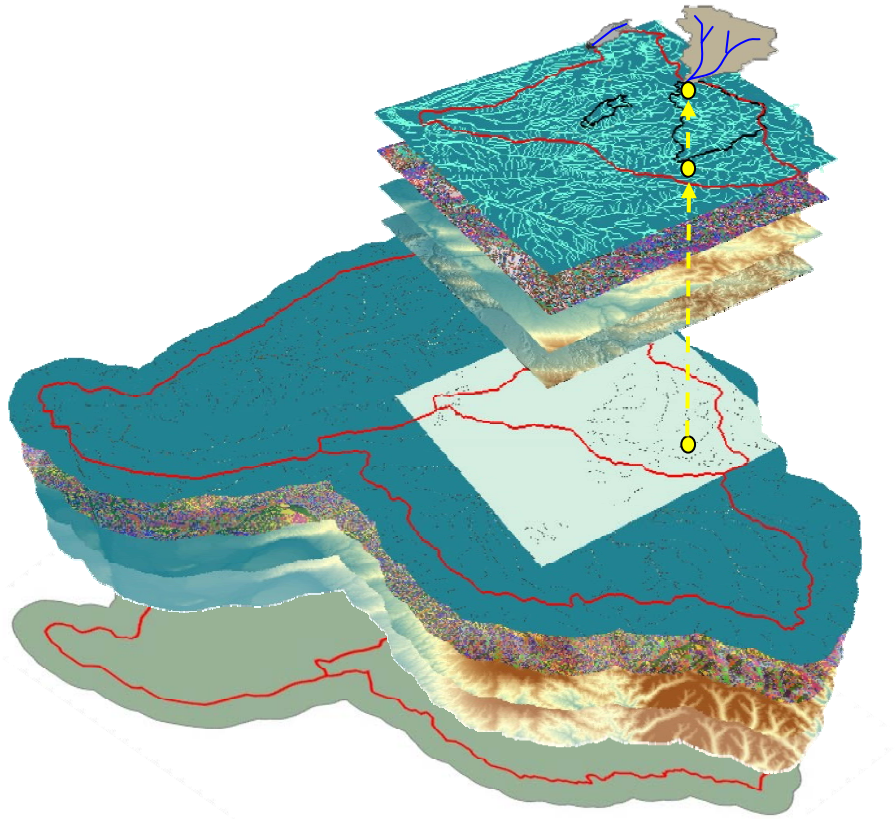


The Multi-Watershed Delineation Tool: GIS Software in Support of Regional Watershed Analyses



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System and software requirements

- Windows operating system (Windows 2000 or later edition)
- MS Excel, MS Access, or a similar data management tool
- ArcGIS 9.x (with ArcInfo license type)
- Text-editor software
- Internet access
- Recommended: 1 Gigabyte or more RAM and RAID 0 hard drive configuration

Installation

Install the MWD tool using the install executable that is included. The installation program will automatically create the directory C:\Program Files\MultiwatershedDelineation, and copy the tool and supporting dynamic linked library (.dll) files into it.

Summary

The Multi-Watershed Delineation (MWD) Tool is a standalone windows program that uses ArcObjects and TauDEM functionalities to derive watershed polygons, river networks, and watershed attributes for multiple sites across large geographic extents. This manual describes the steps required to run the MWD software, including input of data, data pre-processing, and final watershed delineation. The MWD software also provides a tool to summarize several physical and environmental characteristics of the delineated watersheds. The manual is written for aquatic scientists with intermediate GIS skills who need to delineate watersheds and derive associated attributes for multiple sample sites across a large geographic area.

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Part I: Introduction to GIS Based Watershed Delineation

1.1 Introduction

Aquatic resource managers increasingly require information about the characteristics of watersheds that drain to stream reaches of interest. Furthermore, they need this information for multiple watersheds within states or larger regions. Geographic information systems (GIS), coupled with increased spatial data availability, allow researchers to obtain this information. Information obtained from a GIS-based watershed analysis can include data such as watershed area, watershed climate statistics, soil/geology types, topographic statistics, hydrology, and landuse.

The multi-watershed delineation (MWD) tool is designed to create a shapefile containing watershed boundaries and attributes for multiple stream sites that occur within a large geographic area. The purpose of this manual is to describe the steps to:

- (1) generate watershed boundaries from multiple sample locations, and
- (2) use these boundaries to summarize watershed level information (Figure 1.1).

This manual is written for users with intermediate GIS skills, and we assume users have an understanding of how to:

- Obtain and manage spatial data with ArcCatalog
- Analyze and project GIS datasets with ArcToolbox
- Select and edit features and join data in ArcMap

The MWD tool is designed to delineate watersheds for hundreds of sample sites located within a large region and provide data characterizing those watersheds. If the user only needs to delineate and calculate stream watershed attributes for small numbers of watersheds, it may be easier to use other software such as ESRI's ArcHydro *extension* (<http://www.cwr.utexas.edu/giswr/>), *hydrology toolset in ArcToolbox*, or the *TauDEM software* (<http://hydrology.neng.usu.edu/taudem/>).

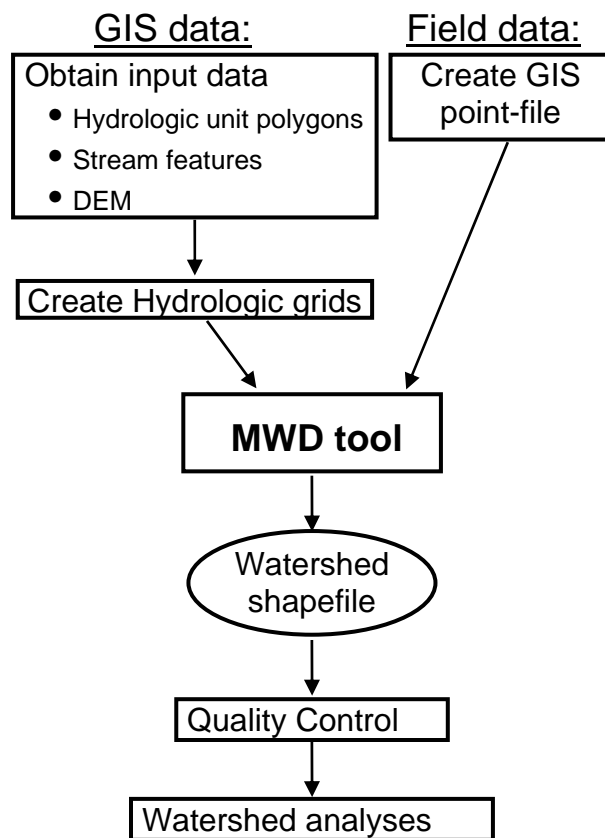


Figure 1.1. Flow-chart of watershed delineation process.

1.2 Theory behind GIS-based watershed delineation

Although watershed area is easy to conceptualize and delineate on a paper map, GIS delineations are less labor intensive, more reproducible, and less dependant on subjective judgment. The GIS delineation process starts with a grid representation of topography called a digital elevation model (DEM, Figure 1.2). From the DEM a series of additional grids are produced that represent various hydrologic characteristics of the landscape (see Figure 1.3, sections 1.2a-1.2d). From these “hydrologic grids”, a GIS can delineate watershed boundaries by identifying all locations within a DEM that are uphill of an outlet (Figure 1.2).

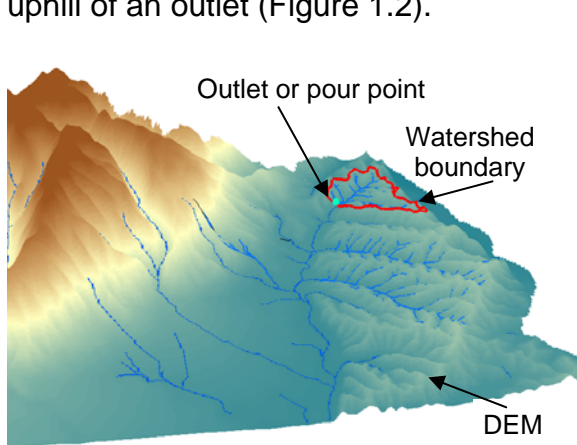


Figure 1.2. Representation of a DEM, a pour point and the watershed boundary

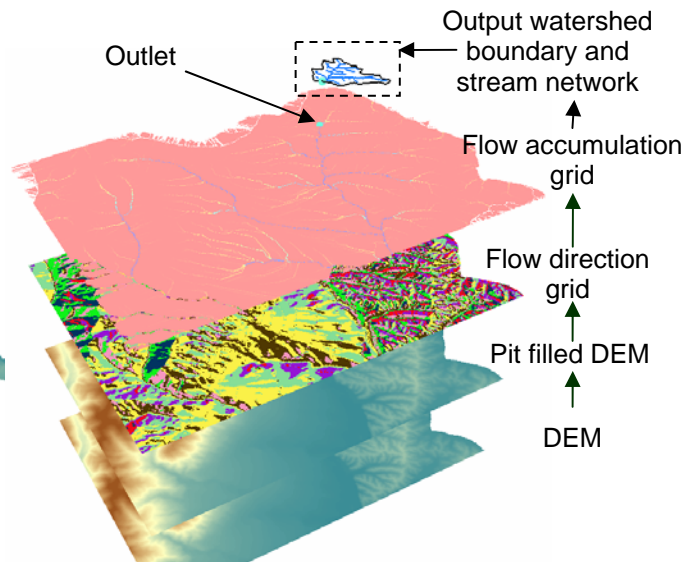


Figure 1.3. Hydrologic grids needed for watershed delineation.

1.2a Filling “pits” in the raw DEM

To conduct watershed analyses with a DEM, its surface must be hydrologically connected. In other words, every DEM cell must flow into the next downstream cell until the “water” flows off the edge of the grid. This connectivity within the DEM can be disrupted by “pits”. Pits are low elevation areas in DEMs that are surrounded by higher terrain that disrupts the flow path (Figure 1.4). Pits can be naturally occurring or simply artifacts of modeling the continuous surface of the earth. Filling pits creates a hydrologically connected DEM for watershed analyses. The “fill” is accomplished by raising the value of a cell identified as a pit to match the elevation of its downhill neighbor (Figure 1.4).

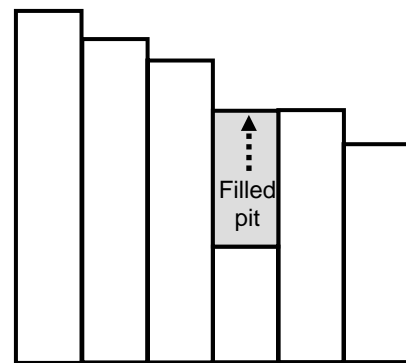


Figure 1.4. Cross-section of DEM surface. The grey region represents a pit within the elevation model raised to match the elevation of the next downhill pixel.

1.2b Flow direction

The direction of flow from each grid cell to its downhill neighbor is calculated from the pit-filled DEM. The flow direction is calculated by examining the eight neighbors of a cell and determining the neighbor with the steepest downhill slope. This direction is then coded as a value in a new “flow direction” grid (Figure 1.5a). This process is repeated to create a grid with flow-directions coded for the entire landscape (Figure 1.5b). Note that other hydrologic software (e.g. ArcHydro or ArcToolbox hydrology toolset) use a different coding system than those presented here to represent flow-direction.

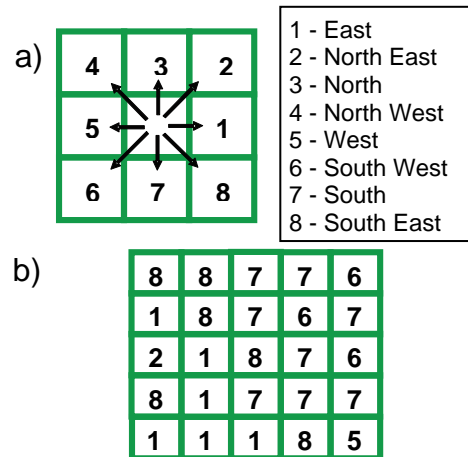


Figure 1.5. a) Eight direction pour point model. b) Numerical depiction of a flow-direction grid.

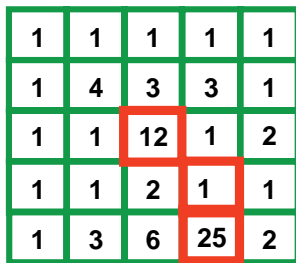


Figure 1.6. Flow-accumulation grid values, with values above the threshold highlighted showing a derived stream network (red).

1.2c Flow accumulation, stream grids, and drainage area

With the flow-direction grid, it is possible to sum the number of uphill cells that “flow” to any other cell. This summing can be done for all cells within a grid to create a “flow-accumulation” grid in which each cell-value represents the number of uphill cells flowing to it (Figure 1.6). Because a cell represents a geographic area (i.e., each cell of a 30-meter resolution grid is 900 m²), the flow-accumulation grid can be multiplied by this area to calculate the total drainage area. In addition, a grid representing a stream network can be created by querying the flow-accumulation grid for cell values above a certain threshold. For example, in figure 1.6 a cell receiving flow from more than 12 other cells is defined as a stream channel.

1.2d Watershed delineation

The hydrologic grids discussed in sections 1.2a-1.2c are then used to delineate watershed boundaries (Figure 1.7). By following a flow direction grid backward, we can determine all of the cells that drain through a given outlet (yellow cells in Figure 1.7). These can then be selected and converted to a polygon representing the watershed. The stream grid is necessary to ensure that the cell selected as an outlet is on the modeled “stream” and not on the adjacent hill slope.

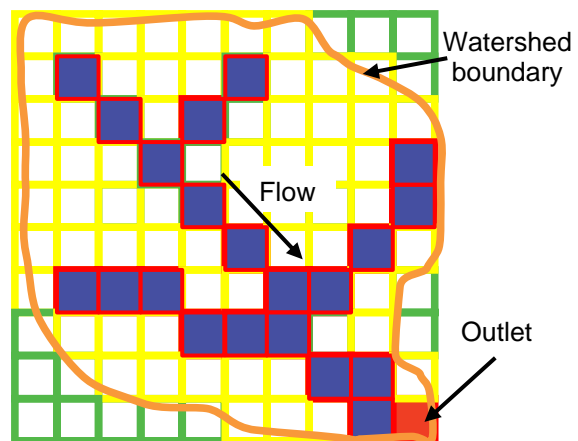


Figure 1.7. A grid representation of a watershed boundary, stream network and outlet.

