\right)} \quad \text{.......... Equation D.95}$$

where
f_{ws} = soil mercury water fraction
θ_w = soil volumetric water content per cell (cm/cm)
K_{ds} = soil water partition coefficient (ml/g)
BD = soil bulk density (g/cm^3)

Calculate Soil Mercury Solid Fraction

$$f_{ps} = 1 - f_{ws} \quad \text{.......... Equation D.96}$$

where
f_{ps} = soil mercury solid fraction
f_{ws} = soil mercury water fraction

Calculate Leaching Loss Rate

$$Ks_L = \frac{\left(P_{tot} - R_o - ET\right) * f_{ws}}{\left(\theta_w * z_d\right)} \quad \text{.......... Equation D.97}$$

where
Ks_L = leaching loss rate (per day)
P_{tot} = total available input water at the surface (cm/day)
R_o = surface runoff (cm/day)

ET = actual evapotranspiration (cm/day)
f_{ws} = soil mercury water fraction
θ_w = soil volumetric water content per cell (cm/cm)
z_d = watershed soil incorporation depth or mixing depth (cm)

Calculate Runoff Loss Rate

$$Ks_{ro} = \frac{R_o * f_{ws}}{(\theta_w * z_d)} \quad \text{............Equation D.98}$$

where
Ks_{ro} = runoff loss rate (per day)
R_o = surface runoff (cm/day)
f_{ws} = soil mercury water fraction
θ_w = soil volumetric water content per cell (cm/cm)
z_d = watershed soil incorporation depth or mixing depth (cm)

Calculate Reduction Loss Rate

$$Ks_r = \frac{K_{rs} * \theta_w * z_r}{z_d} \quad \text{............Equation D.99}$$

where
Ks_r = reduction loss rate (per day)
K_{rs} = soil base reduction rate (per day)
θ_w = soil volumetric water content per cell (cm/cm)
z_r = soil reduction depth (cm)
z_d = watershed soil incorporation depth or mixing depth (cm)

Calculate Erosion Loss Rate

$$Ks_{se} = \frac{10^2 * S_s * ef}{A_c} * \frac{f_{ps}}{BD * z_d} \quad \text{............Equation D.100}$$

where
Ks_{se} = erosion loss rate (per day)
S_s = sediment load from each cell to the assessment point (tons/day)
A_c = grid area (m^2)
ef = pollutant enrichment factor
f_{ps} = soil mercury solid fraction
BD = soil bulk density (g/cm^3)
z_d = watershed soil incorporation depth or mixing depth (cm)

Calculate Resultant Watershed Soil Concentration

The ordinary differential equation (Equation 92) for mercury soil concentration is solved by using Euler's method.

$$C_s = C_0 + \Delta t * \frac{dC_s}{dt} \quad \text{.......... Equation D.101}$$

where

C_s = concentration of mercury in watershed soils at the end of the time step (μg/m^3)
C_0 = concentration of mercury in watershed soils at the start of the time step (μg/m^3)
Δt = time step (day)
$\frac{dC_s}{dt}$ = change in concentration per day (μg/m^3/day)

D.3.5 Overland Mercury Load

Calculate Mercury Runoff Load on Pervious Surface

$$Ls_{ro} = 10^{-2} * Ks_{ro} * C_s * A_c * z_d \quad \text{.......... Equation D.102}$$

where

Ls_{ro} = mercury runoff load per grid on pervious surface (μg/day)
Ks_{ro} = runoff loss rate constant (per day)
C_s = concentration of mercury in watershed soils (μg /m^3)
A_c = grid area (m^2)
z_d = watershed soil incorporation depth or mixing depth (cm)

Calculate Mercury Runoff Load on Impervious Surface

$$L_{Iro} = \left(L_{Iw} + L_{Id} * Dy_{dry}\right) * f_{ws} \quad \text{.......... Equation D.103}$$

where

L_{Iro} = mercury runoff load per grid on impervious surface (μg/day)
L_{Iw} = mercury wet deposition load on impervious land (μg/day)
L_{Id} = mercury dry deposition load on impervious land (μg/day)
Dy_{dry} = number of dry days before rainy day (days)
f_{ws} = soil mercury water fraction

Calculate Mercury Erosion Load on Pervious Surface

$$Ls_{se} = 10^{-2} * Ks_{se} * C_s * A_c * z_d \quad \text{.......... Equation D.104}$$

where

Ls_{se} = mercury erosion load per grid on pervious surface (µg/day)
Ks_{se} = soil erosion loss rate constant (per day)
C_s = concentration of mercury in watershed soils (µg/m^3)
A_c = grid area (m^2)
z_d = watershed soil incorporation depth or mixing depth (cm)

