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Arc Hydro: A Framework for Integrating GIS and Hydrology

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Arc Hydro is a state-of-the-art geospatial relational database management system (RDBMS) technology for integrating hydrography and hydrology with GIS. Arc Hydro is a geospatial and temporal data model for water resources designed to operate within ArcGIS. A data model is distinct from a simulation model in that a data model provides a standardized framework for storing information, but contains no routines to simulate hydrologic processes. The data model is typically coupled with one or more simulation models with data and information being transferred from Arc Hydro to a model and results being returned to Arc Hydro. Arc Hydro, therefore, provides a means for linking simulation models through a common data storage system. *Arc Hydro Tools* is a set of ArcGIS tools that exercises the Arc Hydro model. It populates various fields within an Arc Hydro geodatabase for a river basin starting from a digital elevation model (DEM). This chapter describes the Arc Hydro data model and Arc Hydro tools for ArcGIS. A case study is presented demonstrating the application of Arc Hydro tools for modeling a watershed located in Pennsylvania. The lessons learned are discussed. Typical problems and challenges in using the Arc Hydro are identified and solutions and workarounds are presented.

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11.1 Definitions

11.1.1 Geodatabase

A geodatabase is a geographic database that stores both geographic and attribute data in the same RDBMS file. It is a geographic information database that organizes GIS data into thematic layers and spatial representations. There are two types of geodatabases:

- Personal geodatabase: For single user without versioning (only one user can edit a database at a given time)
- Multiuser geodatabase: For several users with versioning (several users can edit the same database simultaneously).

11.1.2 Data Model

A conceptual model is a set of concepts that describe a subject and allow reasoning about it. A mathematical model is a conceptual model expressed by equations. A data model is a conceptual model expressed in a data structure. A geographic data model is a data model for geographic data that works in a GIS. It is commonly referred to as the *Data Model*. For Environmental System research Institute's (ESRI) ArcGIS software users, a data model can be defined as a geographic data model for storing geospatial data in ArcGIS.

A data model is a collection of objects, feature classes and attributes defined for a certain type of system (e.g., water, wastewater, stormwater). It is a generic template for geodatabase design called *schema*. The generic model can be tailored to meet project specific requirements.

The goal of a data model is to simplify the process of implementing projects, and to promote and support standards. A data model is not a simulation model since it does not contain routines to simulate hydrologic or hydraulic processes.

ESRI has built many industry-specific data models for ArcGIS, such as:

- Arc Hydro data model
- Watersheds, streams, and water bodies
- Water Utilities (formerly ArcFM) data model
- Water, wastewater, and stormwater systems
- Groundwater data model
- Parcels data model

- Pipelines data model
- Biodiversity data model

11.1.3 Digital Elevation Model (DEM)

A DEM is a numerical representation of terrain elevation. It stores the terrain data for coordinates and corresponding elevation values. DEM data files contain information for the digital representation of elevation values in a raster form. DEM data are generally stored using one of the following three data structures:

- Grid structures
- Triangular Irregular Network (TIN) structures
- Contour-based structures

Regardless of the underlying data structure, most DEMs can be defined in terms of (x,y,z) data values, where (x,y) represents the location coordinates and z represents the elevation values. Grid DEMs consist of a sampled array of elevations for a number of ground positions at regularly spaced intervals. This data structures creates a square grid matrix with the elevation of each grid square, called a pixel, stored in a matrix format. Figure 11.1 shows a 3D plot of grid type DEM data from United States Geological Survey (USGS) for Lewisburg, Pennsylvania 7.5-minute quadrangle . DEM selection for a particular application is generally driven by data availability, judgment, experience, and test applications (ASCE, 1999). Maidment (1998) suggests DEM resolutions for various applications. Seybert (1996) concluded that modeled watershed runoff peak flow values are more sensitive to changes in spatial resolution than modeled runoff volumes. An overall subbasin area to grid cell area ratio of 10^2 was found to produce reasonable model results.

