

DEM Applications in Hydrologic Modeling

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This chapter shows how digital elevation models (DEM) can be used to develop hydrologic models using off-the-shelf GIS software. A review of DEM analysis software is presented. The chapter shows how to automatically delineate watershed subbasins and streams using DEMs. A case study is presented to compare the DEM results with the conventional manual delineation approach. It is found that for rural and moderately hilly watersheds, 30 m resolution DEMs are appropriate for automatic delineation of watershed subbasins and streams. For 30 m DEMs a cell threshold of 500 is appropriate.

12.1 Introduction

Cell-based raster data sets, or grids, are especially suited to representing traditional geographic phenomena that vary continuously over space such as elevation, slope, precipitation, etc. Grids are also ideal for spatial modeling and analysis of data trends represented as continuous surfaces, such as in hydrologic modeling. DEM are data files containing information for the digital representations of elevation information in a raster form. DEMs are generally stored using one of the following three data structures:

- grid structures,
- triangular irregular network (TIN) structures, or
- 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. The focus of this chapter is on grid

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DEMs. Grid DEMs consist of a sampled array of elevations for a number of ground positions at regularly spaced intervals. This data structure creates a square grid matrix with the elevation of each grid square, called a pixel, stored in a matrix node (ASCE, 1999).

The size of a DEM file depends on the DEM resolution, i.e., the finer the DEM resolution, the smaller the grid, and the larger the DEM file. For example, if the grid size is reduced by one-third, the file size will increase nine times. Plotting and analysis of high resolution DEM files is slower because of their large file sizes.

DEMs can be used as source data for digital orthophotos and as layers in geographic information systems (GIS). DEMs can also serve as tools for many activities including volumetric analysis, site location of towers, or for drainage basin delineation. The DEM files may be used in the generation of graphics such as isometric projections displaying slope, direction of slope (aspect), and terrain profiles between designated points. They may also be combined with other data types such as stream location data and weather data to assist in forest fire control or they may be combined with remote sensing data to aid in the classification of vegetation. DEM applications include (USGS, 2000):

- modeling terrain gravity data for use in locating energy resources,
- determining the volume of proposed reservoirs,
- calculating the amount of material removed during strip mining,
- determining landslide probability, and
- developing parameters for hydrologic models.

This chapter focuses on the hydrologic modeling applications of DEMs.

12.2 DEMs

12.2.1 USGS DEMs

In the United States, the U.S. Geological Survey (USGS) provides DEM data for the entire country as part of the National Mapping Program. The USGS DEMs are available in 7.5-minute, 15-minute, 2-arc-second (also known as 30-minute), and 1-degree units. The 7.5- and 15-minute DEMs are included in the large scale category while 2-arc-second DEMs fall within the intermediate scale category and 1-degree DEMs fall within the small scale category. This chapter is based on the applications of 7.5 minute USGS DEMs. The DEM data for 7.5-minute units correspond to the USGS 1:24,000 scale topographic quadrangle map series for all of the United States and its territories. Each 7.5-minute DEM is based on 30-meter by 30-meter data spacing with the universal transverse mercator (UTM) projection. Each 7.5-minute by 7.5-minute block provides the

same coverage as the standard USGS 7.5-minute map series. Table 12.1 summarizes the USGS DEM data types.

Table 12.1 USGS DEM data formats.

DEM Type	Scale	Block Size	Grid Spacing
Large	1:24,000	7.5' x 7.5'	30 m
Intermediate	Between large and small	30' x 30'	2 seconds
Small	1:250,000	1° x 1°	3 seconds

12.2.2 DEM Accuracy

The accuracy of a DEM is dependent upon its source and the spatial resolution (grid spacing). The vertical accuracy of 7.5-minute DEMs is equal to or better than 15 meters. A minimum of 28 test points per DEM is required (20 interior points and 8 edge points). The accuracy of the 7.5-minute DEM data, together with the data spacing, adequately support computer applications that analyze hypsographic features to a level of detail similar to manual interpretations of information as printed at map scales not larger than 1:24,000 scale.