Calculate Mercury Erosion Load on Impervious Surface

$$L_{Ise} = \frac{S_s}{PD} * C_s * f_{ps} \qquad \text{Equation D.105}$$

where
L_{Ise} = mercury sediment load per cell on impervious surface (µg/day)
S_s = sediment load from each cell to the assessment point (tons/day)
C_s = concentration of mercury in watershed soils (µg/m^3)
f_{ps} = soil mercury solid fraction
PD = soil particle density (g/cm^3)

D.3.6 Groundwater Mercury Load

The mercury concentration in saturated soil, C_{ss}, can be obtained by solving the following ordinary differential equation

$$V_{ss} * \frac{dC_{ss}}{dt} = L_L + L_{rock} - L_{gw} - L_{sp} \qquad \text{Equation D.106}$$

where
C_{ss} = mercury concentration in shallow saturated soil (µg/m^3)
V_{ss} = shallow saturated soil volume (m^3)
L_L = mercury load entering through leaching (µg/day)
L_{rock} = mercury load entering from bedrock weathering (µg/day)
L_{gw} = mercury load leaving through groundwater outflow (µg/day)
L_{sp} = mercury load leaving through seepage to deep aquifer (µg/day)
t = time (day)

Calculate Mercury Load from Leaching

Mercury input from soil leaching can be calculated as

$$L_L = 10^{-2} * Ks_L * C_s * A_c * z_d \qquad \text{Equation D.107}$$

where
L_L = mercury load entering through soil leaching (µg/day)
Ks_L = leaching loss rate constant (per day)
C_s = concentration of mercury in watershed soils (µg/m^3)

A_c = grid area (m^2)
z_d = watershed soil incorporation depth or mixing depth (cm)

Calculate Mercury Load from Bedrock Weathering

Mercury input from bedrock weathering can be calculated as

$$L_{rock} = 10^{-3} * K_{cw} * C_{rock} * A_c * RD \quad \text{Equation D.108}$$

where
L_{rock} = mercury load entering from bedrock weathering (µg/day)
K_{cw} = chemical weathering rate constant (µm/day)
C_{rock} = concentration of mercury in bedrock (µg/kg)
A_c = grid area (m^2)
RD = bedrock density (g/cm^3)

Calculate Groundwater Mercury Load

Mercury output from groundwater can be calculated as

$$L_{gw} = C_{ss} * A_c * G_o * f_{ws} * 10^{-2} \quad \text{Equation D.109}$$

where
L_{gw} = mercury load from shallow groundwater (µg/day)
C_{ss} = mercury concentration in shallow saturated soil (µg/m^3)
A_c = grid area (m^2)
G_o = shallow groundwater outflow (cm/day)
f_{ws} = soil mercury water fraction

Calculate Seepage Mercury Load

Mercury output from seepage to the deep aquifer can be calculated as

$$L_{sp} = C_{ss} * A_c * S_p * f_{ws} * 10^{-2} \quad \text{Equation D.110}$$

where
L_{sp} = mercury load leaving through seepage to the deep aquifer (µg/day)
C_{ss} = mercury concentration in shallow saturated soil (µg/m^3)
A_c = grid area (m^2)
S_p = seepage to the deep aquifer (cm/day)
f_{ws} = soil mercury water fraction

Calculate Shallow Saturated Soil Volume

The shallow saturated soil volume is calculated as

$$V_{ss} = A_c * (d_{rock} - d_{unsat}) \text{ ....Equation D.111}$$

where

V_{ss} = shallow saturated soil volume (m^3)
A_c = grid area (m^2)
d_{rock} = depth to bedrock (m)
d_{unsat} = unsaturated soil depth (m)

Mierle (1995) estimated the weathering rates of individual minerals from silicon release rates compiled from the literature and the silica content of individual minerals that are characteristic of Precambrian soils for small watersheds in Ontario, Canada. The median value was 100 kg/ha/y, and 80 percent of the values were between 42 and 179 kg/ha/y. For a typical mercury content of 60 µg/kg of acidic rocks (Jonasson and Boyle, 1979), these weathering rates suggest a mercury release rate of 0.6, (0.25 to 1.07) µg/m^2/y. These release rates are 7.0 percent (3.0 to 12.6 percent) of wet deposition. Weathering rates vary by rock types and climate conditions as shown in Table D.4.