Before starting a DEM analysis, users must define the minimum number of upstream cells contributing flow into a cell to classify that cell as the origin of a stream. This number, referred to as the cell *threshold*, defines the minimum upstream drainage area necessary to start and maintain a stream. For example, if a stream definition value of ten cells is specified, then for a single grid location of the DEM to be in a stream, it must drain at least ten cells. It is assumed that there is flow in a stream if its upstream area exceeds the critical threshold value. In this case, the cell is considered to be a part of the stream. The threshold value can be estimated from existing topographic maps or hydrographic layers of the real stream network. Selection of an appropriate cell threshold size requires some user judgment. Users may start the analysis with an assumed or estimated value and adjust the initial value by comparing the delineation results with the existing topographic maps or hydrographic layers. The cell threshold value directly effects the number of subwatersheds (subbasins or subareas). Smaller threshold values result in a smaller subwatershed size, larger number of subwatersheds, and slower computation speed for the DEM analysis.

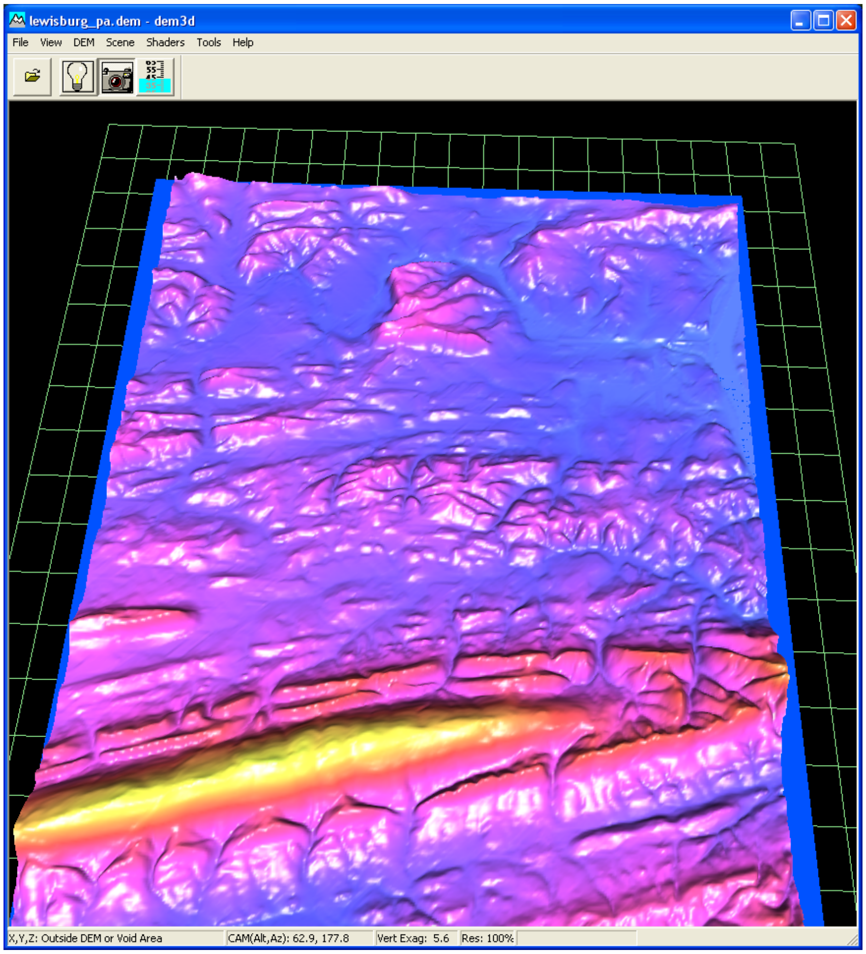

Figure 11.1 3D plot of Digital Elevation Model (DEM) data.

11.2 Arc Hydro Data Model

Arc Hydro is a geographic data model for storing geospatial and temporal water resources data in ArcGIS. Hydro includes both hydrography and hydrology. Arc Hydro consists of a set of hydro objects, such as HydroEdge for representing storm sewers and HydroJunction for representing storm sewer inlets. Arc Hydro provides a set of standardized attributes and a toolset for implementing the data model. Figure 11.2 shows the Arc Hydro data model.