12.2.3 DEM Formats

USGS DEMs are available in two formats:

1. DEM File format: This older file format stores DEM data as ASCII text and have an extension of dem (e.g. lewisburg_PA.dem).
2. Spatial Data Transfer Standard (SDTS): This is the latest DEM file format. SDTS is a robust way of transferring geo-referenced spatial data between dissimilar computer systems and has the potential for transfer with no information loss. It is a transfer standard that embraces the philosophy of self-contained transfers, i.e. spatial data, attribute, georeferencing, data quality report, data dictionary, and other supporting metadata all are included in the transfer. SDTS DEM data are available as tar.gz compressed files. Each compressed file contains 18 *.ddf files and two readme text files.

Some DEM analysis software may not read the new SDTS data. For such programs, the user should translate the SDTS data to a DEM file format. SDTS translator utilities, like SDTS2DEM or MicroDEM, are available from the USGS SDTS web site (<http://software.geocomm.com/translators/sdts.html>) to convert the SDTS data to other file formats.

12.2.4 DEM Availability

USGS DEMs can be downloaded gratis from the USGS Global Land Information System web site (<http://edc.usgs.gov/webglis>). DEM data on CD-ROM can also be purchased for an entire county or state for a small fee to cover the shipping and handling cost. DEM data for other parts of the world are also available. The 30 arc-second DEMs (approximately 1 km² square cells) for the entire world have been developed by the USGS Earth Resources Observation Systems (EROS) Data Center and can be downloaded from the above mentioned website. More information can be found on the World Wide Web at the USGS node of the National Geospatial Data Clearinghouse site (<http://nsdi.usgs.gov/nsdi/>).

12.3 Software Tools

Some sample DEM analysis software tools and utilities are listed below:

- ArcView Spatial Analyst, ArcView 3-D Analyst, and Hydro extensions (ESRI, Redlands, California; www.esri.com)
- IDRISI (Clark University, Worcester, Massachusetts, www.clarklabs.org)
- TOPAZ (US Department of Agriculture, Agricultural Research Service, El Reno, Oklahoma, grl.ars.usda.gov)
- MIKE 11 GIS (Danish Hydraulic Institute, Denmark, www.dhi.dk)
- The Soil and Water Assessment Tool (SWAT) (US Department of Agriculture, Agricultural Research Service, Temple, Texas, www.brc.tamus.edu/swat/)
- Watershed Modeling System (WMS) (Engineering Computer Graphics Lab, Brigham Young University (BYU), Provo, Utah, www.ecgl.byu.edu/software/wms/)
- RiverTools (Research Systems, Boulder, Colorado, www.rsinc.com)
- MicroDEM (Developed by Professor Peter Guth of the Oceanography Department, U.S. Naval Academy, www.usna.edu/Users/oceano/pguth/website/microdem.htm)

Some programs such as Spatial Analyst, Mike 11 GIS, and WMS provide both the DEM analysis and hydrologic modeling capabilities. ASCE (1999) has compiled an excellent review of the above and other hydrologic modeling systems that use DEMs. Major DEM software programs are discussed in the following pages.

12.3.1 Spatial Analyst and Hydro Extension

Spatial Analyst is an optional extension (add-on program) for ESRI's ArcView GIS software, which must be purchased separately. The Spatial Analyst extension adds raster GIS capability to the vector based ArcView GIS. The Spatial Analyst enables desktop GIS users to create, query, and analyze cell-based raster maps; derive new information from existing data; query information across multiple data layers; and fully integrate cell-based raster data with traditional vector data sources.

Spatial Analyst is supplied with a hydro (or hydrology) extension which further extends the Spatial Analyst user interface for creating input data for hydrologic models. This extension provides functionality to create watersheds and stream networks from a DEM, calculate physical and geometric properties of the watersheds, and aggregate these properties into a single attribute table that can be attached to a grid or shapefile.

Before starting any DEM analysis, the user 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, also referred to as the cell "threshold", defines the minimum upstream drainage area necessary to start and maintain a stream. The smaller the threshold, the smaller the subbasin size, the larger the number of subbasins, and hence the slower the computations. This is an important part of the DEM analysis where user judgement is required.

Depending upon the user needs, there are two approaches to use the hydro extension:

1. *Hydro Pulldown Menu Options*: To create watershed subbasins or the stream network, work directly with the Hydro pulldown menu options. Table 12.2 provides a brief description of each of these menu options. The following steps should be performed to create watersheds using the Hydro pulldown menu options. The output grid from each step serves as the input grid for the next step.