Table D.4. Rates of weathering of clean rock surfaces (µm/1,000 years)

Rock Type	Cold climate	Warm, humid climate
Basalt	10	100
Granite	1	10
Marble	20	200

Source: Space Physics Research Laboratory at The University of Michigan. Website updated Nov 12, 2005. <http://www.sprl.umich.edu>.

Soil depth also affects the weathering rate of bedrocks, and a linear relationship between weathering rate and soil depth was shown by Heimsath et al. (1997) in Martin County, California (greenstone, greywacke sandstone, and chert). Chemical weathering rates of rocks and minerals can be found in Colman and Dethier (1986) and Johnson et al. (1994).

Calculate Resultant Shallow Saturated Soil Concentration

The ordinary differential equation for mercury soil concentration is solved by using Euler's method:

$$C_{ss} = C_{s0} + \Delta t * \frac{dC_{ss}}{dt} \text{ ....Equation D.112}$$

where

C_{ss} = mercury concentration in shallow saturated soil ($\mu g/m^3$)
C_{s0} = concentration of mercury in shallow saturated soils at the start of time step ($\mu g/m^3$)
Δt = time step (day)
$\frac{dC_{ss}}{dt}$ = change in concentration per day ($\mu g/m^3/day$)

D.3.7 Wetland/Lake

The net mercury methylation rate (the net result of methylation and demethylation) for most soils appears to be quite low, with much of the measured methylmercury in soils potentially resulting from wet fall. A significant and important exception appears to be wetlands. In addition to input from upland and precipitation, wetlands appear to produce methylmercury by chemical and microbial processes. Therefore, wetlands are sources of methylmercury (Kamman, 1998). In Europe, Schwesig et al. (1999) found that although the storage of total mercury (60 cm of soil) was significantly lower in wetland soils as compared to upland soils, methylmercury content was much higher in wetland soils; mercury methylation and reduction were the important processes in wetland soils. Wetlands appear to convert a small but significant fraction of the input mercury into methylmercury, which can be exported to nearby water bodies and potentially bioaccumulated in the aquatic food chain (USEPA, 1997).

Atmospheric Deposition Load

The atmospheric deposition load on a water surface is calculated by multiplying the local deposition rate with the surface area of the water body:

$$L_w = D * A_c \quad \text{for dry day} \qquad \text{Equation D.113}$$

$$L_w = W * A_c \quad \text{for wet day} \qquad \text{Equation D.114}$$

where

L_w = mercury deposition load on the water surface ($\mu g/day$)
D = daily dry deposition rate ($\mu g/m^2/day$)
W = daily wet deposition rate ($\mu g/m^2/day$)
A_c = grid area (m^2)

Watershed Load

$$L_s = Ls_{ro} + L_{Iro} + Ls_{se} + L_{Ise} \qquad \text{Equation D.115}$$

where

L_s = mercury load from the watershed ($\mu g/day$)
Ls_{ro} = runoff mercury load from pervious surface ($\mu g/day$)
L_{Iro} = runoff mercury load from impervious surface ($\mu g/day$)

Ls_{se} = sediment mercury load from pervious surface (μg/day)
L_{Ise} = sediment mercury load from impervious surface (μg/day)

Total Mercury Load

$$L_{Hg} = L_w + L_s + L_{pt} + L_{gw} + L_{up} \text{ ....Equation D.116}$$

where

L_{Hg} = total mercury load (μg/day)
L_w = mercury deposition load on the water surface (μg/day)
L_s = mercury load from the watershed (μg/day)
L_{pt} = mercury point source load (μg/day)
L_{gw} = mercury load from shallow groundwater (μg/day)
L_{up} = mercury load from upstream (μg/day)

Mercury Mass Balance in Lake/Wetland

For GBMM, a simple wetland module that includes burial loss and methylation rate was developed. The daily concentration of mercury in the water column can be written as

$$\begin{aligned} V_w * \frac{dC_{wt}}{dt} &= [L_{Hg}] - [(q_o + R_{sw}) * C_{wt} * f_{dw}] - \left[(S_{qo} + S_{set}) * \frac{C_{wt} * f_{sw}}{PD}\right] \\ &- [(\alpha_w * Kw_r + \beta_w * Kw_m) * V_w * C_{wt}] - [v_{sb} * A_w * C_{wt} * f_{bw}] \\ &+ [v_{rs} * A_w * C_{bt} * f_{sb}] + \left[R_{sw} * C_{bt} * \frac{f_{db}}{\theta_{bs}}\right] \text{........................Equation D.117} \end{aligned}$$