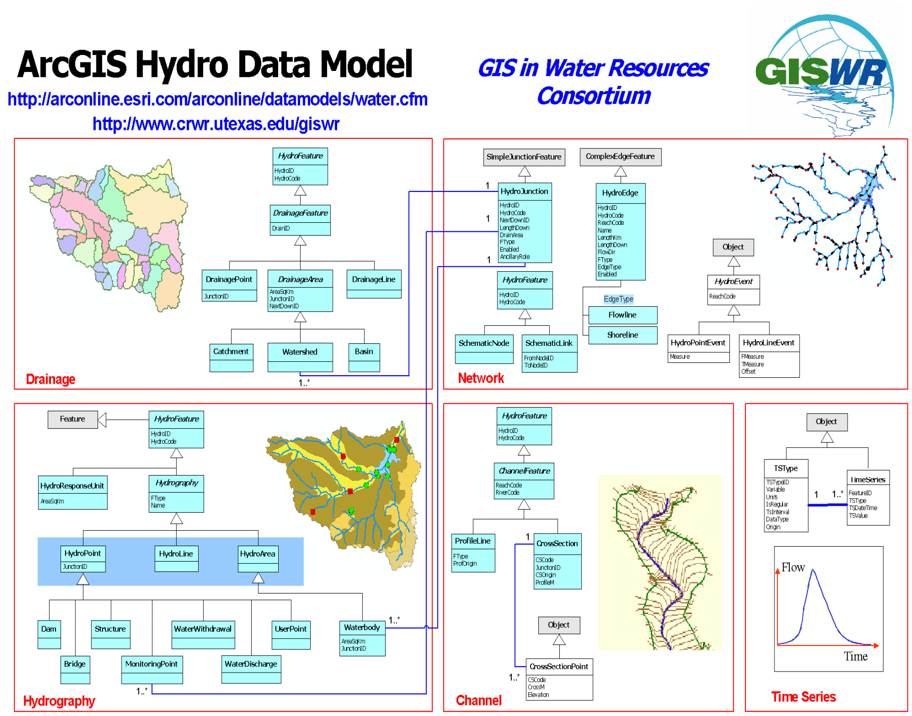

Figure 11.2 Arc Hydro data model.

Arc Hydro was developed by the GIS Water Resources Consortium, a team of researchers lead by Prof. David R. Maidment at the Center for Research in Water Resources, University of Texas at Austin and ESRI. The Arc Hydro design took three years of development from 1999 – 2002. Detailed Arc Hydro information is available in the book Arc Hydro GIS for

Water Resources by Maidment (2002). The Arc Hydro data model and tools are in the public domain. Free download is available from www.crwr.utexas.edu/giswr/hydro/.

11.2.1 Arc Hydro Tools

Arc Hydro Tools is a set of ArcGIS tools that exercises the Arc Hydro model. It populates various fields within an Arc Hydro geodatabase for a river basin starting from a Digital Elevation Model (DEM). These tools are installed as an Arc Hydro toolbar (Figure 11.3) which includes the following menus:

- Terrain Preprocessing
- Terrain Morphology
- Watershed Processing
- Attribute Tools
- Network Tools
- ApUtilities
- Buttons

Figure 11.3 Arc Hydro Toolbar for ArcGIS

The functions of these menus are described below.

Terrain Preprocessing: This menu provides functions dealing with DEM processing. They are mostly used once in order to prepare spatial information for later use.

Terrain Morphology: This menu provides functions dealing with non-dendritic terrain's preparation for further processing.

Watershed Processing: This menu provides functions dealing with watershed and subwatershed delineation, and basin characteristic determination. They operate on top of the spatial data prepared in the terrain preprocessing stage.

Attribute Tools: This menu provides functions allowing to generate key attributes (fields) in the Arc Hydro data model. Some of the tools require the existence of a geometric network.

Network Tools: This menu provides functions allowing to generate or manipulate properties of geometric (hydro) network.

ApUtilities: This menu provides functions allowing to manage Arc Hydro project properties. In general, they will be seldom used.

Buttons and Tools

- Flow Path Tracing
- Point Delineation
- Batch Point Generation
- Assign Related Identifier
- Global Point Delineation
- Trace By NextDownID Attribute

The tools have two key purposes. The first purpose is to manipulate (assign) key attributes in the Arc Hydro data model. These attributes form the basis for further analyses. They include the key identifiers (such as HydroID, DrainID, NextDownID, etc.) and the measure attributes (such as LengthDown). The second purpose is to provide some core functionality often used in water resources applications. This includes DEM-based watershed delineation, network generation, and attribute-based tracing.