1.3 How the Multi-Watershed Delineation tool works

When delineating multiple watersheds across a large geographic area, two technical challenges may arise that other delineation tools are not equipped to handle. First, the field site coordinates may not align with the modeled stream grid because of human recording or instrument error, or differences between the actual and the modeled stream. If this situation occurs, the delineation will result in an incorrect watershed boundary (Figure 1.8). To solve this problem the MWD tool simply “rolls” an incorrectly placed site downhill until it contacts the stream channel. The watershed is then delineated from this new location. Second, delineating watersheds across broad geographic areas requires grid datasets too large for the memory capacity of most computers. The MWD tool solves this problem by automatically clipping large hydrologic grids to a more manageable size with the use of a polygon shapefile that approximates hydrologic boundaries for a moderate sized area, referred to as a “medium hydrologic unit” (MHU, Figure 1.9). To ensure that the large hydrologic grids contain complete medium hydrologic units, we create the hydrologic grids from a series of medium hydrologic units merged to create a “large hydrologic unit” (LHU). Typically, we use the USGS’ 8-digit HUCs for medium hydrologic units and 4-digit HUCs for large hydrologic units, but each of these may be smaller or larger depending on the situation. The MWD tool uses a medium hydrologic unit, with a buffer to account for any inaccuracies, to clip only the area required for delineation from each of the hydrologic grids (Figure 1.9). Each site within a medium hydrologic unit is then delineated automatically with the routines of the TauDEM program (see Tarboton 2000). The MWD tool then automatically moves to the next medium hydrologic unit and repeats the process until it delineates all of the sites within the large hydrologic unit. We illustrate a typical application of the MWD tool in Figure 1.10 (a) for a typical data set with 178 sites, spread across northern Utah. The MWD tool provides an efficient way to derive watersheds, stream networks, and associated topographic attributes for each of these sites (Figure 1.10 (b)).

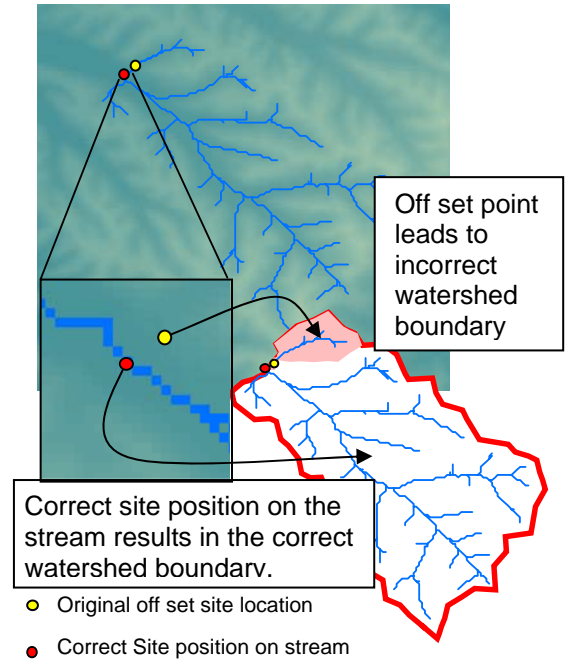


Figure 1.8. Effect of the site offset on watershed delineation

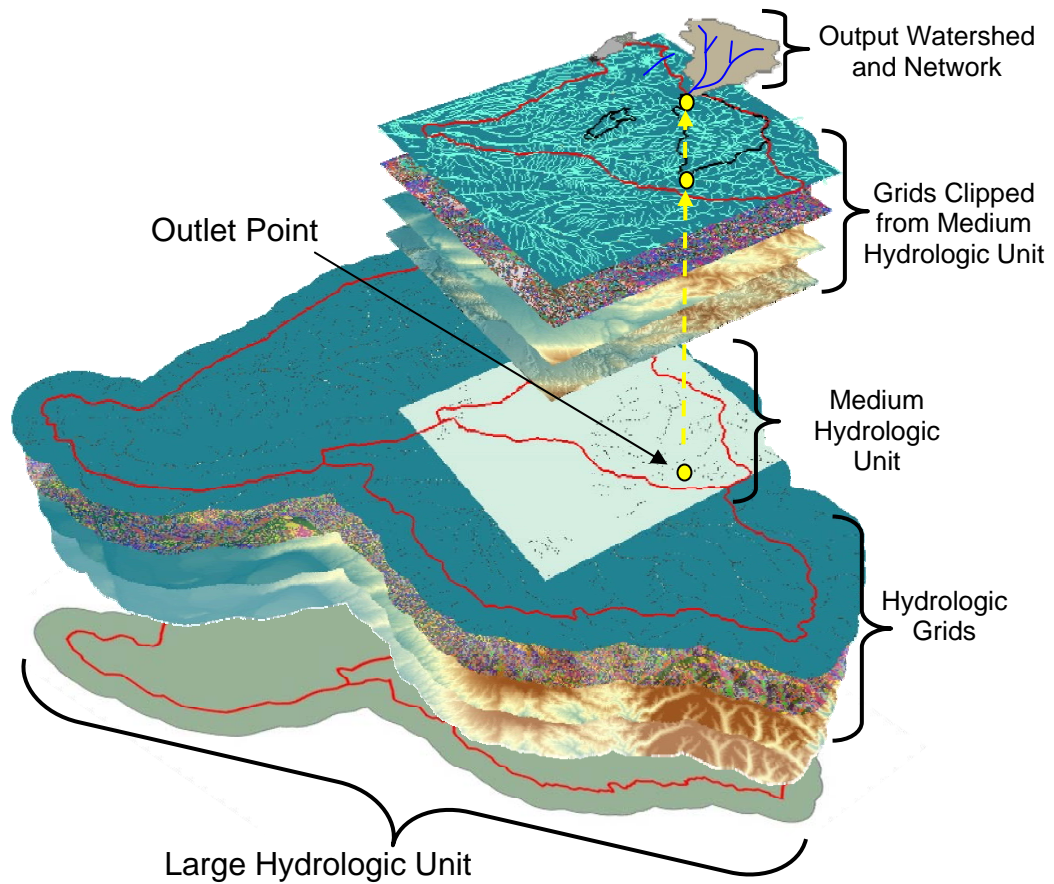


Figure 1.9. A “medium hydrologic unit” can be automatically clipped from a “large hydrologic unit” for easier delineation of individual watersheds.

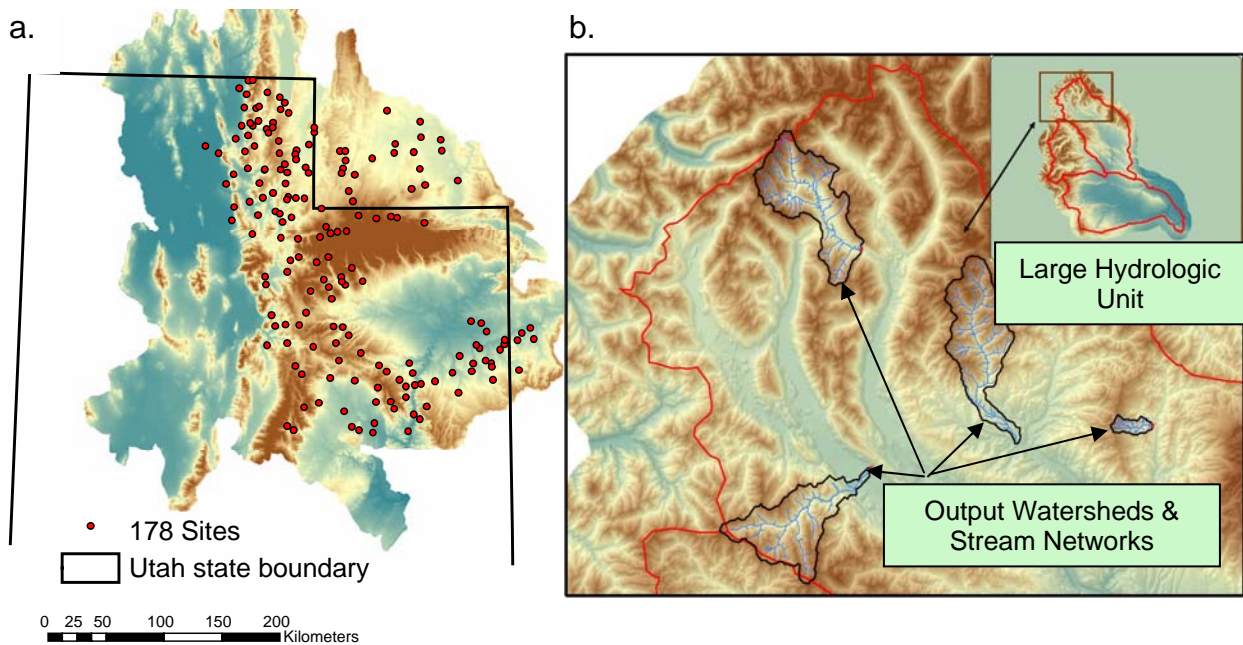


Figure 1.10. (a) A typical data set for the MWD tool. (b) Typical output of the MWD tool.

Part II: Instructions for watershed delineation

Included with the MWD tool materials is a set of example monitoring sites (practice_sites.csv) to practice both creating hydrologic grids and delineating watersheds with the tool. These sites are within the USGS' sub-region 1703 (Yakima). Also included are two ArcInfo Arc Macro Language (AML) scripts, hydrogrid.aml and agree.aml.

2.1 Before you start

Before beginning the watershed delineation process, it is important to take time to decide on the extent, resolution, and projection to use for your analysis.

2.1a Data extent and large hydrologic units

The spatial extent of your analysis and the processing abilities of your computer determine the number and size of the large hydrologic units you can process. Because the hydrologic grids you create can be used for sites you are interested in analyzing both now and in the future, the extent should cover your entire area of interest. Four-digit HUCs make useful hydrologic regions, although the larger ones often need to be cut in half. For a state the size of Utah, we use 11 different hydrologic regions.

2.1b Data resolutions

DEMs and other grids are available at various spatial resolutions (e.g. 10-meter, 30-meter, and 90-meter). Delineations produced by finer resolution grids are more accurate, but require more storage space and processing time. We recommend 30-meter resolution grids for watersheds <10,000 km² (about the size of an 8-digit USGS HUC), and 90-meter resolution for larger basins.

2.1c Data projections

Analysis of features found on the earth's curved surface with models that treat the surface as flat requires projecting geographic features from the curved to flat surface in a way that minimizes distortion. We recommend an Albers Equal-Area Conic projection, or other projection that minimizes area distortion. The linear units of your projection also determine the units of subsequent measurements, so we use meters. All examples in this manual use the USGS standard Albers projection. Other projections such as Universal Transverse Mercator can also be used, but within a narrower geographic extent.

2.1d Choosing a method for hydrologic grid creation

The grids described in section 1.2 can be created with various tools. In this manual, we describe an Arc Macro Language (AML) script that is run in ArcInfo (see section 2.2i). These grids can also be created with ArcHydro, the hydrology tool set in ArcToolbox, or TauDEM. The user should decide which method to use based on tool availability. In addition, each method has advantages that the user should consider (see section 2.2i3).

2.1e Data management

To keep your GIS data organized, we recommend creating a working directory for each large hydrologic unit. To improve processing reliability in ArcInfo, all subdirectories in the path should have names consisting of less than 12 characters and without spaces. For example, if we are conducting an analysis of a large hydrologic unit named “r1703”, we will create a new directory called: C:\GIS\r1703 (we discuss large hydrologic unit naming conventions in section 2.2c). All data should be downloaded and processed within that folder.

2.2 Obtaining and creating input data

Hydrographic and DEM data are needed to create 6 of the inputs from which we create hydrologic grids and run the MWD tool (Table 1). These data are obtained from various internet sources, primarily the USGS’ National Hydrologic Dataset (NHD) and National Elevation Dataset (NED). The outlet file is created from points the user wants to delineate, based either on field GPS coordinates or points chosen from a map.

Table 1: Inputs required to create hydrologic grids and use the Multi-Watershed Delineation tool

| Inputs | Purpose | Type of File |
|---|--|-------------------|
| Large Hydrologic Unit Files | Used to delineate large watersheds and create buffered hydrologic region coverages | Polygon Shapefile |
| Projected Buffer of Hydrologic Unit | Used to create hydrologic grids the same shape as the hydrologic unit | Coverage |
| Medium Hydrologic Units File | Clips hydrologic grids during delineation | Polygon Shapefile |
| Stream Files (from NHD or other source) | Verification of site locations and creation of projected stream coverage | Line Shapefile |
| Projected Stream Coverage | Burns stream grid into the DEM to force modeled flow to match known streams | Coverage |
| Outlet File (sites) | Determines location of the watershed | Point Shapefile |
| Raw DEM (from NED or other source) | Generate pit filled DEM for topographic analysis of resulting watersheds | Raster |

2.2a Obtain hydrographic data

Stream features and approximate hydrologic polygons can be obtained from a variety of sources, including the National Hydrologic Dataset for US and Mexican data and Geogratis for Canadian data (http://geogratis.cgdi.gc.ca/download/frameworkdata/hydrology/analytical/drainage_network/). NHD data can be downloaded as either a high (1:24k) or medium resolution (1:100k) ESRI geodatabase. We recommend using the high-resolution data where available.

1. Go to: <http://nhd.usgs.gov/data.html>
2. Select the “DATA” tab at the left side of the screen and choose either:
 - a. “NHD viewer”, or
 - b. <ftp://nhdftp.usgs.gov/SubRegions>
3. Download and unzip the geodatabase for NHD region of interest.

If you will be using the example practice_sites.csv provided, you need to download the Yakima region (See Appendix B for details about this region)

2.2b Create the large hydrologic unit

To create the large hydrologic unit, select the desired 4-digit HUC, project it, and add a 10-km buffer. The buffer is added because of inaccuracies in HUC boundaries and ensures that the clipped grids are hydrologically complete:

1. Open ArcMap and set the dataframe's projection to "USA Contiguous Albers Equal Area Conic USGS.prj" in: Coordinate Systems/Projected Coordinate Systems/Continental/North America (or your chosen projection)
2. Add the "Subregion" features found in the "HydrologicUnits" Feature Dataset in the downloaded NHD data.
3. Select the desired 4-digit HUC with the selection tool and export it as a new shapefile called "HUC4.shp", selecting the "use the same coordinate system as the dataframe" option.
4. Create a 10km buffer of HUC4.shp with ArcToolbox: Analysis Tools → Proximity → Buffer. Set buffer distance to 10 km, and "Dissolve Type" to "ALL".
5. Convert the buffered large hydrologic unit to ArcInfo coverages in ArcToolbox: Conversion Tools → to Coverage → Feature Class to Coverage.
6. For this example, we name the new projected coverage "buffer_alb".

NOTE: Remember to save the output file to the working directory.

2.2c Create medium hydrologic units

The MWD tool will use the medium hydrologic unit shapefile to extract portions from the hydrologic grids during delineations. Create the medium hydrologic unit shapefile:

1. Add the "Subbasin" features found in the "HydrologicUnits" Feature Dataset (in the downloaded NHD geodatabase) to the same projected dataframe in ArcMap as the hydrologic regions.
2. Select all required medium hydrologic units (8-digit HUCs) and export the output as "HUC.shp", selecting the "use dataframe projection" option.

NOTE: The naming conventions used here are not required but are recommended to make using the MWD tool easier.

The final output of steps 2.2b-2.2c is two GIS files: (1) a medium hydrologic unit shapefile, and (2) a large hydrologic unit coverage in the projected coordinate system (Figure 2.1).