where

C_{wt} = total water column mercury concentration (μg/m^3)
C_{bt} = total benthic mercury concentration (μg/m^3)
V_w = volume of water column (m^3)
L_{Hg} = mercury load entering the water column (μg/day)
q_o = water discharge from the water body (m^3/day)
R_{sw} = pore water diffusion volume (m^3/day)
S_{qo} = sediment load leaving through outflow (tons/day)
S_{set} = sediment load removed by settling (tons/day)
PD = soil particle density (g/cm^3)
f_{dw} = fraction of dissolved water mercury in the water column
f_{sw} = fraction of solid-water mercury in the water column
f_{bw} = fraction of biomass mercury in the water column
f_{sb} = fraction of solid-water mercury in the benthic sediments
f_{db} = fraction of dissolved benthic mercury in the benthic sediments
α_w = net reduction loss factor in the water column
Kw_r = water body mercury reduction rate constant (per day)

β_w = net methylation loss factor in the water column
Kw_m = water body mercury methylation rate constant (per day)
v_{sb} = biomass settling velocity in the water column (m/day)
A_w = surface area of the water body (m^2)
v_{rs} = sediment resuspension velocity (m/day)
θ_{bs} = porosity of the benthic sediment bed

The daily concentration of mercury in benthic sediments is

$$V_b * \frac{dC_{bt}}{dt} = \left[R_{sw} * C_{wt} * f_{dw}\right] + \left[S_{set} * \frac{C_{wt} * f_{sw}}{PD}\right] - \left[\left(\alpha_b * Kb_r + \beta_b * Kb_m\right) * V_b * C_{bt}\right]$$
$$- \left[R_{sw} * C_{bt} * \frac{f_{db}}{\theta_{bs}}\right] + \left[v_{sb} * A_w * C_{wt} * f_{bw}\right] - \left[v_{rs} * A_w * C_{bt} * f_{sb}\right]$$
$$- \left[v_{bur} * A_w * C_{bt} * f_{sb}\right] \text{...Equation D.118}$$

where

C_{bt} = total benthic mercury concentration ($\mu g/m^3$)
C_{wt} = total water column mercury concentration ($\mu g/m^3$)
V_b = volume of benthic sediment bed (m^3)
R_{sw} = pore water diffusion volume (m^3/day)
S_{set} = sediment load removed by settling (tons/day)
PD = soil particle density (g/cm^3)
f_{dw} = fraction of dissolved water mercury in the water column
f_{sw} = fraction of solid water mercury in the water column
f_{db} = fraction of dissolved benthic mercury in the benthic sediments
f_{bw} = fraction of biomass mercury in the water column
f_{sb} = fraction of solid water mercury in the benthic sediments
α_b = net reduction loss factor in the benthic sediments
Kb_r = benthic sediment mercury reduction rate constant (per day)
β_b = net methylation loss factor in benthic sediments
Kb_m = benthic sediment mercury methylation rate constant (per day)
θ_{bs} = porosity of the benthic sediment bed
v_{sb} = biobass settling velocity in water column (m/day)
v_{rs} = sediment resuspension velocity (m/day)
v_{bur} = burial velocity (m/day)
A_w = surface area of the water body (m^2)

Equations D117 and D118 were modified from EPA's *Mercury Study, Report to Congress*, Volume III (USEPA, 1997).

Calculate Water Column Volume

The volume of water column is calculated as

$$V_w = A_w * H \text{ .... Equation D.119}$$

where

V_w = volume of the water column (m^3)
A_w = surface area of the water body (m^2)
H = depth of the water column (m)

Calculate Benthic Sediments Volume

The volume of benthic sediments is calculated as

$$V_b = A_w * Z_b \text{ .... Equation D.120}$$

where

V_b = volume of the benthic sediment bed (m^3)
A_w = surface area of the water body (m^2)
Z_b = depth of the benthic sediment bed (m)

Calculate Pore Water Diffusion Volume

Pore water diffusion volume is computed as

$$R_{sw} = \frac{E_{sw} * A_w * \theta_{bs}}{Z_b} * 86400 \text{ .... Equation D.121}$$

where

R_{sw} = pore water diffusion volume (m^3/day)
E_{sw} = pore water diffusion coefficient (m^2/sec)
A_w = surface area of the water body (m^2)
θ_{bs} = porosity of the benthic sediment bed
Z_b = depth of the benthic sediment bed (m)

Calculate Water Mercury Fraction in Water Column

The fraction of mercury concentration is given as

$$f_{dw} = \frac{1}{1 + \left(Kd_{sw} * C_{TSS} + K_{bio} * C_{bio}\right) * 10^{-6}} \text{ .... Equation D.122}$$

where

f_{dw} = fraction of dissolved water mercury in the water column
Kd_{sw} = sediment/water partition coefficient in the water column
C_{TSS} = total suspended solids concentration in the water column (g/m^3)
K_{bio} = biomass/water partition coefficient in the water column
C_{bio} = biomass concentration in the water column (g/m^3)