- Import the raw USGS DEM
- Fill the sinks using the "Fill Sinks" menu option (input = raw USGS DEM). This is a very important intermediate step. Though some sinks are valid, most are data errors and should be filled.
- Compute flow directions using the "Flow Direction" menu option (input = filled DEM grid).
- Compute flow accumulation using the "Flow Accumulation" menu option (input = flow directions grid).
- Delineate streams using the "Stream Network" menu option (input = flow accumulation grid).
- Delineate watersheds using the "Watershed" menu option.

Table 12.2 Hydro Extension Menu Options.

Hydro Menu Option	Function
Hydrologic Modeling	Creates watersheds and calculates their attributes
Flow Direction	Computes the direction of flow for each cell in a DEM
Identify Sinks	Creates a grid showing the location of sinks or areas of internal drainage in a DEM
Fill Sinks	Fills the sinks in a DEM, creating a new DEM
Flow Accumulation	Calculates the accumulated flow, or number of up-slope cells, based on a flow direction grid
Watershed	Creates watersheds based upon a user specified flow accumulation threshold
Area	Calculates the area of each watershed in a watershed grid
Perimeter	Calculates the perimeter of each watershed in a watershed grid
Length	Calculates the straight-line distance from the pour point to the furthest perimeter point for each watershed
Flow Length	Calculates the length of flow path for each cell to the pour point for each watershed
Flow Length by Watershed	Calculates the maximum distance along the flow path within each watershed
Shape Factor by Watershed	Calculates a shape factor for each watershed. Shape factor is calculated as watershed length squared, divided by watershed area
Stream Network As Line Shape	Creates a vector stream network from a flow accumulation grid based on a user specified threshold
Centroid as Point Shape	Creates a point shape file of watershed centroids
Pour Points as Point Shape	Creates a point shape file of watershed pour points
Mean Elevation	Calculates the mean elevation within each watershed
Mean Slope	Calculates the mean slope within each watershed
Mean Precipitation	Calculates the mean precipitation in each watershed
Mean Curve Number	Calculates the mean curve number for each watershed

2. *Hydrologic Modeling Dialogue*: To create subbasins and calculate many additional attributes for them, use the hydrologic modeling dialogue, which is the first choice under the Hydro pulldown menu. The hydrologic modeling dialog is designed to be a quick one-step method for calculating and then aggregating a set of watershed attributes into a single file. This file can then be

used directly in a hydrologic model such as BYU's WMS, or it can be reformatted for input into HEC's HMS model, or others. The following steps should be performed to create watersheds using the hydrologic modeling dialogue:

- Choose Delineate from DEM and select an elevation surface.
- Fill the sinks when prompted.
- Specify the cell threshold value when prompted. This will create watersheds based on the number of cells, or up-slope area defined by the user as being the smallest watershed the user wants.

Detailed DEM analysis instructions are provided at the following web sites:

1. ESRI web site at <http://www.esri.com/arcuser/> (click on the "Terrain Modeling with ArcView GIS")
2. University of Texas at Austin (Center for Research in Water Resources) web site at <http://www.crwr.utexas.edu/gis/> (click on GIS Hydro button)

The last four hydro options (Table 12.2) work with existing data layers. They do not create elevation, slope, precipitation, and runoff curve number coverages. They simply compute mean areal values of these four parameters for the subbasins using the existing GIS coverages of these parameters. Thus, the GIS coverages of elevation, slope, precipitation, and runoff curve number must be available for the mean functions of the hydro extension to work.

Hydro also has a raindrop or pourpoint feature which helps the user to trace the flow path from a specified point to the watershed outlet. Hydro also calculates a flow length as the maximum distance along the flow path within each watershed. The subbasin area can be divided by flow length to estimate the overland flow width for input to a rainfall-runoff model like EPA's Storm Water Management Model (SWMM).