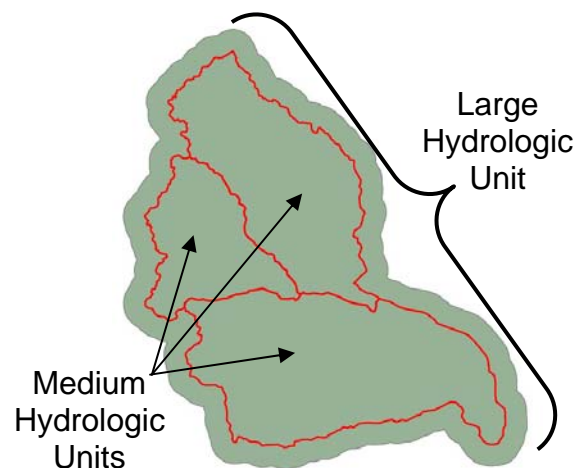


Figure 2.1. 10km buffered Large Hydrologic Unit and Medium Hydrologic Units

2.2d Create stream features from the NHD

Stream features will be used to verify the location of field sample coordinates (section 2.2f) and to force flow paths modeled from the DEM to match mapped streams by “burning” streams into the DEM (section 2.2i). Burning in streams is accomplished by lowering the elevation of the DEM where a stream exists, which results in a “trench”. These trenches will then route flow, matching the actual stream pattern, if they extend to the edge of the DEM. Otherwise, they are treated as “pits” and are filled. Therefore, stream features must cover the entire large hydrologic unit out to the edge of the buffer.

1. Add the “NHDflowline” features found in the “Hydrography” Feature Dataset of the NHD geodatabase to your projected dataframe in ArcMap.
2. Compare the NHD flowline features with the large hydrologic unit coverage “buffer_alb” in ArcMap. Determine which additional NHD data will be needed to completely cover the large hydrologic unit, download the data, and add the additional flowline features to your dataframe.
3. Select features from each of the flowline files that overlap the large hydrologic unit (buffer_alb): Selection menu → Select by Location. Select features from NHD flowline that intersect with buffer_alb.

We further want to select only those stream features that represent natural water bodies and not canals or pipelines and combine the output with the surrounding stream files:

1. Selection menu → Select by Attribute.
 - 1a. In the Select by Attribute window: Layer = NHDFlowlines, Method = **Select from Current Selection**.
 - 1b. Place the following code in the query window: [FCode] = 46003 OR [FCode] = 46006 OR [FCode] = 55800 OR [FCode] = 33400 OR [FCode] = 36100 OR [FCode] = 43100 OR [FCode] = 46000 OR [FCode] = 46100 OR [FCode] = 48400 OR [FCode] = 48700.
2. Export the selected streams from each of the flowline files as a temporary shapefile, with the “use original data’s projection” option.
3. Merge the temporary stream shapefiles into a single file with ArcMap Toolbox: Data Management Tools → General → Append.
4. Project the merged stream shapefile in ArcToolbox: Data Management Tools → Projections and Transformations → Features → Project.
 - 4a. Save the output file as “stream_verify.shp”. This shapefile will be used to verify GPS point locations.
 - 4b. Select the output projection “USA Contiguous Albers Equal Area Conic USGS.prj” in: Coordinate Systems/Projected Coordinate Systems/Continental/North America.
5. Convert the stream_verify.shp file to an ArcInfo coverage (section 2.2c) named “stream_alb” (naming convention not required).

2.2e Create point shapefile from field site coordinates

A spreadsheet or database of GPS coordinates is used to create a table of sample locations from which a point shapefile is created. Included in this table must be the following fields:

1. Latitude in decimal degrees.
2. Longitude in decimal degrees.
3. A unique site identifier. The site code **SHOULD NOT** begin with a numeric character (any numeric data in a text field causes ArcMap to read that field as numeric and lose all text data) and **must be less than 35 characters long (e.g. Yak-b123)**. The field heading **must** be labeled: "Sitecode".
4. A descriptive site or stream name, less than 30 characters long (e.g. "tributary to Cascade Ck above confluence" or "Flanigan Ck below HWY 66"). This field is used to verify the accuracy of the point-data coordinates (section 2.2h). The field heading **must** be labeled: "Sitename".

NOTE: a) We recommend that the user limit input tables to these 4 fields for simplicity and to avoid errors in processing.

b) The file practice_sites.csv for the Yakima region may be used if you do not wish to create your own monitoring site coordinates.

To create the point shapefile:

1. Verify in a spreadsheet that the table contains no missing latitude, longitude, Sitecode, or Sitename records. Fill in any missing values.
2. Save the file as a database file or comma-delimited text file.
3. Add the table to ArcMap and verify that the table imported correctly by examining its contents. Note: the program used to create the table must be closed prior to adding the table to ArcMap.
4. Create a point shapefile from the table by: (1) right-clicking on the name of the text file in ArcMap Table of Contents → Display XY Data and inputting the longitude/latitude fields and defining the current geographic projection for the dataset (e.g., NAD 27 or NAD 83), (2) exporting the new theme as a shapefile and, (3) projecting it to the desired coordinate system and transforming the datum to NAD 83 if necessary (ArcToolbox: Data Management Tools → Projections and Transformations → Features → Project). For ease of reference within this manual, we will call the point file "site.shp", although this naming convention is not required.

2.2f Verify point shapefile accuracy

Often with field coordinates, GPS or technician error results in incorrect specification of site locations. We therefore need to verify that each point location is on the correct stream. The following procedure allows the user to compare the descriptive name of each point to the name of the NHD stream closest to it. In addition, it determines the distance of each point to the closest stream segment:

1. Add site.shp and stream_verify.shp to your projected dataframe in ArcMap.
2. Join by spatial location the stream_verify.shp to the site.shp giving both the attributes of the closest stream line and its distance to each point. This join can be done by (1) right-clicking on the name of site.shp in ArcMap Table of Contents → Joins and Relates → Join, (2) within the Join window select the options to: (a) join data from another layer based on spatial location, (b) use stream_verify.shp as the join file, and (c) give all the attributes of the closest line to each point, and (3) save as a new point shapefile.
3. Open the attribute table of the joined shapefile and compare the fields Sitename with GNIS_name or Name (stream name field within NHD, Figure 2.2). Also, examine the distance from each point to the closest stream feature listed in the distance field. Flag those points with mismatched names or that are further than 500m from a stream for further inspection. We recommend creating a new field in the point shapefile to record comments on sources of error and their correction status. For large datasets, we recommend exporting the attribute table and comparing fields in Excel rather than using the attribute table itself. This method allows you to use “if” statements to compare data fields rather than manual observation. Although this method adds steps to the process it is more efficient for large datasets.

| SITECODE | SITEMAME | GNIS_Name | Distance | Code |
|--------------|----------------------------|--------------------------|-----------|------|
| 00 Yaki-10 | Yakima River | Yakima River | 46.867224 | q |
| 10 Yak-b123 | Yakima River | | 27.669229 | n |
| 20 Medi_122 | Medicine Creek | Medicine Creek | 9.441962 | q |
| 30 Rattle-10 | Rattlesnake Creek | Dry Creek | 57.327611 | n |
| 40 Yak-d/s1 | Yakima River | Yakima River | 2.057872 | q |
| 50 Nacho-1 | Naches River | Naches River | 18.023027 | q |
| 60 Yak-001 | Yakima River | Yakima River | 5.516766 | q |
| 70 Tean-10 | Middle Fork Teanaway River | West Fork Teanaway River | 37.515166 | n |
| 80 Coop1.A | Cooper River | Cooper River | 8.994565 | q |

Figure 2.2. Table of spatially joined points to NHD stream data. Notice Yakima River matches exactly, whereas Middle Fork Teanaway and West Fork Teanaway may be the same but need to be verified. Rattlesnake Creek is closest to the steam named Dry Creek in the NHD and requires more research. Many streams in the NHD datasets are unnamed, such as the unnamed stream to which site Yak-b123 is closest and require checking against a map.

Once problem points are identified, determine the cause of the error. Four common causes and solutions of mismatched names are:

- **Cause:** Transposed or incorrect coordinates (e.g., 34.9876 becomes 39.9876 or 34.8976). **Solution:** Verify coordinates from original datasheet or GPS unit, or adjust location in a cardinal direction.
- **Cause:** Correct stream and location, but no name or incorrect name in the NHD file. **Solution:** Verify site names against stream names from USGS quadrangles, available at Topozone.com or Terraserver.com.

- **Cause:** The sampling location is very close to a confluence of two streams and the point was joined to the wrong one. **Solution:** Edit the shapefile and manually move the point slightly to the correct stream.
- **Cause:** Incorrect stream name recorded in the field (e.g., tributary given main-stem's name). **Solution:** Verify location from field notes or site description and correct name.

NOTE: Create a copy of the point file before editing it to correct errors, in case the file becomes corrupted during the editing process.

2.2g Separate points into outlet files for each large hydrologic unit

Create the outlet file needed to delineate all of the sites within a large hydrologic unit.

1. Add the verified site.shp file and the HUC4 file of a medium hydrologic unit to a projected dataframe in ArcMap
2. Select points from site.shp that overlap the large hydrologic unit (HUC4): Selection menu → Select by Location. Export these points into a new shapefile named "large hydrologic unit name_outlets.shp"(e.g., "r1703_outlets.shp").

2.2h Download raw DEM data

DEM data for the U.S. can be downloaded from the USGS National Elevation Dataset (NED) website: <http://seamless.usgs.gov/website/seamless/viewer.php> (see section 2.5a for discussion of Canadian DEMs). At the right side of the page select the "Download" tab and check that "1" NED is selected (30-meter DEM). Select the desired DEMs either by dragging a box or by entering the coordinates of the extent of buffer_dd coverage. Each DEM downloaded from the USGS website is contained within its own directory. Move the grids to a common storage directory and rename. In this manual we call the DEM storage directory "c:\GIS\raw_dems", but this naming convention is not required.

2.2i Process DEM and hydrologic grids

Here we describe an ArcInfo AML to create the hydrologic grids necessary for watershed delineation (Figure 2.3). An AML is a text script that combines several

sequential commands from the ArcInfo GIS software package into a single process.

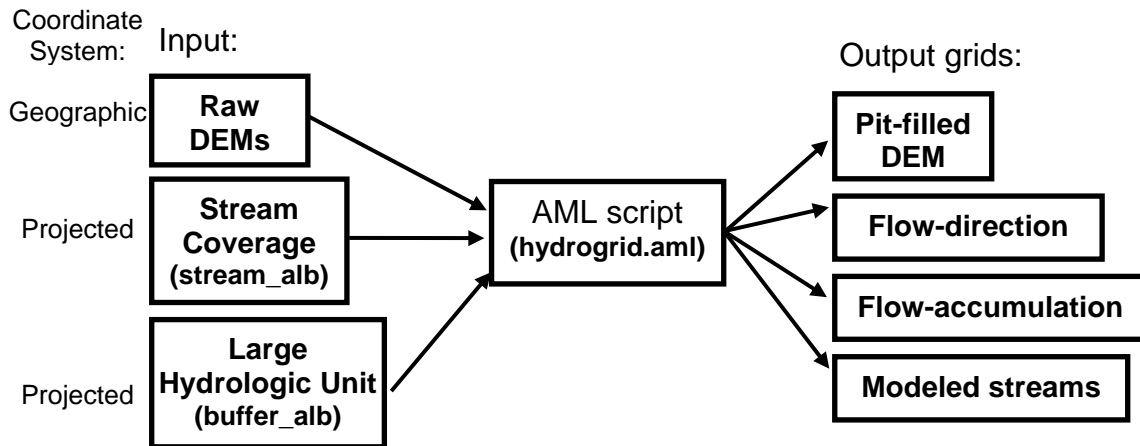


Figure 2.3. Required input files and resulting output grids for the AML script.

This AML completes 6 basic functions:

1. The AML clips and merges several to many DEM tiles to create a single DEM that covers the extent of the large hydrologic unit.
2. DEM elevation values are then multiplied by 10 and the DEM is converted to an integer grid. This step greatly reduces the space require to store the DEM, while retaining most of the elevation information.
3. The DEM is projected to the USGS Albers projection.
4. A trench is “burned” into the DEM with the stream coverage. The trench ensures that modeled stream locations match those of the NHD. Trenching is done with the Agree AML (Hellweger 1997, <http://www.ce.utexas.edu/prof/maidment/gishydro/ferdi/research/agree/agree.html>). This process first lowers elevation values over a certain distance from the mapped stream (the buffer distance), producing the “smooth drop”. The process then lowers elevations again at the stream, producing the “sharp drop”.
5. The hydrologic grids (section 1.2) are created with the output from steps 1-4. The final grids are: (1) filled DEM, (2) flow-direction grid, (3) flow-accumulation grid, and (4) modeled stream grid. The AML produces the hydrologic grids at both 30-meter and 90-meter resolutions.
6. The AML cleans the working directory of temporary files created during the process.

NOTE: The AML will complete this process for most large hydrologic units within a few hours, however some very large ones can require processing times as long as 20 hours or more. We recommend that the user run large datasets over night or a weekend.

The naming convention of the output grids requires that the user provide a prefix, less than seven characters long starting with a character such as the name of the large hydrologic unit. For example, if the name of the large hydrologic unit is r1703, then the name of the pit-filled DEM is “r1703_fill”. The flow-direction, flow-accumulation, and modeled stream grid suffixes are “fd8”, “fa”, and “str” respectively.

NOTE: The AML produces two flow direction grids. The suffix “fd” uses ESRI’s flow direction convention to assign cell values, however the MWD tool uses a 1-8 value convention so the “fd” is reclassified as “fd8” (section 2.2i3).

2.2i-1 Running the AML

A copy of the AML is provided in the zipfile of the MWD tool. The AML file is named “hydrogrid.aml”. A second AML named “agree.aml” is also run from within hydrogrid.aml and is provided in the MWD tool zipfile. To run the Hydrogrid AML copy both the hydrogrid.aml and the agree.aml to the working directory that contains the stream and hydrologic unit coverages.

The AML script is run in ArcInfo. To access ArcInfo and run the script:

1. Open a Windows Command Prompt: Windows Start Menu → Programs → Accessories → Command Prompt.
2. Change the current directory location to the working directory. At the DOS-prompt type: “cd” and the path to the working directory (Figure 2.4).
3. Type “arc” to start ArcInfo (Figure 2.4), and hit enter.