Calculate Solid Mercury Fraction in Water Column

$$f_{sw} = f_{dw} * Kd_{sw} * C_{TSS} * 10^{-6} \quad \text{...Equation D.123}$$

where

f_{sw} = fraction of solid water mercury in the water column
f_{dw} = fraction of dissolved water mercury in the water column
Kd_{sw} = sediment/water partition coefficient in the water column
C_{TSS} = total suspended solids concentration in the water column (g/m^3)

Calculate Biomass Mercury Fraction in Water Column

$$f_{bw} = f_{dw} * K_{bio} * C_{bio} * 10^{-6} \quad \text{...Equation D.124}$$

where

f_{bw} = fraction of biomass mercury in the water column
f_{dw} = fraction of dissolved water mercury in the water column
K_{bio} = biomass/water partition coefficient in the water column
C_{bio} = biomass concentration in the water column (g/m^3)

Calculate Water Mercury Fraction in Benthic Sediments

$$f_{db} = \frac{\theta_{bs}}{\theta_{bs} + Kd_{bs} * C_{bs} * 10^{-6}} \quad \text{...Equation D.125}$$

where

f_{db} = fraction of dissolved water mercury in the water column
θ_{bs} = porosity of the benthic sediment bed
Kd_{bs} = bed sediment/sediment pore water partition coefficient
C_{bs} = solids concentration in the benthic sediments (g/m^3)

Calculate Sediment Mercury Fraction in Benthic Sediments

$$f_{sb} = 1 - f_{db} \quad \text{...Equation D.126}$$

where

f_{sb} = fraction of solid water mercury in the benthic sediments
f_{db} = fraction of dissolved water mercury in the benthic sediments

Calculate Resultant Water Column Mercury Concentration

The ordinary differential equation (Equation D.117) for mercury water column concentration can be solved using Euler's method:

$$C_{wt} = C_{w0} + \Delta t * \frac{dC_{wt}}{dt} \text{ .... Equation D.127}$$

where

C_{wt} = total water column mercury concentration at the end of the day ($\mu g/m^3$)
C_{w0} = total water column mercury concentration at the start of the day ($\mu g/m^3$)
Δt = time step (day)
$\frac{dC_{wt}}{dt}$ = change in concentration per day ($\mu g/m^3$/day)

Calculate Resultant Benthic Mercury Concentration

The ordinary differential equation (Equation D.118) for benthic mercury concentration can be solved using Euler's method.

$$C_{bt} = C_{b0} + \Delta t * \frac{dC_{bt}}{dt} \text{ .... Equation D.128}$$

where

C_{bt} = total benthic mercury concentration at the end of day ($\mu g/m^3$)
C_{b0} = total benthic mercury concentration at the start of day ($\mu g/m^3$)
Δt = time step (day)
$\frac{dC_{bt}}{dt}$ = change in concentration per day ($\mu g/m^3$/day)

Calculate Mercury Output Load from Wetland/Lake

Once the mercury concentration in the water column is known, the output of mercury (load) from lakes/wetlands can be calculated as follows:

$$L_o = \left[q_o * f_{dw} + \frac{S_{qo}}{PD} * f_{sw} \right] * C_{wt} \text{ .... Equation D.129}$$

where

L_o = total mercury load at the water body outlet (μg/day)
q_o = water discharge from the water body (m^3/day)
C_{wt} = total water column mercury concentration ($\mu g/m^3$)
f_{dw} = fraction of dissolved water mercury in the water column
S_{qo} = sediment load leaving through outflow (tons/day)
PD = soil particle density (g/cm^3)
f_{sw} = fraction of solid water mercury in the water column

D.3.8 Tributary Transport

The mercury load reduction through a tributary is calculated based on the travel time (T_{tot}) and first-order decay rate (k_d). The mercury load at the outlet is calculated as

$$L_o = \sum_0^n \left[L_{Hg} * (1 - e^{-k_d * T_{tot}}) \right] \text{..........Equation D.130}$$

where

L_o = total mercury load at the outlet/assessment point (µg/day)
L_{Hg} = mercury load at each grid (µg/day)
k_d = mercury decay rate (per day)
T_{tot} = total travel time for each grid to the outlet (day)
n = total number of cells that drain to the outlet/assessment point