12.3.2 IDRISI

IDRISI is not an acronym; it is named after a cartographer born in 1099 AD in Morocco, N. Africa. IDRISI was developed by the Graduate School of Geography at Clark University. IDRISI covers the full spectrum of GIS and Remote Sensing needs from database query, to spatial modeling, to image enhancement and classification. Special facilities are included for environmental monitoring and natural resource management, including change and time series analysis, multi-criteria and multi-objective decision support, uncertainty analysis (including Bayesian and Fuzzy Set analysis) and simulation modeling (including force modeling and anisotropic friction analysis). TIN interpolation, Kriging and conditional simulation are also offered.

IDRISI is basically a raster GIS. IDRISI includes tools for manipulating DEM data to extract streams and watershed boundaries. IDRISI GIS data has an open format and can be manipulated by external computer programs written by users. This capability makes IDRISI a suitable tool to develop hydrologic applications. For example, Quimpo and Al-Medeij (1998) wrote FORTRAN programs to model surface runoff using IDRISI. Their approach consisted of delineating watershed subbasins from DEM data and estimating subbasin SCS runoff curve numbers from soils and land use data.

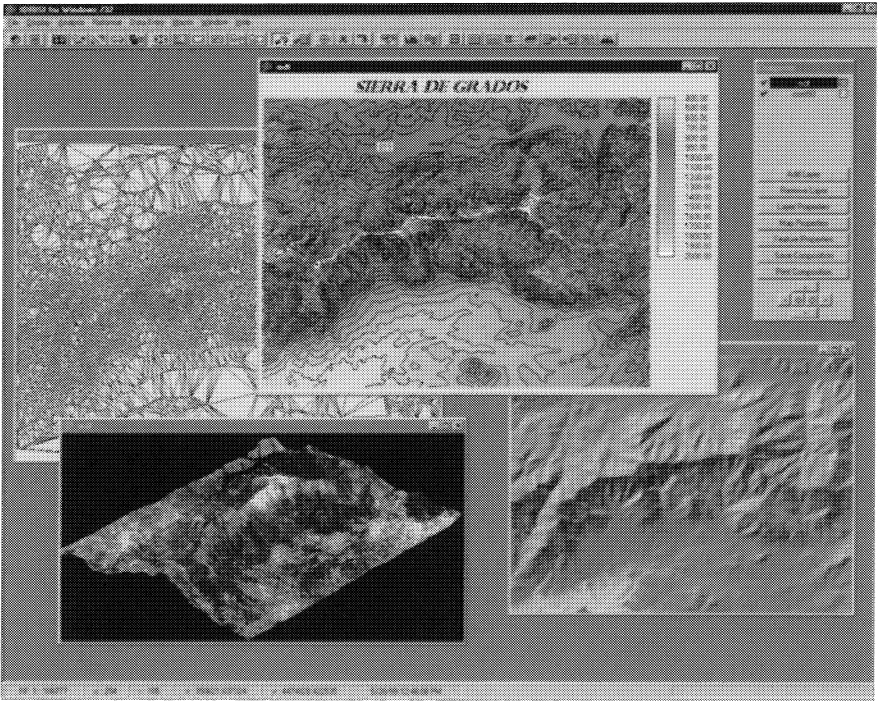


Figure 12.1 IDRISI's DEM analysis features.

Figure 12.1 shows IDRISI's DEM analysis capabilities. The upper left window shows a Triangulated Irregular Network (TIN) model created from digital contour data. The upper right window shows a DEM created from the TIN with original contours overlaid. The lower right window shows an illuminated DEM emphasizing relief. The lower left window shows a false color composite image (TM bands 234) draped over the DEM (IDRISI, 2000).

12.3.3 TOPAZ

TOPAZ is a software system for automated analysis of landscape topography from DEMs. The primary objective of TOPAZ is the rapid and systematic identification and quantification of topographic features in support of investigations related to land-surface processes, hydrologic and hydraulic modeling, assessment of land resources, and management of watersheds and ecosystems. Typical examples of topographic features that are evaluated by TOPAZ include terrain slope and aspect, drainage patterns and divides, channel network, watershed segmentation, subcatchment identification, geometric and topologic properties of channel links, drainage distances, representative subcatchment properties, and channel network analysis (Garbrecht and Martz, 2000).