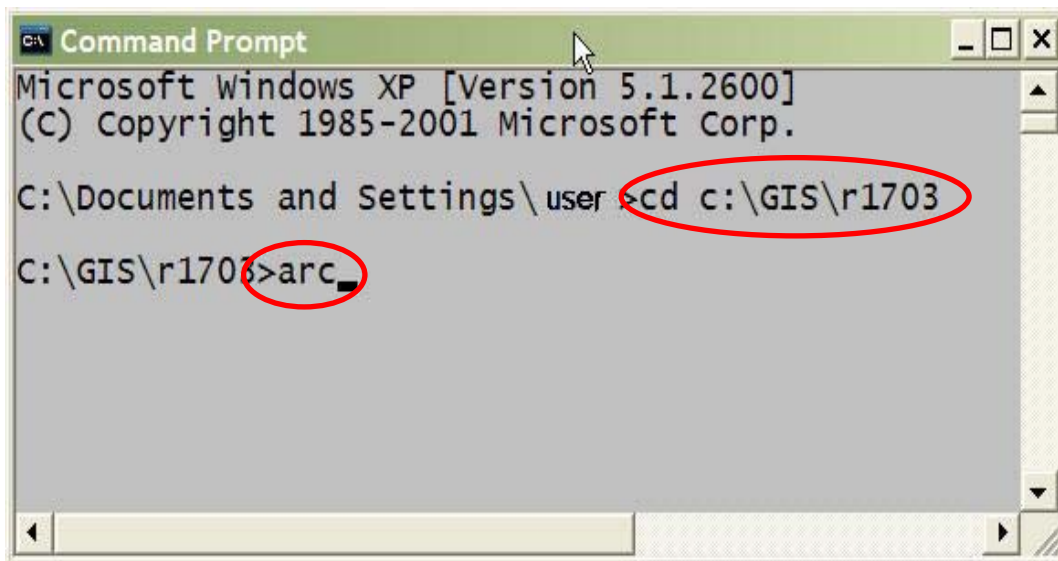


Figure 2.4. Commands to change directories and start ArcInfo.

4. Type “&r hydrogrid.aml” (Figure 2.5), and hit enter.



Figure 2.5. Command to run hydrogrid.aml.

At this point, the user is prompted for several inputs (Figure 2.6):

1. The name of the large hydrologic unit.
2. The name of the buffered coverage representing the large hydrologic unit (2.2b).
3. The name of the stream coverage (2.2d).
4. The path to the directory containing the raw DEMs to be processed.
5. A list of the names of the DEMs to be processed separated by a comma. For this example, the names of the DEMs are area1, area2, area3, and area4.
6. If desired the user can use a projection other than the USGS Albers for the output hydrologic grids. When prompted for a projection file the user can provide a text file with projection parameters (Figure 2.6). The projection file must also be located in the working directory. If the user wishes to use the default projection (USGS Albers) simply press <ENTER> to skip this input.

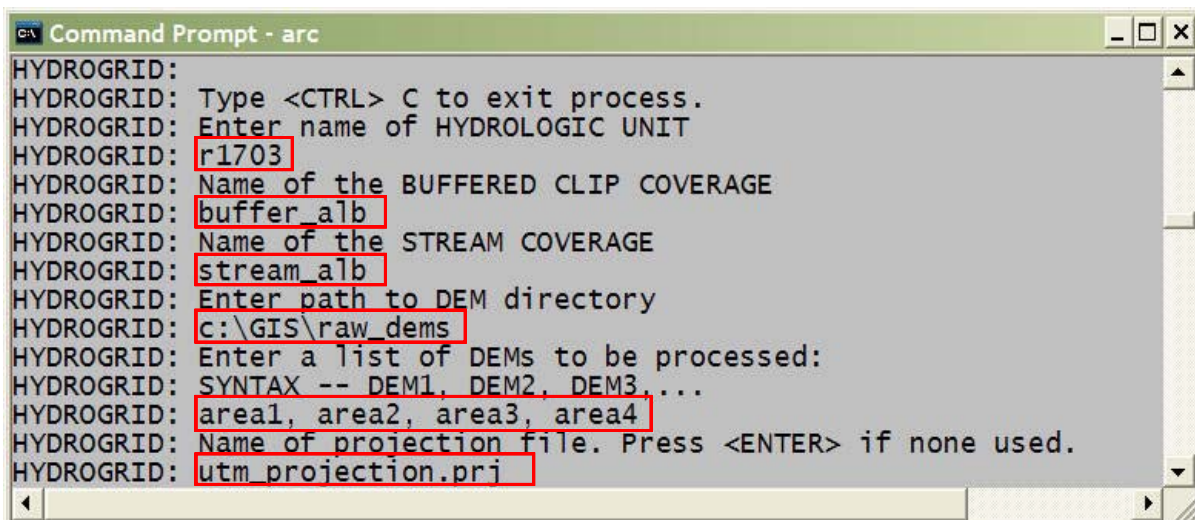


Figure 2.6. Series of requests and inputs to run hydrogrid.aml. The naming conventions used here are not required.

Optionally, the Hydrogrid AML can be run from beginning to end to skip the queries, by stringing together all of the input parameters. With the current example, the syntax of this command should be:

```
&r hydrogrid.aml r1703 buffer_alb stream_alb c:\GIS\raw_dems 'area1,
area2, area3, area4' utm_projection.prj
```

NOTE: The list of DEMs must be enclosed with single quotations, only when stringing all of the input parameters together.

2.2i-2 Editing options in the AML

Within the default Hydrogrid AML, values have been defined for the trench depth and width to be burned with the Agree AML. The user can specify different values other than those used by the Hydrogrid AML if desired. To do so, open and edit hydrogrid.aml in a text editor. In this example of the Hydrogrid AML code, lines that begin with “/*” are documentation that explains what the code does, and code that can optionally be modified depending on the user’s needs is highlighted with blue:

```
/* Add 300 decimeters (30 meters) to the elevation to ensure the trench stays above sea-level.
/* Replace <large hydrologic unit name> with appropriate name. Example: r1703.
/* Optionally, a value other than 300 can be used
demtmp = < large hydrologic unit name >_dem + 300
/*
/* Call the Agree AML to dig trenches with the streams coverage.
/* See MWD tool manual, for additional explanation of the Agree AML.
/* Replace <name of stream coverage> with appropriate name. Example: stream_alb.
/* Optionally, change buffer width (150m), smooth drop depth (-300), or sharp drop depth (-100).
/* Optionally, change the name of the stream coverage if not using our naming conventions.
&r agree.aml demtmp stream_alb 150 -300 -100
```

Within the code, 300 decimeters are first added to the DEM to ensure that trenches near coastal regions do not reach below sea level. When the Agree AML is run, values of 150, -300, and -100 are used for the buffer width, smooth drop distance, and sharp drop depth respectively (see Hellweger 1997, <http://www.ce.utexas.edu/prof/maidment/gishydro/ferdi/research/agree/agree.html>). The user can change these parameter values if a trench with a different depth and width is required.

2.2i-3 Alternative methods to create hydrologic grids

ArchHydro extension for ArcGIS:

The ArchHydro extension is an easy to use, menu driven addition to ArcGIS. The extension and documentation are available at <http://www.cwrw.utexas.edu/giswr/>. ArchHydro’s convention to code the flow-direction grid is different from that used in TauDEM (Figure 2.7) and must be reclassified before use in the MWD tool. Although the menu driven format is simpler, creating each grid requires a separate action and currently no script exists to batch

| TauDEM | | | ArchHydro | | |
|--------|---|---|-----------|----|-----|
| 4 | 3 | 2 | 32 | 64 | 128 |
| 5 | | 1 | 16 | | 1 |
| 6 | 7 | 8 | 8 | 4 | 2 |

Figure 2.7. Comparison of TauDEM and ArchHydro flow-direction conventions.

the processes.

ArcGIS Hydrology Tool:

The ArcGIS Hydrology tool is found in ArcGIS ArcToolbox → Spatial Analyst Tools. This tool uses the same flow-direction convention as ArcHydro and grids must be converted before use in the MWD tool. Although the ArcGIS ModelBuilder can be used to automate the creation of hydrologic grid, the process is often unstable and output can be corrupt.

NHD Plus:

NHD Plus is a revision of the medium resolution NHD data (1:100,000 scale) that includes additional attributes (elevation, land-use, climate, modeled flow and velocity). In addition, it has the raw DEMs, flow-direction, and flow-accumulation grids already processed and available for download. The data lacks a modeled stream grid, and flow-direction grids follow the ArcHydro convention. NHD Plus is currently available for Columbia and Mississippi River drainages, with other areas pending. NHD Plus data and documentation are available at: <http://www.horizon-systems.com/NHDPlus/index.htm>. Once NHD Plus is available nation-wide, it will be a valuable resource. However, we recommend that users have the ability to produce their own hydrologic grids to address areas where DEMs and NHD data produce incorrect delineations (see section 2.5e)

2.3 Delineate watersheds with the MWD tool

Before beginning, verify that all necessary input files are present **and in the correct projections**. The necessary files are: (1) the medium hydrologic units file (section 2.2b), (2) the verified outlets file for the large hydrologic unit (section 2.2g), and the DEM and hydrologic grids (section 2.2i). We recommend that these files be placed in a single working directory for easier input entry and more reliable processing.

NOTE: As part of the point verification process (section 2.2f), ArcGIS creates additional fields in the point-file attribute table that will cause conflicts with the MWD tool. The problem fields are usually named: "FID_1" or "FID_2". **THE USER MUST REMOVE THESE FIELDS FROM THE FILE BEFORE PROCEEDING.**

There are four main steps in the watershed delineation process (Figure 2.8).

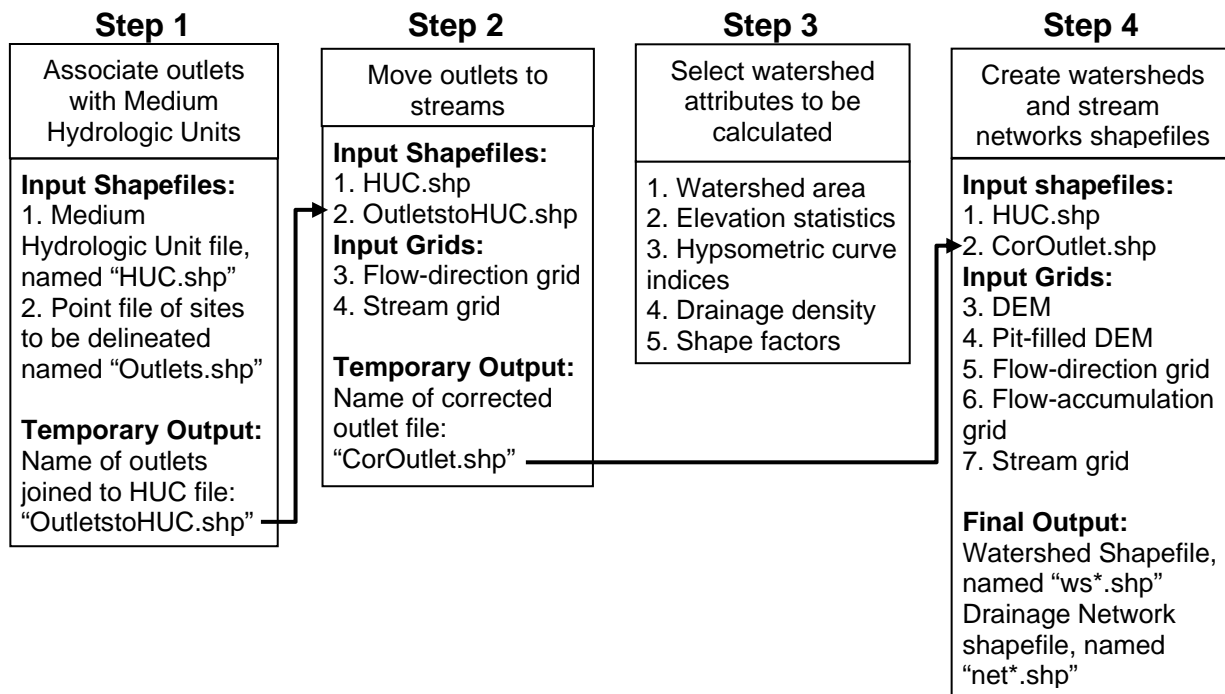


Figure 2.8. The main processing steps in the MWD tool. Arrows identify intermediate outputs from the tool that are then passed to a later step.

2.3a Step 1: Associate outlets with medium hydrologic units

An association is made between each medium hydrologic unit and the outlets that fall within its boundaries. The feature ID (FID) number, which is a unique identifier internal to ArcGIS, of each medium hydrologic unit is assigned to the outlets that fall within its boundaries. The output of Step 1 is a point shapefile called "OutletstoHUC.shp". The OutletstoHUC.shp file contains a new field ("FID_1" or "FID_2") in its attribute table that identifies each outlet's associated medium hydrologic unit (Figure 2.9). The association allows the tool, in step 4, to clip out the appropriate medium hydrologic unit from the large hydrologic unit and delineate watersheds for each outlet within that medium hydrologic unit (section 1.3). This file is passed to step 2 (Figure 2.8).

NOTE: Once this step is executed, the user must not alter the medium hydrologic unit shapefile, because alterations will disrupt the association with the FIDs. If it is altered, the user must run this step again before going to the next step.

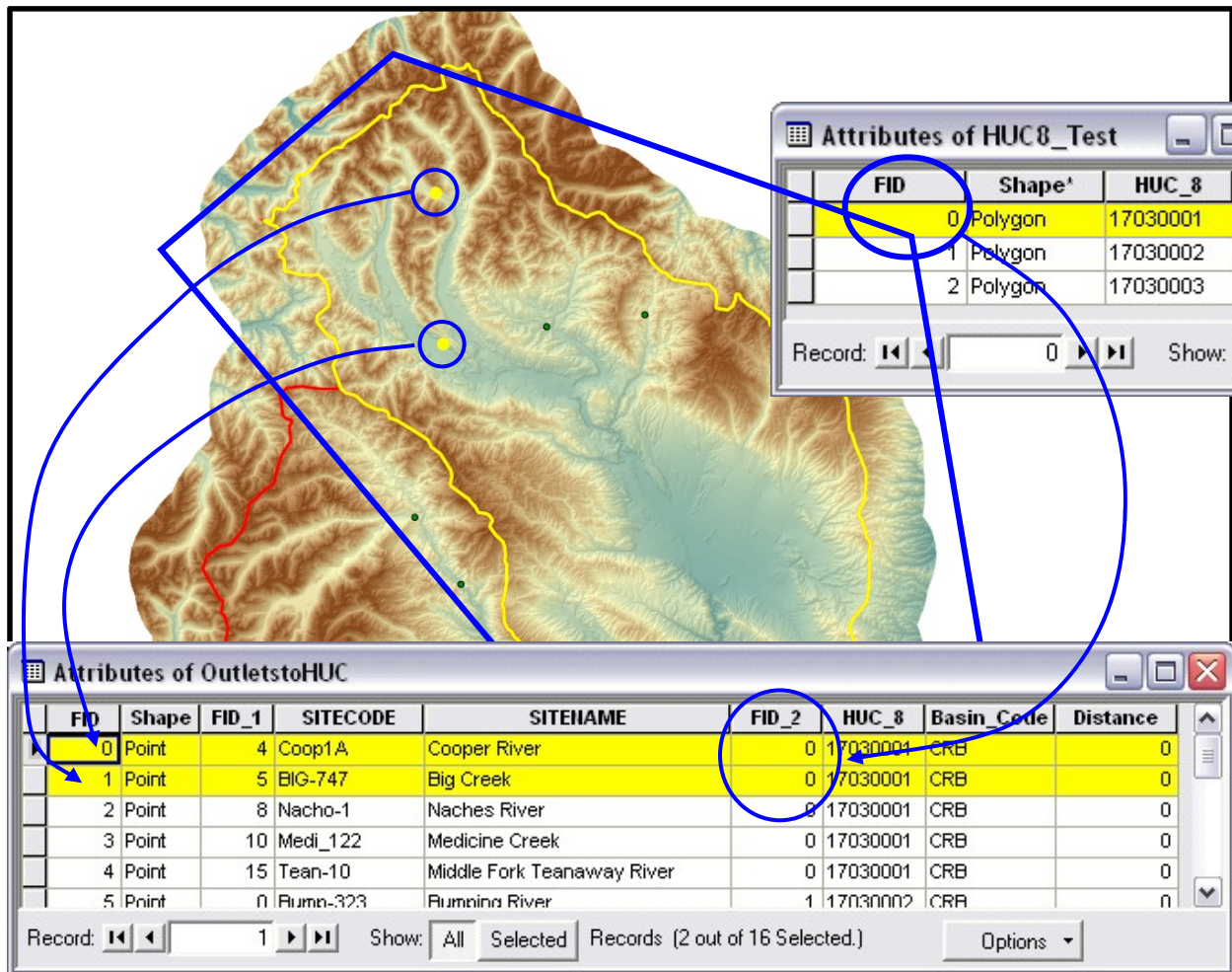


Figure 2.9. Creating association between Medium Hydrologic Units and outlet points during Step 1 of the MWD tool. The FID of the medium hydrologic unit containing the first point (FID = 0 in the HUC attribute table) is recorded in the field "FID_2" in the attribute table of OutletstoHUC.shp.