D.3.9 Mercury Load at Outlet/Assessment Point

Methylmercury Load

The methylmercury load at the outlet/assessment point is calculated based on the fraction of methylmercury. The mercury load at the outlet is calculated as

$$L_{MeHg} = f_{MeHg} * L_o \text{..........Equation D.131}$$

where

L_{MeHg} = methylmercury load at the outlet/assessment point (µg/day)
f_{MeHg} = fraction of methylmercury
L_o = total mercury load at the outlet/assessment point (µg/day)

Divalent Mercury Load

The divalent mercury load at the outlet/assessment point is calculated based on the fraction of methylmercury. The mercury load at the outlet is calculated as

$$L_{DiHg} = (1 - f_{MeHg}) * L_o \text{..........Equation D.132}$$

where

L_{DiHg} = divalent mercury load at the outlet/assessment point (µg/day)
f_{MeHg} = fraction of methylmercury
L_o = total mercury load at the outlet/assessment point (µg/day)

D.4 Stream Network Pre-Processor for WASP

A stream network pre-processor for the WASP model is designed to characterize streams into branches and segments based on user-defined criteria. The GBMM system delineates the subwatershed and computes the physical parameters for each segment, as shown in Table D.5. GBMM also simulates daily flow, sediment load, and mercury load for each segment. Algorithms for the stream network pre-processor are described below.

- NHD streams are characterized into branches by joining the different NHD segments along the same branch. The branches are also labeled with branch IDs and branch node numbers from downstream to upstream, as shown in Figure D.9.

- The branch length is calculated by adding the lengths of the NHD segments that compose the branch.

- The slope for each branch is computed using the elevation difference at the branch nodes and the branch length.

- Stream width and depth at each branch node are calculated based on drainage area using regression equations (Equations D.46, D.47) for different regions (Table D.2).

- Stream cross-sectional area and hydraulic radius for each branch node are computed using equations in section D.1.6 (Equations D.45, D.44).

- The Manning's equation is used to calculate flow velocity in each branch (Equation D.42).

- The travel time for each branch can be calculated using the average flow velocity and length of the stream branch (Equation D.42).

- Each branch is divided into a number of segments based on user-specified length or travel time, and the system assigns a unique ID to each segment as shown in Figure D.10.

- The physical characteristics of each segment are summarized in a text file as shown in Table D.5.

- Following each headwater to the outlet, the flow path connectivity from segment to segment can be generated and exported into a text as shown in Table D.6.

- Finally, after running the modeling modules, flow and pollutant time series for each segment are associated with the segment characterization table (Table D.5). The WASP model will use the characterization and flow connectivity tables as part of its initial input for further simulation.

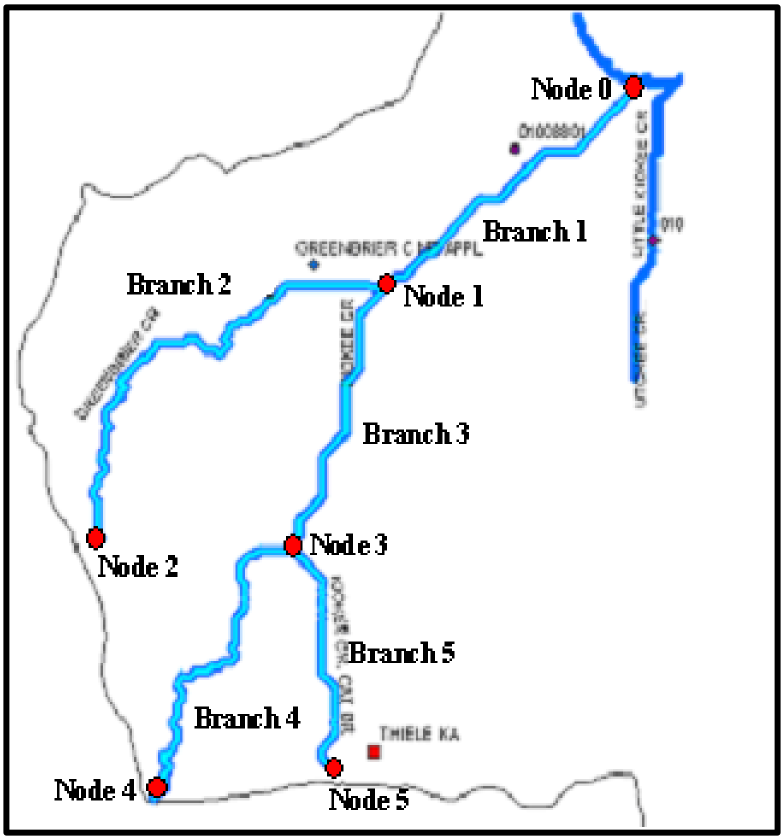


Figure D.9. An example showing streams being characterized into branches.