12.4 Case Study

Although DEM delineation techniques have been 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 subbasins 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). This watershed was selected because of its small size so that the report size GIS maps can be clearly printed. However, the proposed technique has also been successfully applied to large watersheds. Bull Run watershed's 21.8 km² (8.4 mi²) drainage area is tributary to the West Branch Susquehanna River at the eastern boundary of Lewisburg Borough. The 7.5 minute USGS topographic map of the watershed is shown in Figure 12.2. The predominant land use in the watershed is open space and agricultural. Only 20% of the watershed has residential, commercial, and industrial land uses.

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 (sewers, swales, etc.) called reaches, and finally subdividing the watershed into smaller drainage areas called subbasins. All subbasins must enclose one or more reaches. Each reach must correspond

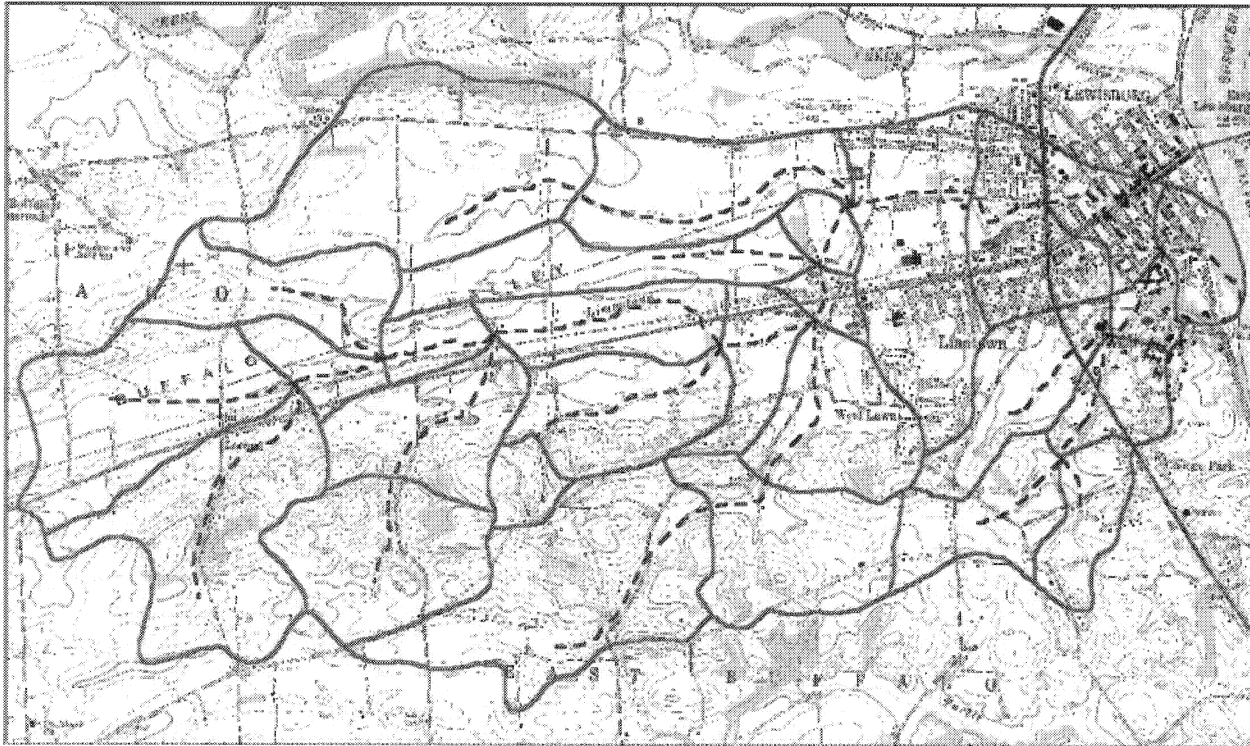


Figure 12.2 The case study watershed showing manual subbasins and streams.

to one and only one subbasin. There are two ways of manual watershed subdivision: (i) multi reach subdivision in which a subbasin may contain several reaches, and (ii) single reach subdivision in which only one reach per subbasin is allowed. The first approach creates large subbasins for which computation of overland flow width and slope is difficult. The single reach subdivision creates the smallest natural subbasins from the available topographic maps. Single reach subbasins are consistent with many modeling packages such as HEC-1, and provide an intuitive nomenclature scheme (same ID for a reach and its tributary subbasin). Note that the distinction between lumped and distributed models becomes unclear when the subbasins are made very small (DeVantier and Feldman 1993). By creating small subbasins, the difference between the lumped and distributed models can be minimized and the inherent inaccuracies of grossly lumped models can be reduced. Due to its many advantages, the single reach subdivision scheme was used in this study. The 7.5-minute USGS topographic map of the study area was used for manual subbasin delineation which resulted in 28 subbasins shown in Figure 12.2. This figure also shows the manually delineated stream reaches (dashed lines).