Execute Step 1 (Figure 2.10):

1. Provide the directory path to: (1) the large hydrologic unit DEM (section 2.2i) (browsing to this directory sets directory paths for all other inputs to that directory, using the same prefix (everything before the underscore) as the DEM, e.g., "r1703_dem"), (2) the medium hydrologic unit shapefile (section 2.2c), (3) the outlet point-file (section 2.2g), and (4) the output of this step.
2. Click on "Create MHU to outlets association".

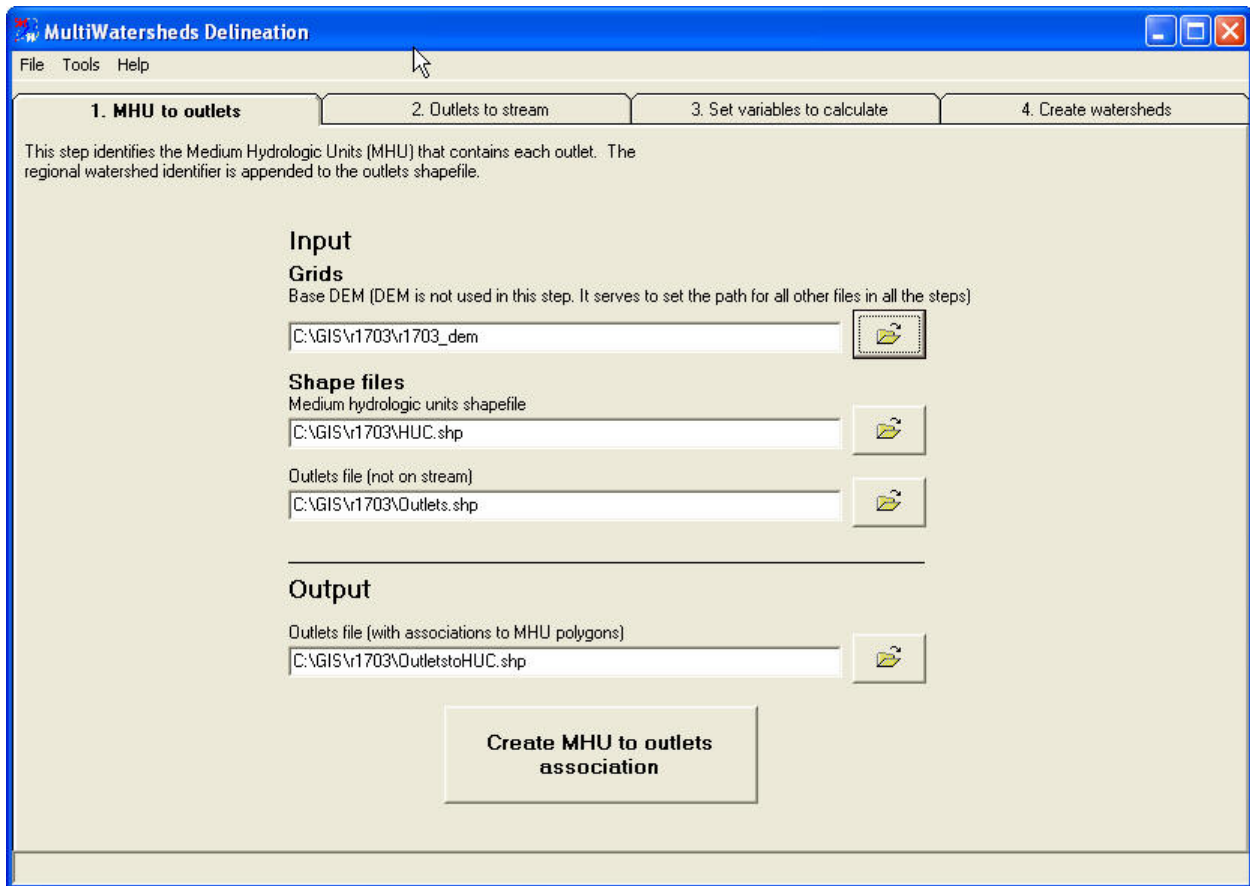


Figure 2.10. MWD tool: step 1 of 4.

2.3b Step 2: Move outlets to streams

Outlets that are slightly off-set from the stream network are moved downhill to the stream (section 1.3). The corrected locations are saved as a point shapefile called “CorOutlets.shp”. Although this shapefile is an intermediate step in the delineation process, the new locations may be of interest to some users. If so, a more descriptive name for the shapefile can be specified. The tool allows the user to set a limit to the number of cells a point will move downhill because a point that is very far from the stream may indicate serious coordinate errors.

The CorOutlets.shp attribute table contains 2 new fields labeled: (1) “ismoved” and (2) “distance moved” (Figure 2.11). The “ismoved” field contains a “1” if the point was already located on the stream or was successfully moved to it. A “0” in the “ismoved” field means the distance to the stream was beyond that specified by the user and the point was not moved. The MWD tool only delineates watersheds for points with a “1” in the “ismoved” field. Although the user may edit the outlet file to get all points to locate to a stream, we recommend that sites not moved be ignored at this step and addressed during the watershed quality control step (section 2.5e). The “distance moved” field states the number of cells a point was moved to the stream. The CorOutlets.shp file is passed to step 4 (Figure 2.8).

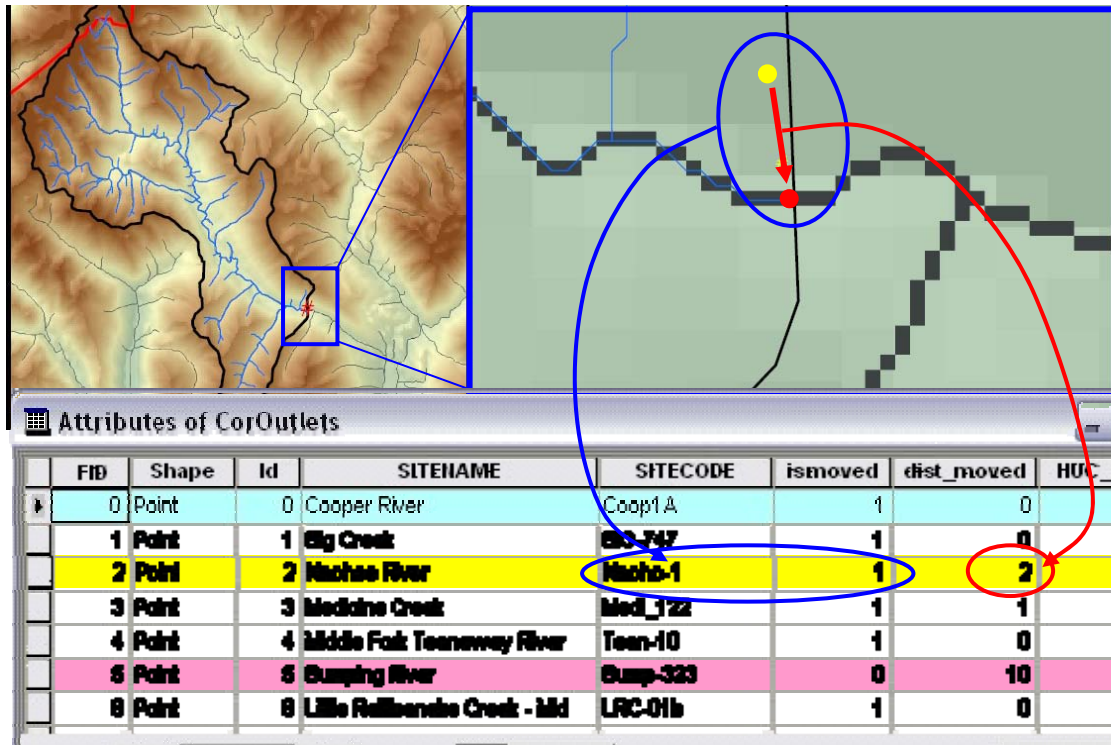


Figure 2.11. Example of the Corrected Outlets File. Note that site Nacho-1 moved two cells (ismoved=1, highlighted in yellow), but site Bump-323 did not move (ismoved=0, highlighted in pink).

Step 2 of the program clips medium hydrologic units from the large hydrologic unit as described in section 1.3. A buffer is added to the medium hydrologic unit to account for any errors in the medium hydrologic unit's boundaries. The default buffer is 500 meters, but the buffer may need to be increased based on the accuracy of the medium hydrologic unit boundaries. However, the larger the buffer used, the larger the area clipped is, and therefore the likelihood of memory management errors increases.

Execute Step 2 (Figure 2.12):

1. Provide the directory path to: (1) the flow-direction grid (section 2.2i2), (2) the stream grid (section 2.2i2), (3) the medium hydrologic unit shapefile (section 2.2c), (4) the OutletstoHuc.shp (Step 1), and (4) the output files.

NOTE: Use the 1-8 coded flow direction grid (*.fd8), not the 1-126 (*.fd) grid. If our naming convention is followed all the directory paths and files should automatically be placed into the correct location, and you will not have to change anything at this point, but only verify that all fields are correctly filled.

2. Specify the maximum number of cells an outlet should move and the buffer distance to be applied the medium hydrologic unit.
3. Click on "Move outlets to stream".

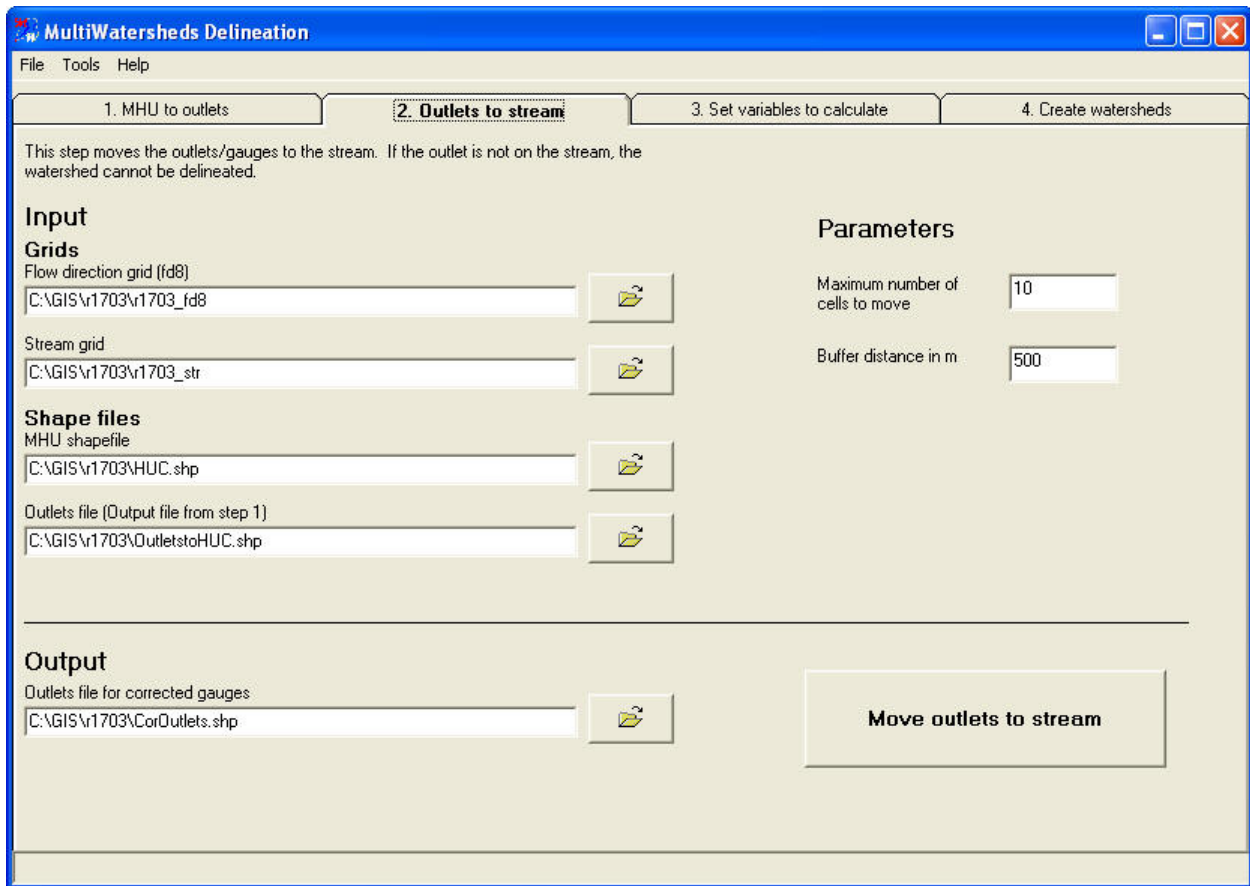


Figure 2.12. MWD tool: step 2 of 4.

2.3c Step 3: Select attributes to be summarized

In addition to deriving watershed boundaries, the MWD tool will calculate and summarize several watershed-level geomorphic and topographic attributes (see section 2.4). These attributes are useful for different types of analysis, and the user should only select those that meet their needs. Note that the functions used to calculate the hypsometric curve indices and shape factors are processor intensive and can double the running time of the program. Therefore, the user should consider deselecting these options unless this output is truly desired.