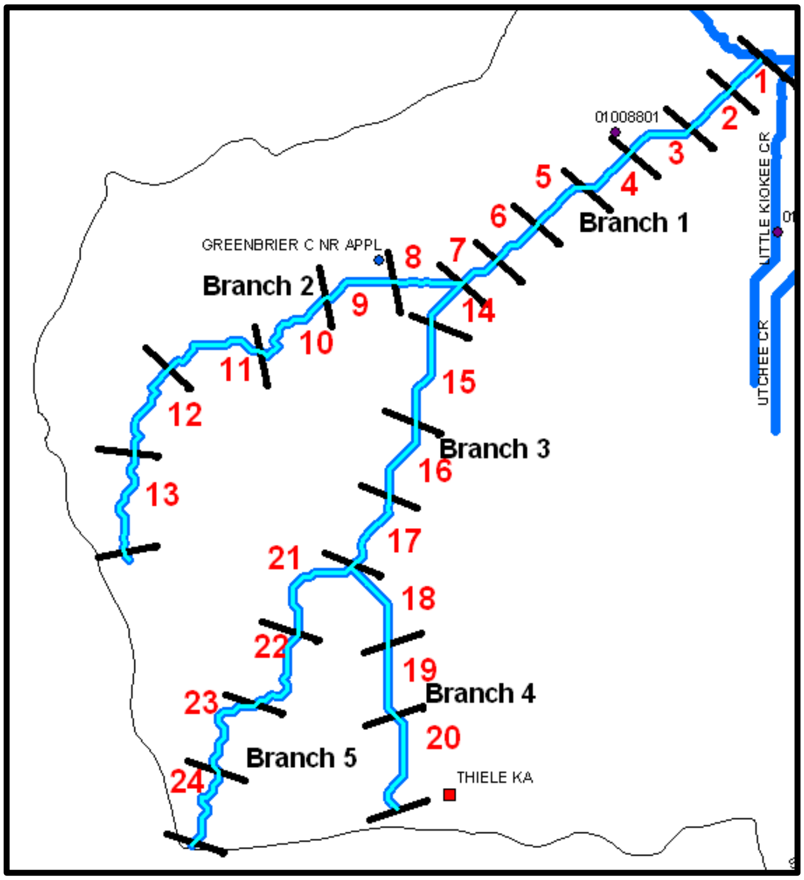


Figure D.10. An example of dividing stream branches into segments.

Table D.5. An example table of physical characteristics of stream segment

Branch ID	River Mile	Segment #	Segment Name	Length Meters	Average Width Meters	Average Depth Meters	Average Velocity Meters	Slope	Roughness
1	0.00	1	Downstream Confluence	500	15	1	0.1	0.003	0.04
1	0.31	2		500	15	1	0.1	0.003	0.04
1	0.62	3		500	15	1	0.1	0.003	0.04
1	0.94	4		500	15	1	0.1	0.003	0.04
1	1.25	5		500	15	1	0.1	0.003	0.04
1	1.56	6		500	15	1	0.1	0.003	0.04
1	1.87	7	Confluence Greenbrier/Kiokee	500	15	1	0.1	0.003	0.04
2	2.18	8		500	15	1	0.1	0.003	0.04
2	2.50	9		500	15	1	0.1	0.003	0.04
2	2.81	10		500	15	1	0.1	0.003	0.04
2	3.12	11		500	15	1	0.1	0.003	0.04
2	3.43	12		500	15	1	0.1	0.003	0.04
2	3.74	13	Greenbrier Cr Boundary	500	15	1	0.1	0.003	0.04
3	2.18	14		500	15	1	0.1	0.003	0.04
3	2.50	15		500	15	1	0.1	0.003	0.04
3	2.81	16		500	15	1	0.1	0.003	0.04
3	3.12	17	Confluence Cat/Kiokee	500	15	1	0.1	0.003	0.04

Table D.6. An example of flow path connectivity table

Flow	From	To
1	0	24
1	24	23
1	23	22
1	22	21
1	21	17
1	17	16
1	16	15
1	15	14
1	14	7
1	7	6
1	6	5
1	5	4
1	4	3
1	3	2
1	2	1
1	1	0

D.5 WhAEM2000 Linkage

GBMM can export data and results to EPA's groundwater model, WhAEM2000 (version 3). During the simulation, GBMM saves the percolation rates in grids. The percolation rate is averaged over the user-specified interval. The percolation/recharge grid values (rates) are classified into 10 classes and then projected into Universal Transverse Mercator (UTM) coordinates with user-defined projection parameters. The projected percolation grids are finally exported in a geo-referenced image format (*.tif).