Some of the Arc Hydro toolbar functions require the Spatial Analyst extension. Arc Hydro does not provide specific tools for DEM editing and modification. Standard Spatial Analyst functionality can be used for such purposes.

11.2.2 Terrain Preprocessing Functions

The functions of the Terrain Preprocessing menu of the Arc Hydro toolbar are the most important and useful menu of the toolbar.

The purpose of terrain preprocessing is to perform an initial analysis of the terrain and to prepare the dataset for further processing. A DEM of the study area is required as input for terrain preprocessing. The DEM must be in ESRI GRID format.

During the preprocessing, potential problems with the terrain representation can be identified, thus preventing the DEM errors from propagating to the later stages of the analysis. A successful preprocessing is an indication that the underlying DEM does not contain major problems that will prevent further analyses.

The initial basin delineation that is performed during the preprocessing has no meaning for later basin processing (except for performance during the extraction stage), since all parameters can be changed. In general, the recommended size for stream threshold definition (which in turn defines the sub-basin delineation during preprocessing) is 1% of the overall area. For increased performance on large DEMs (over 20,000,000 cells), the size of the threshold may be increased to reduce the stream network and the number of catchment polygons.

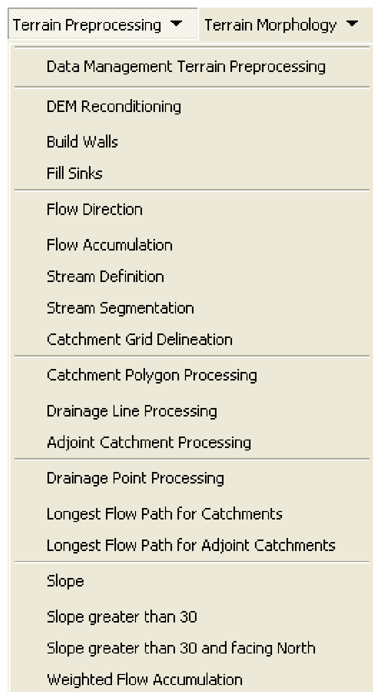

Figure 11.4 Arc Hydro toolbar terrain preprocessing functions.

As shown in Figure 11.4, Terrain Preprocessing contains the following functions:

- Data Management: Sets the tags for the themes used in the Terrain Preprocessing menu.
- DEM Reconditioning: Enforces a linear drainage pattern (vector) onto a DEM grid. Also called AGREE, this function is analogous to *stream burning* of the DEM grid.
- Build Walls: Builds walls onto the DEM (grid) at the boundary of selected polygons.
- Fill Sinks: Fills sinks for an entire DEM (grid).
- Flow Direction: Creates flow direction grid from a DEM grid.
- Flow Accumulation: Creates a flow accumulation grid from a flow direction grid.
- Stream Definition: Creates a new grid (stream grid) with cells from a flow accumulation grid that exceed the user-defined threshold.
- Stream Segmentation: Creates a stream link grid from the stream grid (every link between two stream junction gets a unique identifier).
- Catchment Grid Delineation: Creates a catchment grid for segments in the stream link grid. It identifies areas draining into each stream link.
- Catchment Polygon Processing: Creates catchment polygons based on the catchment grid.
- Drainage Line Processing: Creates streamlines based on the stream link grid.
- Adjoint Catchment Processing: Creates an adjoint catchment polygon for each catchment in the catchment polygon feature class. An adjoint catchment is represented by the total upstream area (if any) draining into a single catchment.
- Drainage Point Processing: Creates a drainage point at the most downstream point in the catchment (center of a grid cell with the largest value in the flow accumulation grid for that catchment).
- Longest Flow Path for Catchments: Creates longest flow paths for catchments that will be used as preprocessed inputs to speed up the generation of longest flow path for subwatersheds.

- Longest Flow Path for Adjoint Catchments: Creates longest flow paths for adjoint catchments that will be used as preprocessed inputs to speed up the generation of longest flow path for watersheds.
- Slope: Creates a slope grid in percent.
- Slope greater than 30: Creates a grid of the slopes that are greater than or equal to 30%.
- Slope greater than 30 and facing North: Creates a grid of the slopes that are greater than or equal to 30% and are facing North.
- Weighted Flow Accumulation: Creates weighted flow accumulation grid from a flow direction grid and a weight grid.