Execute Step 3 (Figure 2.13):

1. Place a checkmark next the desired watershed attributes.
2. Click on “Next →”

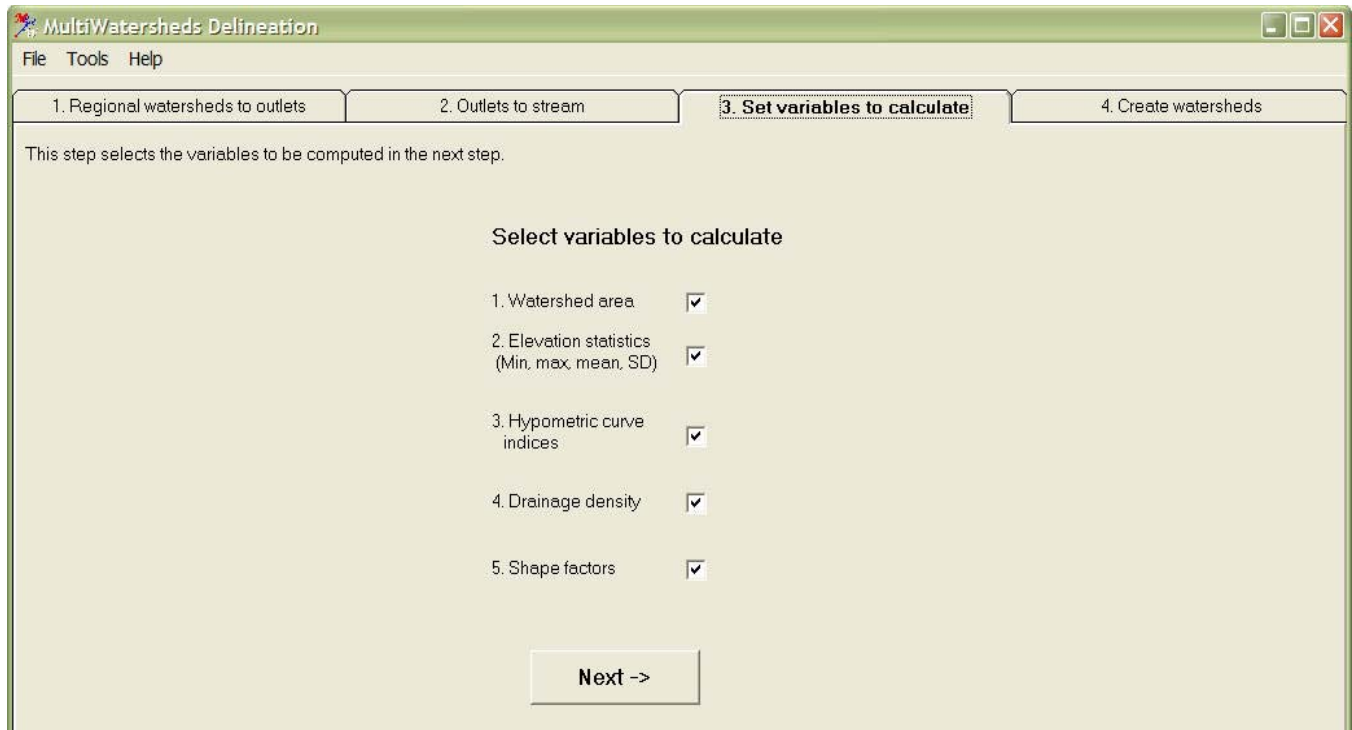


Figure 2.13. MWD tool: step 3 of 4.

2.3d Step 4: Create watershed and stream network shapefiles

The final step in the MWD tool delineates the watershed boundaries, and computes the variables selected in step 3 for each corrected point within the CorOutlets.shp file. In addition, the MWD tool creates a shapefile of stream networks for each output watershed. Determining where a stream starts, as part of stream network delineation, can be done either with the DEM Curvature method or by establishing a contributing area threshold (Figure 2.14). The contributing area method initiates a stream wherever the flow accumulation grid passes a certain threshold (Section 1.2c). **If the user does not need either the stream networks or drainage density**, we recommend using the contributing area method with a user-established threshold of 1000. The DEM curvature method determines every cell in the grid where flow converges (i.e., concave terrain represented by upward curved cells), and creates a weighted drainage area grid from the flow convergence cells and the weight values given in the dialogue box. A stream is initiated when a threshold number of weighted drainage cells is reached. The DEM curvature approach predicts stream initiation over areas with variable topographic texture better than the contributing area method.

The thresholds for both contributing area or flow convergences can either be entered by the user for all watersheds or determined automatically for each watershed with the TauDEM constant drop analysis function. Constant drop analysis is an objective method for determining stream initiation thresholds, based on the hypothesis that the mean drop in elevation of first order streams is not statistically different from the mean drop in elevation of higher order streams (Tarboton et al. 1991). Constant drop analysis makes this comparison of elevation drops for each possible stream network, derived from a number of evenly spaced thresholds over a given range of threshold values. The

number and the range of possible thresholds evaluated are determined by the “Number”, “Lowest”, and “Highest” entries in the constant drop analysis dialogue box (Figure 2.14). We recommend using the default values for these numbers in almost all cases. The function then tests each of these values and picks the first threshold that satisfies the constant drop criterion. For additional information, see Tarboton and Ames 2001 or <http://hydrology.neng.usu.edu/taudem/>.

| | | Threshold Establishment Method | |
|---------------------------|-------------------|--|--|
| | | Constant Drop Analysis | User Selected |
| Stream Delineation Method | DEM Curvature | <p>Stream delineation methods</p> <p><input checked="" type="radio"/> DEM curvature based</p> <p><input type="radio"/> Contributing area threshold</p> <hr/> <p>Stream delineation parameters and settings</p> <p>Weight center: <input type="text" value="0.4"/> Weight side: <input type="text" value="0.1"/> Weight diag.: <input type="text" value="0.05"/></p> <p><input checked="" type="checkbox"/> Perform Constant Drop Analysis</p> <p>Use the range below to automatically select threshold by drop analysis.</p> <p>Lowest: <input type="text" value="5"/> Highest: <input type="text" value="1000"/> Number: <input type="text" value="10"/></p> | <p>Stream delineation methods</p> <p><input checked="" type="radio"/> DEM curvature based</p> <p><input type="radio"/> Contributing area threshold</p> <hr/> <p>Stream delineation parameters and settings</p> <p>Accumulation threshold: <input type="text" value="50"/></p> <p>Weight center: <input type="text" value="0.4"/> Weight side: <input type="text" value="0.1"/> Weight diag.: <input type="text" value="0.05"/></p> <p><input type="checkbox"/> Perform Constant Drop Analysis</p> |
| | Contributing Area | <p>Stream delineation methods</p> <p><input type="radio"/> DEM curvature based</p> <p><input checked="" type="radio"/> Contributing area threshold</p> <hr/> <p>Stream delineation parameters and settings</p> <p><input checked="" type="checkbox"/> Perform Constant Drop Analysis</p> <p>Use the range below to automatically select threshold by drop analysis.</p> <p>Lowest: <input type="text" value="5"/> Highest: <input type="text" value="1000"/> Number: <input type="text" value="10"/></p> | <p>Stream delineation methods</p> <p><input type="radio"/> DEM curvature based</p> <p><input checked="" type="radio"/> Contributing area threshold</p> <hr/> <p>Stream delineation parameters and settings</p> <p>Contributing area threshold (number of grid cells): <input type="text" value="1000"/></p> <p><input type="checkbox"/> Perform Constant Drop Analysis</p> |

Figure 2.14. Stream delineation and threshold establishment methods. Choosing the delineation method and check/unchecking Constant Drop Analysis will change the input options as shown.

Step 4 creates an individual watershed and stream network shapefile for every outlet (i.e., 10 points result in 10 output watershed shapefiles and 10 stream network shapefiles; 20 total shapefiles). The naming convention the MWD tool assigns to the

output shapefiles is based on the FID of the medium hydrologic unit file and the sequential order in which the points are processed. For example, the first watershed delineated in the medium hydrologic unit with a FID = 0 will be named “ws0_0.shp”, and the sixth watershed delineated in the medium hydrologic unit with a FID = 2 will be named “ws2_5.shp”.

There are three additional parameter inputs the user may specify (red box in Figure 2.15). The first parameter, “Buffer distance in meters”, is the same buffer used in step 2 of the MWD tool (see section 2.3b). The other parameters, “Start MHU” and “Start site”, are used to start the delineation process in the middle of an outlet file by specifying which watershed to delineate based on the naming convention just discussed (see section 2.5c). To begin, use the defaults of 0 in both boxes.

NOTE: The MWD tool creates a text file at the beginning of the delineation process (donelog.txt) to track the success or failure of the delineation of each outlet point, and records error messages. Check both this file and the attribute table of the first watershed delineated, to ensure the process is working correctly and Site codes remained intact. If the first several watersheds all fail, close the tool and troubleshoot (see section 2.5c). Remove any previously delineated watersheds or network files before running step 4, because the MWD tool uses the same names when delineating and **will overwrite previous work, without any warning!**

Execute Step 4 (Figure 2.15):

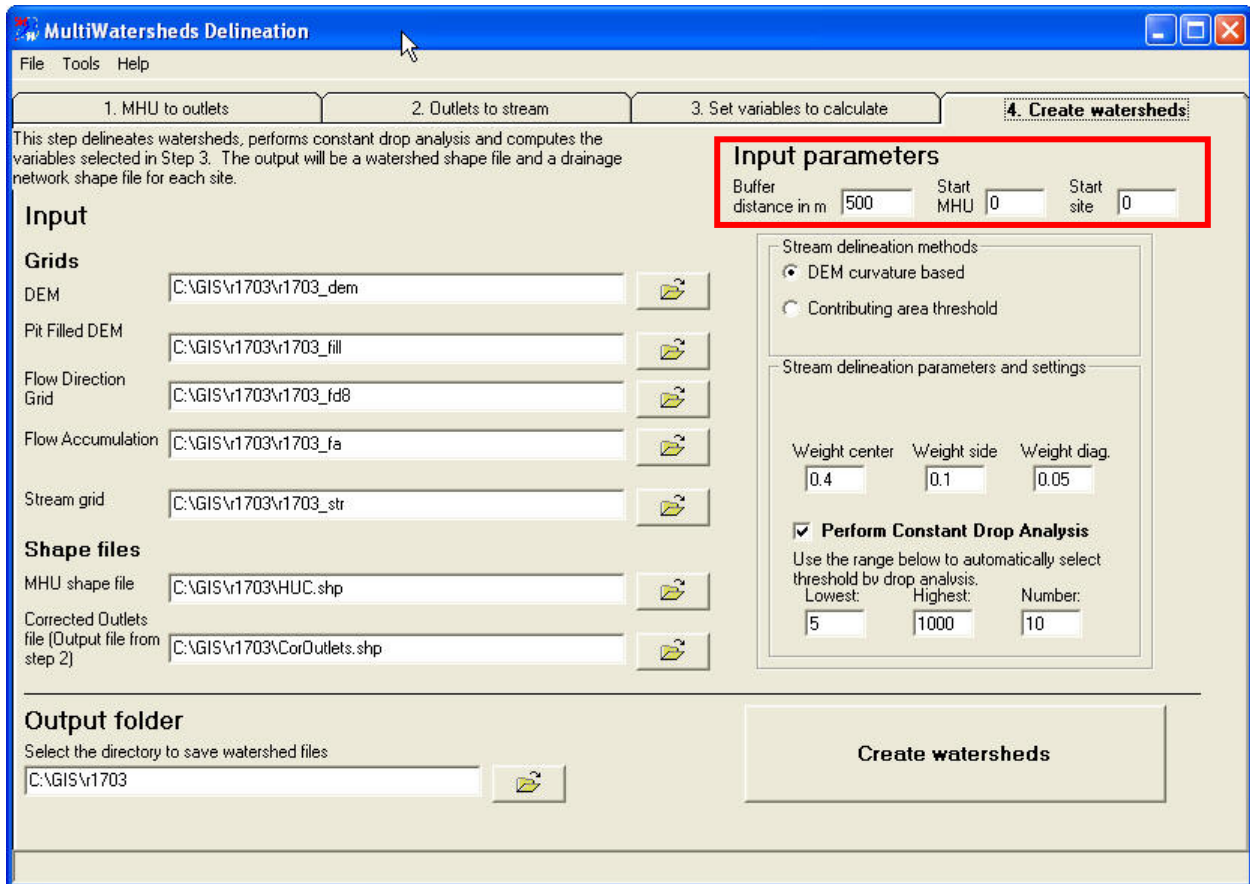


Figure 2.15. MWD tool: step 4 of 4.

1. Provide the directory path to: (1) the large hydrologic unit DEM (section 2.2i2), (2) the pit-filled DEM (section 2.2i2), (3) the 1-8 coded flow-direction grid (section 2.2i2), (4) the flow-accumulation grid (section 2.2i2), (5) the stream grid (section 2.2i2), (6) the medium hydrologic unit shapefile (section 2.2c), (7) CorOutlets.shp (Step 2), and (8) the output watersheds and network shapefiles.
2. Select the desired stream delineation method and threshold.
3. Provide parameter options if needed, and click on “Create watersheds”.
4. Upon completion, create a new feature class with one of the output watersheds as a template (ArcToolbox: Data Management Tools → Feature Class → Create Feature Class) and append all watersheds to this new feature class (shapefile).

2.4 Description of watershed and stream network shapefile attributes

During the delineation process, the MWD tool derives both attributes summarizing the topography of each watershed and the network characteristics. Depending on the user’s needs, these additional terrain-derived attributes may not be necessary, but are most efficiently derived during delineation and can be ignored if not needed.

2.4a Output watershed shapefile

Each watershed shapefile will have its Sitecode and Sitename in the attribute table as well as any of these optional variables selected in step 3:

1. Watershed area (Area): Area of the watershed basin in the horizontal units of the DEM’s projection (e.g., m²).
2. Elevation statistics:
 - a. Minimum, maximum, mean, and standard deviation of elevation within the output watershed, calculated from the DEM. Elevations are in the same vertical units as the DEM. If the DEMs were produced with the AML (see section 2.2i2) the elevation values are in decimeters, and the field must be divided by 10 to convert back to meters.
 - b. The mean dimensionless elevation - relief ratio (RR_mean) is described in Pike and Wilson (1971) as:

$$RR_mean = \frac{Elev_mean - Elev_min}{Elev_max - Elev_min}$$

3. Hypsometric curve indices: A watershed’s hypsometric curve describes how elevation changes as one moves down through a watershed. The curve is a plot of percent area versus elevation (Figure 2.16). The MWD tool automatically determines the elevations for 15 increments of percent watershed area that can then be used to plot a hypsometric curve for each output watershed. The output fields are prefixed with “Hypso” and a numeric suffix is attached that describes the area percentile reported for that field. For example, Hypso50 reports the elevation contour line above which 50% of the catchment area occurs. The hypsometric values are also used to calculate the median dimensionless elevation - relief ratio (RR_median):

$$RR_median = \frac{Hypso50 - Elev_min}{Elev_max - Elev_min}$$

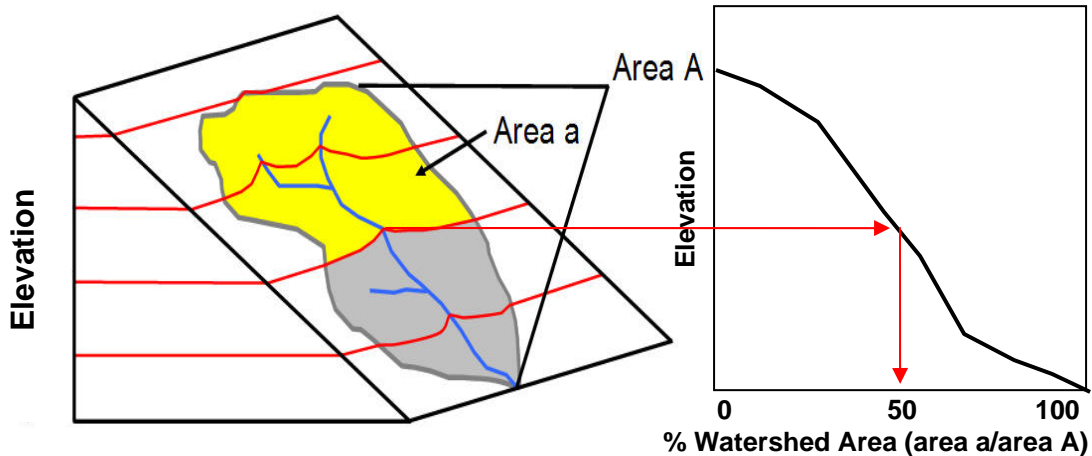


Figure 2.16. a) The elements of watershed hypsometry. Area A is total watershed area, Area a is 50% of total watershed area. b) A Hypsometric curve.