GBMM also exports information on elevations along streams to a format compatible with WhAEM2000. You define a sample distance along the streams, and the elevation values from the DEM for all the sampling points are exported to a text file with a UTM projection.

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Appendix E. Sample Time-Varying Mercury Deposition Input Files for WCS MLM

Below is the sample format for input time-varying mercury dry and wet atmospheric deposition (units: gram m^{-2} yr^{-1}).

The first field name should be "Year", and the following field names should be "W" plus the watershed ID, e.g., W1, W2, W3,… For the simulation period, you must have data for every watershed every year as shown in Figure E1 and E2.

Wet Deposition Timeseries

Year	W1	W2	W3	W4	W5	W6	W7
1990	0.0000040	0.0000040	0.0000100	0.0000080	0.0000080	0.0000090	0.0000010
1991	0.0000070	0.0000060	0.0000050	0.0000090	0.0000060	0.0000100	0.0000020
1992	0.0000020	0.0000080	0.0000040	0.0000100	0.0000070	0.0000060	0.0000020
1993	0.0000030	0.0000010	0.0000030	0.0000070	0.0000100	0.0000040	0.0000020
1994	0.0000020	0.0000060	0.0000050	0.0000080	0.0000080	0.0000090	0.0000020
1995	0.0000100	0.0000050	0.0000000	0.0000050	0.0000010	0.0000040	0.0000040
1996	0.0000060	0.0000020	0.0000050	0.0000030	0.0000030	0.0000040	0.0000080
1997	0.0000030	0.0000000	0.0000030	0.0000040	0.0000050	0.0000070	0.0000000
1998	0.0000090	0.0000010	0.0000060	0.0000060	0.0000070	0.0000040	0.0000090
1999	0.0000020	0.0000000	0.0000030	0.0000000	0.0000020	0.0000060	0.0000020
2000	0.0000060	0.0000040	0.0000050	0.0000100	0.0000010	0.0000010	0.0000030
2001	0.0000090	0.0000040	0.0000020	0.0000020	0.0000090	0.0000060	0.0000000
2002	0.0000050	0.0000010	0.0000080	0.0000010	0.0000050	0.0000030	0.0000090
2003	0.0000080	0.0000090	0.0000070	0.0000030	0.0000080	0.0000040	0.0000080
2004	0.0000020	0.0000020	0.0000070	0.0000090	0.0000090	0.0000010	0.0000030

Figure E1. Sample format for mercury dry deposition annual time series.

Dry Deposition Timeseries

Year	W1	W2	W3	W4	W5	W6	W7
1990	0.0000040	0.0000040	0.0000100	0.0000080	0.0000080	0.0000090	0.0000
1991	0.0000070	0.0000060	0.0000050	0.0000090	0.0000060	0.0000100	0.0000
1992	0.0000020	0.0000080	0.0000040	0.0000100	0.0000070	0.0000060	0.0000
1993	0.0000030	0.0000010	0.0000030	0.0000070	0.0000100	0.0000040	0.0000
1994	0.0000020	0.0000060	0.0000050	0.0000080	0.0000080	0.0000090	0.0000
1995	0.0000100	0.0000050	0.0000000	0.0000050	0.0000010	0.0000040	0.0000
1996	0.0000060	0.0000020	0.0000050	0.0000030	0.0000030	0.0000040	0.0000
1997	0.0000030	0.0000000	0.0000030	0.0000040	0.0000050	0.0000070	0.0000
1998	0.0000090	0.0000010	0.0000060	0.0000060	0.0000070	0.0000040	0.0000
1999	0.0000020	0.0000000	0.0000030	0.0000000	0.0000020	0.0000060	0.0000
2000	0.0000060	0.0000040	0.0000050	0.0000100	0.0000010	0.0000010	0.0000
2001	0.0000090	0.0000040	0.0000020	0.0000020	0.0000090	0.0000060	0.0000
2002	0.0000050	0.0000010	0.0000080	0.0000010	0.0000050	0.0000030	0.0000
2003	0.0000080	0.0000090	0.0000070	0.0000030	0.0000080	0.0000040	0.0000
2004	0.0000020	0.0000020	0.0000070	0.0000090	0.0000090	0.0000010	0.0000

Figure E2. Sample format for mercury wet deposition annual time series.

Mercury deposition tables should be in dbf format, and can be put anywhere on your hard drive, but we recommend put the files under WCS\models\mercury folder.