11.3 Case Study

Although DEM delineation techniques have advanced in recent years, the literature lacks a comparison of manual versus DEM techniques. The objective of this case study was to test the efficacy of DEM-based automatic delineation of watershed subwatersheds and streams. It was assumed that the manual delineations are more accurate than the DEM delineations. Thus, a comparison of manual and DEM delineations was made to test the accuracy of DEM delineations.

The case study watershed is the Bull Run watershed located in Union County in north-central Pennsylvania (Shamsi, 1996; Shamsi, 2005). This watershed was selected because of its small size so that the report size GIS maps can be clearly printed. However, Arc Hydro has been successfully applied to larger watersheds (Maidment, 2002). Bull Run watershed has a 21.8 km^2 (8.4 mi^2) drainage area and is tributary to the West Branch Susquehanna River at the eastern boundary of Lewisburg Borough. The 7.5 min. USGS topographic map of the watershed is shown in Figure 11.5. The predominant land use in the watershed is open space and agricultural. Only 20% of the watershed has residential, commercial, and industrial land uses. The results of the Bull Run watershed DEM analysis using ArcView 3.2 Hydro Extension have been previously published (Shamsi, 2001).

Manual watershed subdivision was the first step of the case study. Manual delineation is done by outlining the watershed boundary on a topographic map, identifying the major drainage paths (streams, rivers, etc.), subdividing the drainage paths into smaller segments, and finally subdividing the watershed into smaller subwatersheds. The 7.5- min. USGS topographic map of the study area was used for manual subwatershed delineation which resulted in 28 subwatersheds shown in Figure 11.5. This figure also shows the manually delineated stream reaches (dashed lines).

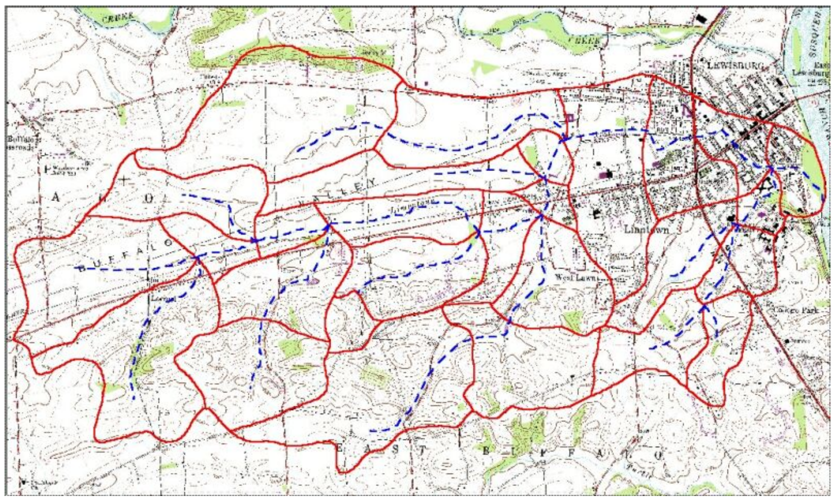

Figure 11.5 Case study watershed showing manual subwatersheds and streams.

Next, Arc Hydro toolbar was used to delineate subwatersheds and streams using the USGS DEM data at two resolutions:

(1) 30 m (1 arc second) and

(2) 10 m (1/3rd arc second).

Many cell threshold values (50, 100, 150, …, 1000) were used repeatedly to determine an appropriate threshold value at which DEM delineations will match the manual delineations. It was found that the 250 and smaller thresholds created too many subwatersheds and streams. The 500 threshold provided the best match between the manual and DEM delineations.

Figure 11.6 shows a comparison of manually delineated (thick line) and DEM-based (thin line) watershed boundary for 30 m DEM data and a cell threshold of 500 cells (0.45 km^2). The two boundaries match well except near the watershed outlet where DEM-based boundary seems to have missed a small part of the watershed. The difference in the two boundaries is due to user subjectivity and human interpretation of the manual method.