4. Drainage density variables:
 - a. CDAdone: Records whether the constant drop analysis was performed (1) or not (0).
 - b. CDAMethod: Method selected to delineate the stream network. (1- contributing-area method, 4- DEM Curvature method).
 - c. CDATHresh: Drainage area threshold used in stream delineation method.
 - d. DDen: Drainage density is the cumulative length of stream within the output watershed divided by the drainage area [$\text{length} \cdot \text{area}^{-1}$]. The length-value will be in the same units as the horizontal units of the DEM.
5. Shape factors:
 - a. Shape1: Is the ratio of the watershed area to the square of the longest distance to the outlet on the flow path (dimensionless).
 - b. Shape2: Is the ratio of the watershed area to the square of the mean distance to the outlet (dimensionless). Flow distance of each grid cell in the watershed to the outlet is calculated and then averaged to obtain the mean distance to the outlet.

2.4b. Output stream network shapefile

This shapefile consists of a single line segment for each link of the delineated stream network. The term link is the basic unit of network composition and is used here as a replacement for Strahler stream segment. It is defined as “an unbroken section of channel between successive nodes (sources, junctions, or outlet)” (Knighton 1998).

1. Network topology. These are used during network analysis to define relationships between the different links of the network.
 - a. LINKNO: The Link Number, a unique identifier associated with each link.
 - b. DSLINKNO: Link Number of the downstream link. A value of -1 indicates that there is no downstream link.
 - c. USLINKNO1: Link Number of first upstream link.
 - d. USLINKNO2: Link Number of second upstream link, assuming that two links confluence upstream, otherwise 0.

- e. DSNODEID: Identifies the furthest downstream link of the network with a number corresponding to the identification number of the outlet point used to delineate the watershed. All upstream links coded as “-1”. (NOTE: THIS FUNCTION STILL HAS A BUG, AND RESULTS IN A “0” INSTEAD OF A NUMBER ASSOCIATED WITH THE WATERSHED)
- 2. WSNO: Watershed number is an identification number that allows the user to cross-reference with the stream network shapefile’s corresponding output watershed shapefile. (NOTE: THIS FUNCTION STILL HAS A BUG, AND RESULTS IN A “0” INSTEAD OF A NUMBER ASSOCIATED WITH THE WATERSHED)
- 3. Stream network characteristics:
 - a. Order: Strahler Stream Order.
 - b. Magnitude: Shreve Magnitude of the link.
 - c. Length: Length of the link.
 - d. Drop: Drop in elevation from the start to the end of the link.
 - e. Slope: Average slope of the link (computed as drop/length).
 - f. DS_Cont_Ar: Drainage area at the downstream end of the link.
 - g. US_Cont_Ar: Drainage area at the upstream end of the link.
 - h. Straight_L: Straight line distance from the start to the end of the link.
 - i. DOUT_END: Distance to the outlet from the downstream end of the link.
 - j. DOUT_START: Distance to the outlet from the upstream end of the link.
 - k. DOUT_MID: Distance to the outlet from the midpoint of the link.

2.5 Troubleshooting and Quality Control of watershed delineations

Although the MWD tool is reasonably robust, some sites can be problematic to delineate. Here we describe solutions to common problems associated with (1) acquiring and importing GIS data, (2) generating intermediate GIS layers, and (3) using the MWD tool.

2.5a Problems acquiring, importing, and manipulating GIS data

1. **Problem:** The site data will not import into ArcGIS.
Causes: Importation problems are commonly caused by (1) characters that are interpreted as delimiters (e.g., spaces in field headings, e.g., Site Code vs. Sitecode or commas in a data record, e.g., Left Fork, North Fork Smith River), (2) mixed numeric and text site codes, or (3) longitude-values in western hemisphere coordinates without a negative (-) sign.
Solutions: Remove all spaces in field headings or replace with “_”, remove all commas from records, add a letter at the beginning of each numeric site code, and verify that longitudes have a negative value.
2. **Problem:** Gaps present in downloaded DEM data.
Causes: Gaps in DEM data can occur if the user fails to select overlapping areas when downloading NED data or fails to download all tiles. Also, if a watershed spans international borders, U.S. DEMs will not provide a hydrologically complete watershed.

Solutions: Download DEMs covering the gaps from the USGS NED or other websites. Some Mexican DEM data can be obtained from the USGS NED. Canadian DEM data can be obtained at <http://geobase.ca/>. Note, that the cell resolution of the Canadian DEM data is 90-m (3 arc-seconds).

3. **Problem:** Hydrologic grids are corrupt (can not be viewed in ArcMap) or are incomplete.

Causes: Incomplete grids will be created if the user does not use coverages that cover their area of interest, or fails to list all appropriate raw DEMs as input. Incomplete or corrupt grids can also be caused by failing to make appropriate sacrifices to the GIS Gods.

Solutions: Ensure the coverage you are using to create the hydrologic grids is complete and you are listing each of the component raw DEMs needed to cover that coverage. If that is not the cause, try rerunning the hydrogrid.aml.

2.5b Problems at Step 1 of the delineation process

1. **Problem:** Nothing functions in the MWD tool, when you attempt to browse to the input data the tool crashes.

Cause: Installation of later versions of ArcGIS (9.1 or later) do not create all environmental variables needed by the MWD tool during installation.

Solution: Go to “My Computer”, right click and select “Properties”, select the “Advanced” tab, click the “Environmental Variables” button, under User Variables click on “New”, enter “Path” for Variable Name, and enter “C:\Program Files\ArcGIS\Bin”. Click OK three times to accept the new variable and rerun the tool.

2. **Problem:** The MWD tool crashes or points are relocated to 1-6 different locations, with multiple points on top of one another.

Cause: Providing the tool an input (usually the outlet file) that is not projected.

Solution: Ensure that all inputs to the tool are projected into the same projection.

2.5c Problems at Step 2 of the delineation process

1. **Problem:** The MWD tool gives the error message “Error 9, Subscript out of range”.

Cause: An extra “FID” field is in the point data, usually named “FID_1” or “FID_2”.

Solution: Remove fields labeled “FID_1” and “FID_2”.

2. **Problem:** Step 2 does not move some of the sites to the stream.

Causes: Unmoved sites are further from the stream network than the threshold number of cells designated by the user. There are four specific causes for this problem (see Figure 2.17): (1) coordinate errors, (2) a point near the stream, but in a flow path that runs parallel to the stream and therefore beyond the threshold value, (3) the stream grid we created does not

go far enough up the valley to accurately represent the stream (i.e., we used too high threshold when creating the hydrologic grids), and (4) the point falls on the wrong channel of a multi-thread river, which is modeled in by the stream grid as a single channel, therefore the point falls further than the movement threshold from the stream.

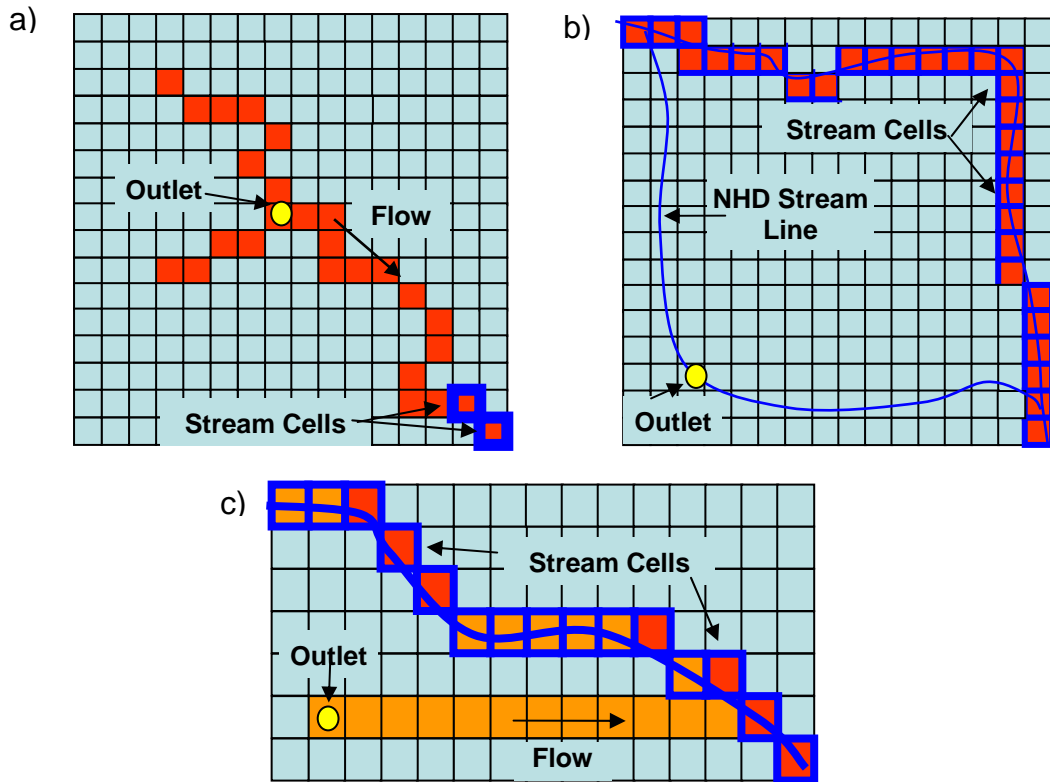


Figure 2.17. Causes of failures for points to move during Step 2. a) Outlet too far from stream threshold. b) Outlet on wrong channel of multi thread stream. c) Outlet on parallel flow line, farther than the movement threshold

Solutions: Respective solutions to unmoved sites are: (1) correct coordinate error or manually move the point, (2) increase the number of cells a point can move (threshold number) or manually move the point, (3) create a new stream grid to use with sites above the current stream grid with the raster calculator's (Spatial Analyst) expression "Con([flow accumulation grid] > 500, 1)", and (4) select and remove additional threads from the stream_alb ArcInfo coverage and reprocess the hydrologic grids, or manually move the point.

3. **Problem:** Step 2 does not move any of the sites to the stream.

Cause: Incorrect projection information for one or more of the input GIS layers.

Solution: Verify projection coordinate systems and project data.

2.5d Problems at Step 4 of the delineation process

1. **Problem:** The MWD tool delineates most of the watersheds but then crashes or freezes. Alternatively, the process finishes without crashing but with only a portion of the watersheds delineated.

Cause: After each successful delineation, the program's memory is cleared, except for a small remainder. After about 50-100 successful delineations (depending on basin sizes) the accumulated uncles memory may stop the delineation process.

Solution: Restart Step 4 of the MWD tool. The MWD tool provides a way to restart the delineation process at the watershed that failed. The donelog.txt file records the success or failure of each point (see Figure 2.18). The progress is recorded sequentially and includes the FID-code of the medium hydrologic unit that is associated with each point. For example, as shown in Figure 2.18 the MWD tool successfully delineated two watersheds in the medium hydrologic unit with FID-code "5". The tool then failed at the third watershed.

```
10,2408419,5899676,1,9,4,"CONGRATULATIONS! you just delineated a Watershed"  
11,2409139,5900966,1,10,5,"CONGRATULATIONS! you just delineated a Watershed"  
12,2409709,5902886,1,11,5,"CONGRATULATIONS! you just delineated a Watershed"  
--Error message--
```

Medium hydrologic unit code

Figure 2.18. Portion of donelog.txt output. The FID-code of each medium hydrologic unit is recorded, shown here as 5

To restart the MWD tool, go to Step 4 of the MWD tool. Input a "5" in the box labeled "Start MHU" and "2" in the box labeled "Start sites" (see Figure 2.19). The point indexing starts from 0, therefore 2 refers to the third site.

| Input parameters | | | | | |
|----------------------|----------------------------------|-----------|--------------------------------|------------|--------------------------------|
| Buffer distance in m | <input type="text" value="500"/> | Start MHU | <input type="text" value="5"/> | Start site | <input type="text" value="2"/> |

Figure 2.19. Example input parameters to restart Step 4 of the MWD tool.

Note: Problems 2-5 require that the delineation process be started over again after correcting the cause of the problem. We recommend that these "problem" outlets first be extracted from the outlets that delineated, and then the "problem" outlets are delineated along with any watersheds that failed the quality control check (section 2.5e). Extraction of "problem" outlets can be accomplished by:

- 1) Join the merged watershed file's attribute table (from the successful delineations) to the attribute table of the original outlet file based on the Sitecode field.
- 2) Open the attribute table of original outlet file and select those points without watershed attributes joined to them. These were not delineated. Export these points as a new outlet shapefile.

- Problem:** The MWD tool fails to delineate any watersheds within a particular medium hydrologic unit, even after restarting.

Cause: The medium hydrologic unit clips portions of the hydrologic grids that are too large for processing.

Solution: Edit the medium hydrologic unit file in ArcMap. Using the “cut polygon features” task, cut the medium hydrologic unit that is too big in two, roughly along a ridge creating upstream and downstream halves. Restart the delineation process at Step 1 using this edited medium hydrologic unit file, because of the new FID assignments that are created during editing. Use a large buffer (5000m or larger) to account for the approximate boundaries of this edited medium hydrologic unit.

- Problem:** The MWD tool finishes the delineation process, but a portion of points remains un-delineated and the donelog.txt file contains the error message: "Sourcedef error 8".

Causes: The portion of the flow direction grid clipped by the medium hydrologic unit does not contain the entire watershed boundary. In other words, the watershed is “edge contaminated” because the delineation process reaches the edge of the grid before it come to the hydrologic divide. This error can be caused either by either (1) inaccuracies in the medium hydrologic unit polygon or (2) by trying to delineate a watershed larger than your medium hydrologic unit (Figure 2.20).

Solutions: Respective solutions to source contamination errors are: (1) account for inaccuracies in the medium hydrologic unit polygon by increasing the buffer size, up to a maximum of 10km, or (2) delineate watersheds larger than your medium hydrologic unit size using the courser resolution 90m data. To delineate using 90m data, start the MWD tool back at Step 1 and use: (1) an outlet file of those points with watersheds larger than your medium hydrologic units, (2) the 90m hydrologic grids (i.e., “r170390_dem”, etc.), and (3) the HUC4.shp as a new, larger, medium hydrologic unit file.