Next, ArcView Spatial Analyst and hydro extension were used to delineate subbasins and streams using the 7.5-minute USGS DEM data. Many cell threshold values (50, 100, 150, ..., 1000) were used repeatedly to determine which DEM delineations agreed with manual delineations. It was found that the 250 and smaller thresholds created too many subbasins and streams. The 500 threshold provided the best agreement between the manual and DEM delineations. Figures 12.3 and 12.4 show the manually delineated and DEM-based subbasins and streams for a cell threshold of 500.

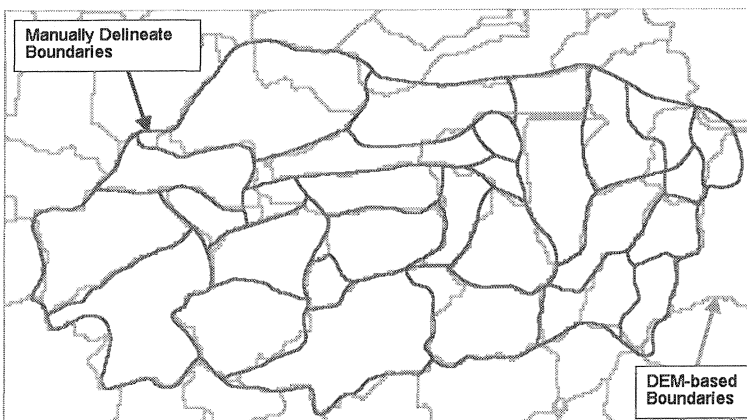


Figure 12.3 Manual versus DEM subbasins for cell threshold of 500.

In Figure 12.4, the upper right boundary of the watershed shows that one of the DEM streams crosses the watershed boundary. This problem is referred to as the boundary “cross-over” problem and must be corrected by manual editing of DEM subbasins.

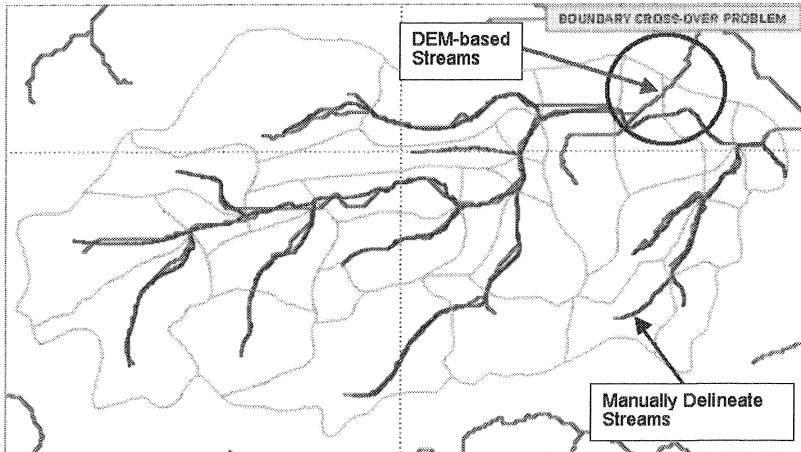


Figure 12.4 Manual versus DEM streams for cell threshold of 500.

12.5 Conclusions

The 30m USGS DEMs generate good watershed subbasin boundaries at a minimum cell threshold value of 500 cells for rural watersheds with mild slopes. Stream networks generated from the 30m USGS DEMs at cell threshold of 500 were satisfactory with minor watershed boundary cross-over problems. Boundary cross-over problems must be corrected manually. Thus, some manual intervention is required and warranted to assure the efficacy of DEM-based automatic watershed delineation approach. Compared to the manual watershed delineation approach, the DEM approach offers significant time savings, eliminates user subjectivity, and produces consistent results.

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