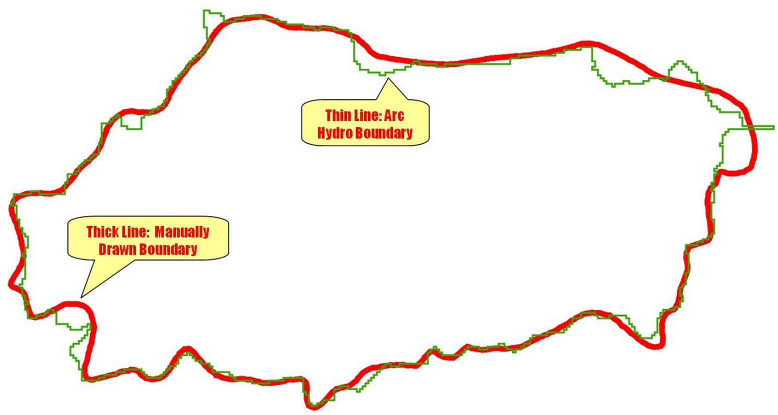

Figure 11.6 Comparison of DEM-based and manually drawn watershed boundary.

Figure 11.7 shows DEM-based streams for 30 m DEM data and a cell threshold of 500 cells without DEM reconditioning from the Terrain Preprocessing menu. The upper right boundary of the watershed shows that one of the DEM streams crosses the watershed boundary. This problem is generally caused by erroneous DEM data and is referred to as the *boundary cross-over* problem.

Figure 11.8 shows DEM-based streams for 30 m DEM data and a cell threshold of 500 cells after DEM reconditioning from the Terrain Preprocessing menu. The boundary cross-over problem shown in Figure 11.7 has disappeared, which clearly demonstrates the usefulness of DEM reconditioning. This figure also shows manually delineated streams as dashed lines. Visual comparison of DEM-based streams (solid lines) and manually delineated (dashed lines) indicates that both layers match reasonably well. Thus, it can be concluded that DEM-based method of stream delineation works well with a cell threshold value of 500 for 30 m resolution USGS DEMs.

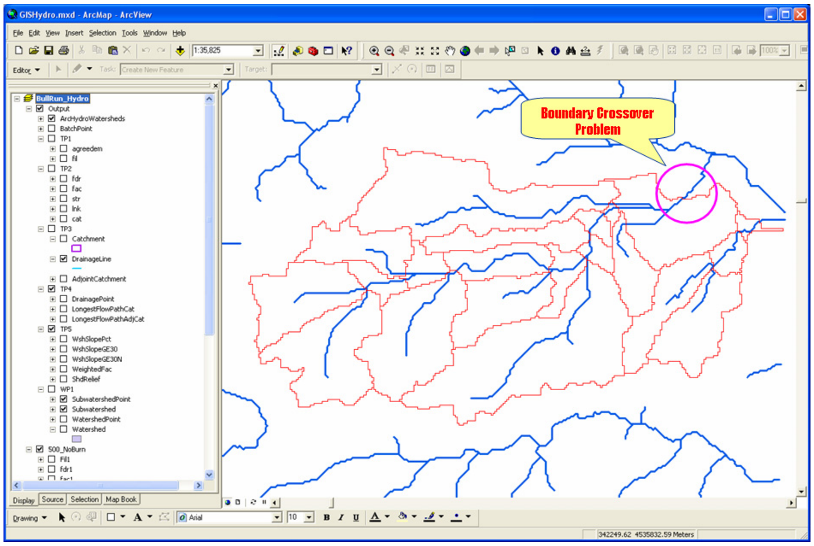

Figure 11.7 DEM-based streams without DEM reconditioning at cell threshold 500.