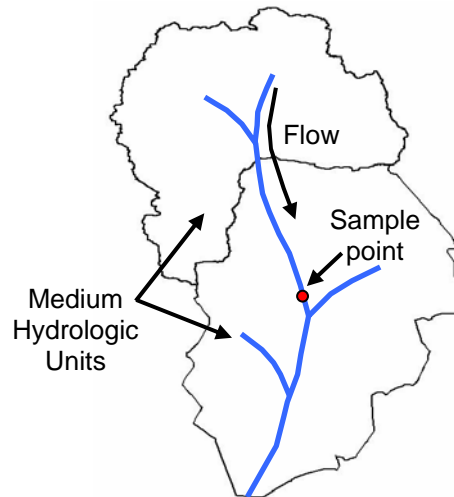


Figure 2.20. A medium hydrologic unit receiving flow from an upstream medium hydrologic unit. Errors occur when the MWD tool attempts to delineate a watershed from the sample point.

- Problem:** The donelog.txt file reports “Source file has one grid with a value of 1”. Points with this error were not delineated.

Cause: The point is located on the upper most cell of the stream network.

Solution: Manually move the point downstream a few cells.

5. **Problem:** The donelog.txt file reports the error: "Error with drop analysis. Grids may be too large or the site is not on the stream0" and no watersheds are delineated.

Causes: Two possible causes for this error are: (1) one or more point(s) failed to move to the stream during Step 2 of the delineation process (section 2.3b), or (2) the regional polygon is too large for the memory capacity of the computer.

Solutions: Two possible solutions are: (1) verify that all points were moved to the stream (section 2.5c), or (2) cut the medium hydrologic unit polygons into smaller sizes (see problem 2 in section 2.5d). If solutions 1 and 2 fail, delineate the watersheds with the Drop Analysis option turned off (selecting a threshold based on points that did run with drop analysis).

2.5e Problems with data output

6. **Problem:** The field DDen (drainage density, section 2.4) in the output watershed shapefile returns a value of -999.

Cause: There are no stream lines in the watershed polygon because the thresholds that define a stream channel are set too high (section 2.3d)

Solutions: If you are using Constant Drop Analysis to establish thresholds, adjust the "Lowest" value to 2 (Figure 2.14). If you are establishing thresholds, choose a lower value.

2.5f Quality control of watershed delineations

After all watershed delineations are complete, the accuracy and completeness of your output delineations should be checked before performing further analyses. We recommend that the user overlay the output watershed polygons with NHD streams in ArcMap. Compare the name of the outlet stream to the name of the output watershed. Ensure that points were moved to the correct streams in Step 2 of the delineation process (section 2.3b). Incorrect placement is especially common near stream confluences. In addition, each output watershed boundary should be compared with the stream network to ensure that the watersheds are complete, capturing all streams upstream of you outlet. In a few cases, burning in streams causes one stream to "capture" another inappropriately. Most cases where multiple NHD streams exit a watershed result from naturally occurring divergent flow, such as lakes with multiple outlets or anastomosing streams. Identify incorrect watershed delineations, fix any problems with the input data, and redelineate.

Part III: Watershed analysis

3.1 Calculating watershed statistics with the MWD tool

Watershed analyses often require information regarding the climatic, geologic, and other conditions that occur within a watershed. The MWD tool can generate these data with a module that calculates a variety of statistics from grids provided by the user for multiple watersheds. The MWD tool uses the internal functionalities of the ArcGIS Zonal Statistics tool to generate the information. However, whereas the Zonal Statistics tool is limited to a single grid for each analysis, the MWD tool processes multiple grids at once. Here we demonstrate the process of generating watershed level statistics with 2 grids representing climate information (Figure 3.1): (1) mean annual air temperature (tmean) and mean annual precipitation (prcp). The MWD tool is currently limited to grids of continuous data type and will not summarize categorical information such as geology class (see section 3.2).

NOTE: Before calculating watershed statistics ensure that the input grids and the watershed shapefile are in the same projection.

To generate watershed statistics with the MWD tool:

1. Click on the Tools menu → Watershed Statistics. A new window will appear.
2. Provide the directory path to the watersheds shapefile.
3. Click the “Add” button and provide the directory path to the grid datasets.
4. Select the statistics to be computed and click on the “Add →” button.
5. Provide a directory path for the output database file (DBF). Click on the “Get Statistics” button.

In the current example, the MWD tool creates a DBF table that contains 8 fields with the mean, minimum, maximum and standard deviation of the 2 climate grids within each watershed (Figure3.2). The file also contains a field with the SiteCode of each of the output watersheds. Based on the SiteCode field, this table can be appended to the output watershed shapefile attribute table in ArcGIS with the Table Join function (section 2.2h).

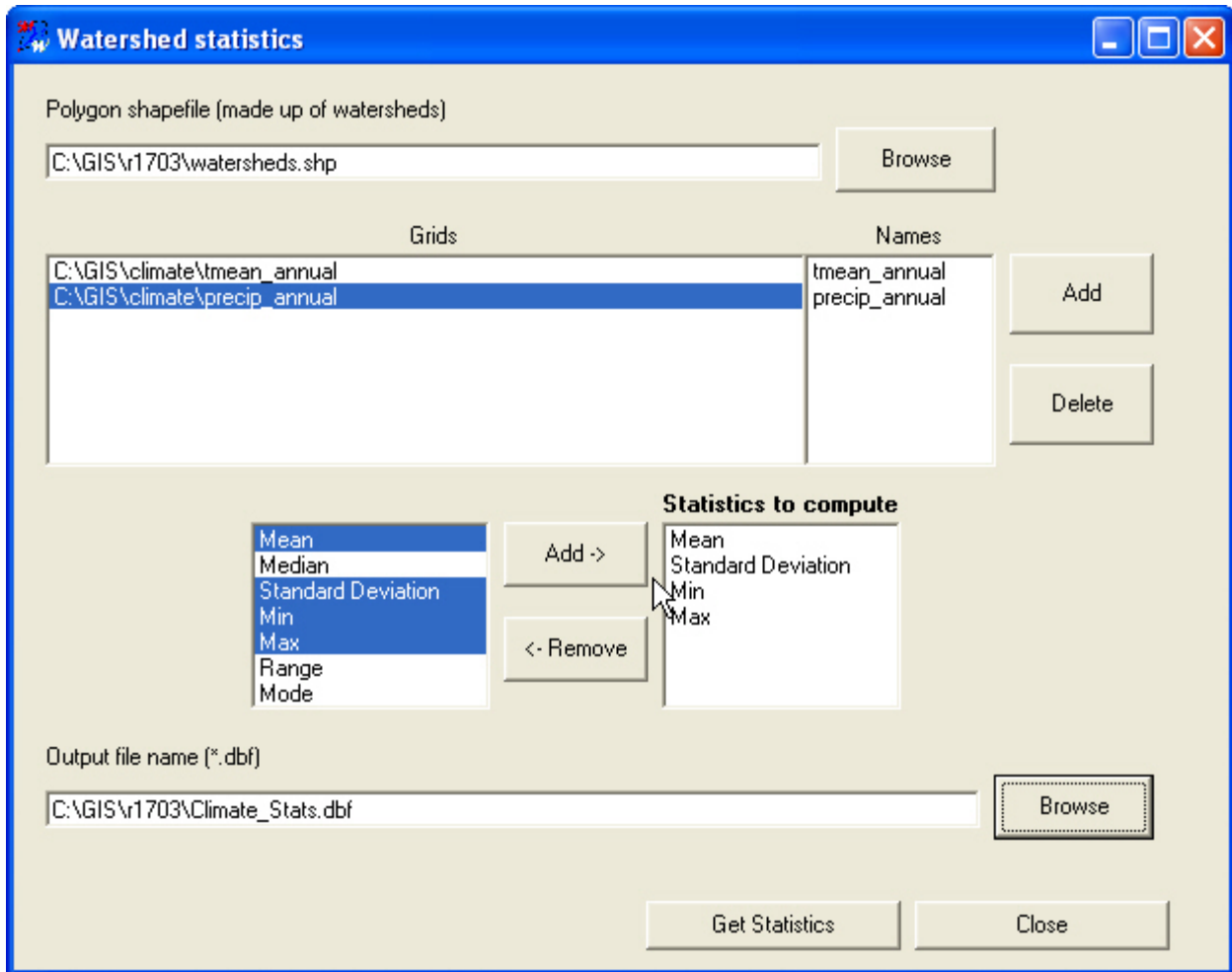


Figure 3.1. The MWD tool Watershed Statistics module. Multiple grids can be selected and processed at one time.

3.2 Other available tools

Other tools are available to calculate watershed-level statistics from grids. Here we briefly describe 3 that are available either through download or ArcGIS.

3.2a StatMod Zone Extension for ArcView 3.x

Not exclusive to hydrologic studies, the StatMod Zone extension summarizes both continuous and categorical grid information for polygons. Similar to the MWD tool, several grid layers can be processed at one time. In addition to polygon statistics, grid information can be spatially joined to point data. The StatMod Zone extension is available for download at <http://www.gis.usu.edu/~chrisg/avext/>.

3.2b ATtILA Extension for ArcView 3.x

The Analytical Tools Interface for Landscape Assessments (ATtILA) was developed by the EPA for quickly calculating landscape metrics for watershed polygons. Four metric groups are currently included in ATtILA: landscape characteristics, riparian

characteristics, human stressors and physical characteristics. Given output watershed polygons and grid (elevation, climate, or landuse), line (streams and roads), and polygon data (U.S. census data), ATtILA summarizes different characteristics for each, including population density, percent landuse, predicted nutrient run-off, number of stream-road crossings, etc. ATtILA is available for download at <http://www.epa.gov/esd/land-sci/attila/index.htm>.

3.2c Zonal Statistics in ArcGIS

Zonal Statistics, available through the Spatial Analyst Tool in ArcGIS, calculates summary statistics for portions of grids within polygons (zones), including watershed polygons. Although the Zonal Statistics tool can only process a single grid at a time, it will calculate additional statistics not available through the MWD tool that may be of interest to some users. The additional statistics available through the Zonal Statistics tool are: (1) sum, (2) variety, (3) majority, and (4) minority.

APPENDIX A References:

Hellweger F. 1997. Agree AML. Center for Research in Water Resources, University of Texas at Austin. <http://www.ce.utexas.edu/prof/maidment/gishydro/ferdi/research/agree/agree.html#Part1b>

Knighton, D. Fluvial Forms and Processes. New York: Oxford University Press. p. 383
Pike, R. J. and S. E. Wilson. 1971. Elevation -relief ratio, hypsometric integral, and geomorphic area-altitude analysis. Geological Society of America Bulletin 82: 1079-1084.

Tarboton, D. G., R. L. Bras and I. Rodriguez-Iturbe, (1991), "On the Extraction of Channel Networks from Digital Elevation Data," Hydrologic Processes, 5(1): 81-100

Tarboton, D. G. and D. P. Ames. 2001. Advances in the mapping of flow networks from digital elevation data. World Water and Environmental Resources Congress, Orlando, Florida, ASCE.

APPENDIX B Glossary

- **ArclInfo Syntax:** The following syntax consist of commands (show in CAPS), mandatory input parameters (shown between "<>" brackets) and optional input parameters (show between "{}" brackets). An example command would be: GRIDCLIP <in_grid> <out_grid> {* | COVER <clip_cover> | BOX <xmin ymin xmax ymax>. Syntax for any command can be accessed by typing help [enter], to start ArclInfo help.

- **Delineation:** The process of drawing, or mapping, the watershed boundary or stream network.

- **HUC:** HUCs are hydrologically defined areas that are hierarchically arranged. The largest level is the region, with each region given a two-digit code. Smaller areas within in each region are: sub-region (4-digit), basin (6-digit), and sub-basin (8-digit). Figure B1 shows the outlines of the Pacific Northwest Region in blue (a 2 digit HUC, number 17), the sub-regions in red (with the Yakima sub-region, HUC 1703, in brackets), and the three sub-basins colored pink (with the Lower Yakima sub-basin indicated). For more information, see <http://water.usgs.gov/GIS/huc.html>.

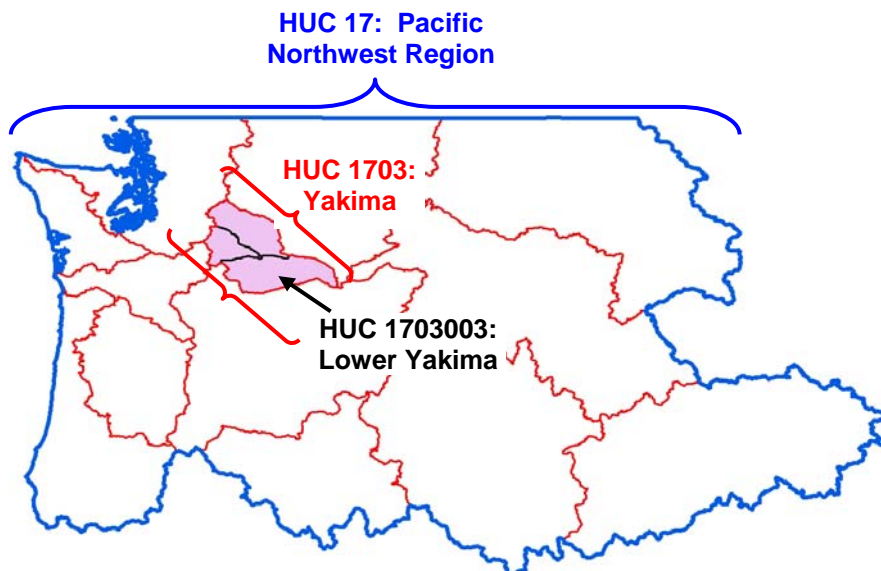


Figure B1. Hierarchical structure of USGS hydrologic units

- **Resolution:** DEM resolution or raster cell size (i.e. 30m x 30m pixels, or 90m x 90m pixels). Resolution will determine the precision of data produced.

- **Medium Hydrologic Units:** A hydrologically correct geographic region that contains points representing sites of interest. Each medium hydrologic unit will be based on both the user's area of interest and computer memory limitations. Our medium hydrologic units are typically comprised of a set of 8-digit HUCs (i.e., if the user is interested in study sites located on the Colorado River, an appropriately large hydrologic unit might be all HUCs upstream of the lowest study point, or if points are on smaller tributary the appropriate study area might only be those HUCs covering the headwater streams (see also HUC in glossary)).

- **Outlet Point (or Site):** A point on a stream where data are collected or samples are taken. Its location is described by a set of coordinates.

- Projection: A projection is a method of drawing the curved surface of the Earth on a flat surface, such as a map. Since the Earth is a sphere when transferring it to a flat surface the image will be distorted to an extent. The appropriate projection to use will depend on the amount and type (area or angular) of distortion best suited to the project.

- Watershed: The area above (or uphill) of a specific point on a stream that contributes all water that falls within that area to that specific point. Synonymous with the term with “catchment”.