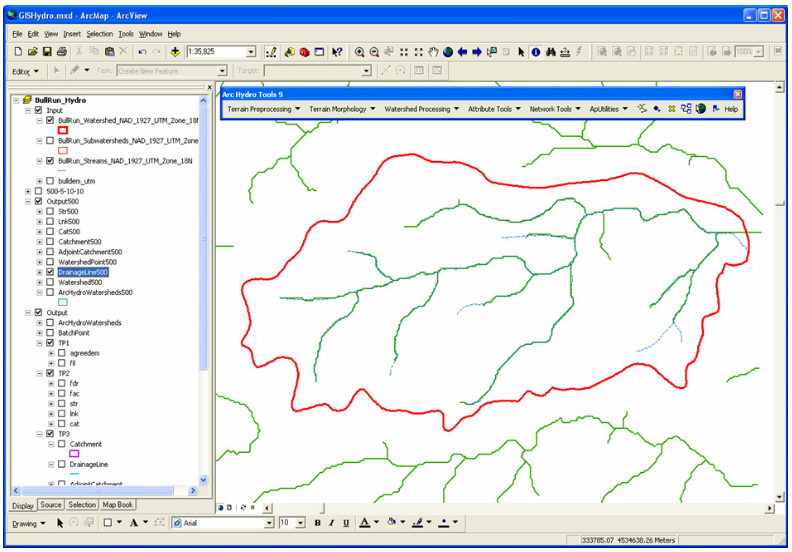

Figure 11.8 DEM-based streams after DEM reconditioning at cell threshold 500.

Figure 11.9 shows a comparison of manually delineated (unfilled polygons) and DEM-based (filled polygons) subwatersheds for 30 m DEM data and a cell threshold of 500 cells. The two layers do not match well. The DEM-based layer does not have as many subwatersheds as the manually delineated layer, especially in the southern part of the watershed.

Figure 11.10 shows a comparison of manually delineated (unfilled polygons) and DEM-based (filled polygons) subwatersheds for 10 m DEM data and a cell threshold of 500 cells. The two subwatershed layers match reasonably well. There are more DEM-based subwatersheds in the southern part of the watershed. This result indicates that higher resolution DEM data provides better subwatershed boundaries.

Finally, Figure 11.11 shows the functionality of the Point Delineation button of the Arc Hydro toolbar. This button allows interactive delineation of a watershed upstream of a user specified point. The hatched area on the map represents the interactively delineated watershed upstream of the user specified point.

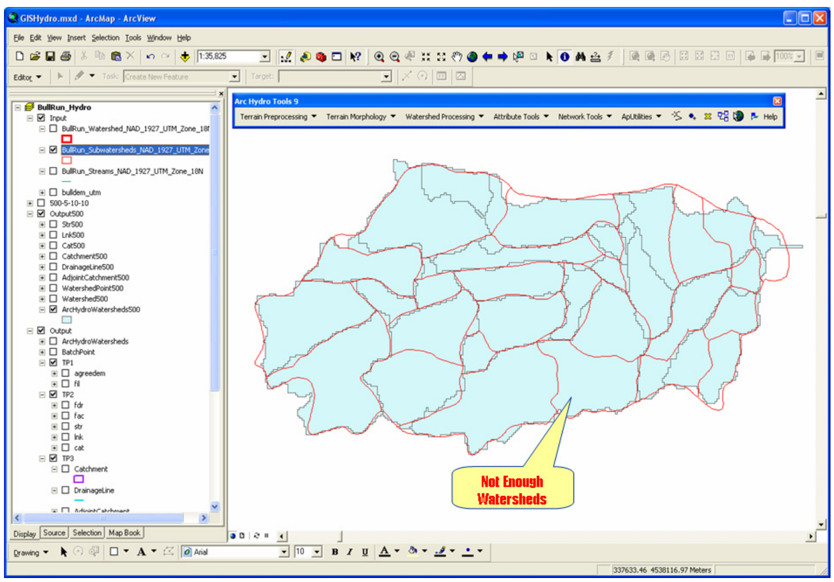

Figure 11.9 Comparison of manually-delineated and DEM-based subwatersheds using 30 m DEM data.

11.4 Conclusions and Recommendations

Arc Hydro is not a hydrologic modeling software but it is an excellent free tool to "facilitate" hydrologic modeling of watersheds. It is a unique GIS program that maintains topology (connectivity) of hydrologic features. The program does not have a user's manual and has a steep learning curve. It is an ideal learning and application development tool for water resources engineering graduate students. Abundant Arc Hydro literature is available but most of it is available online using the Internet. Version 9 of the program tested at this time has a few bugs that cause the program to crash periodically. Several versions are available for free downloads from different Web sites which makes it very difficult for the users to know if they are downloading the latest release.

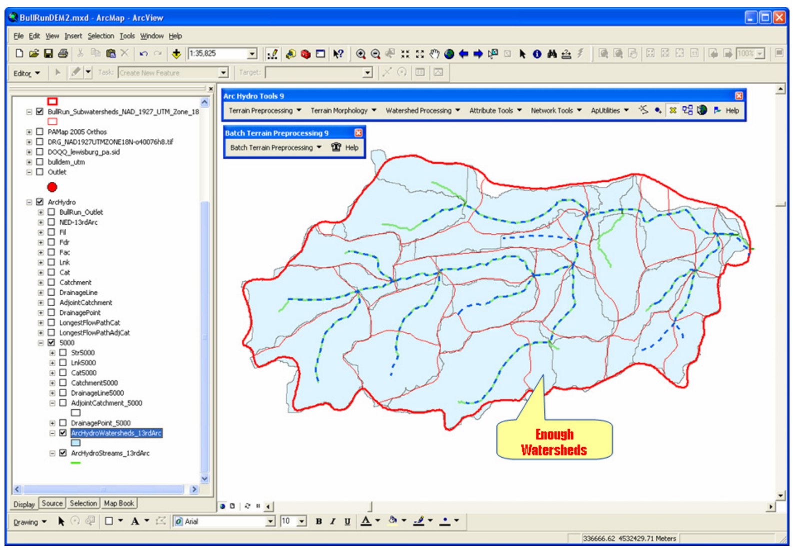

Figure 11.10 Comparison of manually-delineated and DEM-based subwatersheds using 10 m DEM data.

The stream network generated using Arc Hydro toolbar from the 30 m USGS DEMs at cell threshold value of 500 was satisfactory for a small rural watershed with mild slopes provided that the raw DEM data is reconditioned before any further analysis. Without DEM reconditioning, watershed boundary cross-over problems were observed.

Using Arc Hydro toolbar, the 30 m USGS DEMs did not generate an adequate number of subwatersheds at a cell threshold value of 500 cells for rural watersheds with mild slopes. The 10 m USGS DEMs generated an adequate number of subwatersheds.

Compared to the manual subwatershed and stream network delineation approach, the Arc Hydro toolbar offers significant time savings.

GIS provides an integrated platform for using DEMs. DEM data can be used for automatic watershed and stream delineation and computation of watershed hydrologic parameters. DEMs are not intended to replace elevation data obtained from surveys, high accuracy GPS, or even well-calibrated altimeters. Rather, DEMs should be used as a labor-saving process to relieve the user of the tedium and human error involved in the conventional manual interpolation method from paper maps. Massachusetts Water Resources Authority (MWRA) recently determined that DEMs were not too helpful in delineating sewershed boundaries (Herrlin, 2000).

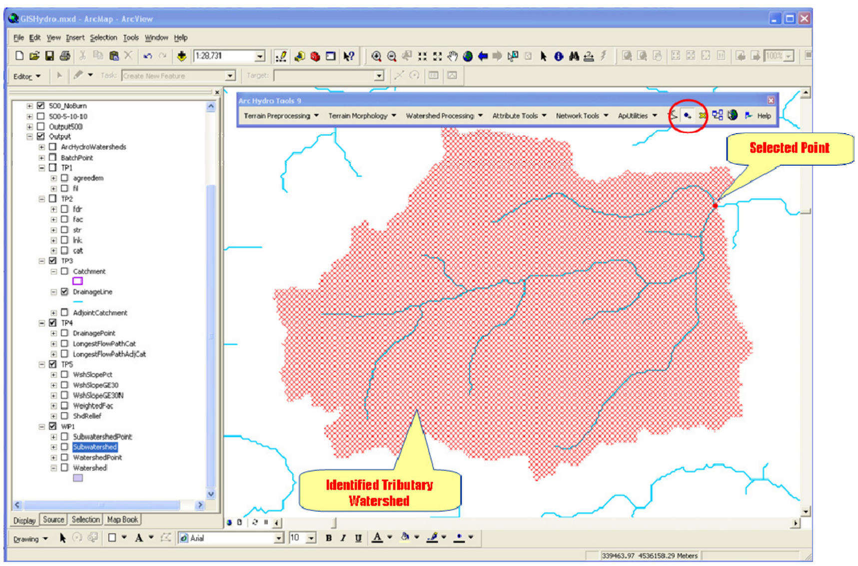

Figure 11.11 Interactive watershed delineation using the point delineation button of the Arc Hydro toolbar.

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