A GIS-based Approach to Watershed Analysis in Texas

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December 6, 2010
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Abstract

This project explores the use of ArcGIS, its Spatial Analyst extension, and the HEC-GeoHMS extension for watershed delineation and analysis. The study area for the project includes the Guadalupe River Basin in South Central Texas. All subbasins and stream segments in this general vicinity were first delineated using the Arc Hydro Tools toolbar, with those belonging to the Guadalupe River Basin then being extracted using the HEC-GeoHMS Main View toolbar. The desired hydrologic parameters for the subbasins and rivers were calculated through a series of analysis procedures using the HEC-GeoHMS Project View toolbar. These parameters include the area, average slope, percentage impervious, initial abstraction, curve number, 2-yr return period rainfall, time of concentration, and lag time for each of the delineated subbasins and the length, upstream elevation, downstream elevation, and average slope for each of the delineated stream segments. These parameters can then be exported into HEC-HMS for further hydrologic analysis as desired. ArcGIS and HEC-GeoHMS are clearly very useful tools for water resources engineers and the knowledge of their workings is an invaluable asset.

1.0 Introduction

The purpose of this project was to become familiar with the many functions of HEC-GeoHMS as they are used in union with ArcGIS to delineate and analyze watersheds. HEC-GeoHMS is a Geospatial Hydrologic Modeling Extension developed by the US Army Corps of Engineers Hydrologic Engineering Center (USACE HEC) in cooperation with the Environmental Systems Research Institute (ESRI). It is used in conjunction with ArcGIS and its Spatial Analyst extension to delineate watersheds and develop stream and subbasin parameters for these watersheds that can be easily input into HEC-HMS for further hydrologic modeling. This specific project will focus on the Guadalupe River Basin in South Central Texas. Both ArcGIS and HEC-GeoHMS are powerful tools that are regularly used by water resources engineers in many aspects of their work.

2.0 Literature Review

The US Army Corps of Engineers Hydrologic Engineering Center distributes a User’s Manual along with the HEC-GeoHMS software that details the capabilities, features, and applications of the extension. This manual was followed in a step-by-step manner in the completion of this project. However, the use of GIS technologies in the field of water resources is rapidly expanding with research continuously producing additional, updated information. This version of HEC-GeoHMS is simply the latest in development in the field with more advancements sure to come. The predecessor to the current HEC-GeoHMS software was PrePro, a data-preprocessor developed at the University of Texas Center for Research in Water Resources (CRWR) by Dr. Francisco Olivera. There are large amounts of literature on this software and its uses as well including several tutorials, with some also using the Guadalupe River Basin as the study area. Additionally, the CRWR has a sample dataset for the Guadalupe River Basin in an Arc Hydro Geodatabase form. The linkage between ArcGIS and hydrologic modeling is an evolving, collaborative process with more developments to come.
3.0 Methodology

This project utilized ArcGIS Version 9.3 along with the Spatial Analyst Extension and HEC-GeoHMS Version 4.2. Before any work began, all data along with the data frame was converted into the same projection – the State Plane Texas South Central Projection. This projection was deemed suitable for the project study area; however any number of projections could have been used. The Spatial Analyst Extension and Toolbar were activated and added, along with the Arc Hydro Tools, HEC-GeoHMS Main View, and HEC-GeoHMS Project View Toolbars as seen in Figure 1 below. The subsequent analysis utilized these toolbars to perform the following tasks: Terrain Preprocessing, Project Setup, Basin Processing, Stream and Subbasin Characteristics, and Hydrologic Parameter Estimation.

3.1 Terrain Preprocessing

The first step that must be completed is Terrain Preprocessing, part of the Arc Hydro Tools, which uses a digital elevation model (DEM) to determine drainage patterns and delineate streams and subbasins. If a large area (such as the Guadalupe River Basin) is to be analyzed, several DEMs may be needed and must first be merged together using the Mosaic to New Raster tool in ArcGIS. The first function in the Terrain Preprocessing is to “Fill Sinks” in the raw DEM. This process raises any depressions in the terrain to match the elevation of the surrounding area so that the runoff can be more accurately modeled. The result of this step is a new Hydro DEM grid that looks nearly identical to the Raw DEM grid but with new elevation values for some of the cells.

The next function in the Terrain Preprocessing is “Flow Direction.” This determines the direction of maximum slope for each of the cells in the Hydro DEM grid. The result of this step is a new Flow Direction Grid. The “Flow Accumulation” function then uses this Flow Direction Grid to determine how and where rainfall will runoff by calculating how many upstream cells will drain to a given cell in the grid. The result is a Flow Accumulation Grid, where the cells with the highest values (most cells draining to them) are the streams and river segments. The “Stream Definition” function then creates a stream network that includes all cells from the Flow Accumulation Grid that have a value greater than a user-defined threshold. For this project, I used a threshold of 200,000 cells which is the equivalent of an approximately 170 square kilometer (65 square mile) drainage area (~1% of the total area of the Guadalupe River Basin). The result of this step is a new Stream Grid. Next, the “Stream Segmentation” function uses the Stream Grid and the Flow Direction Grid to divide the stream network into individual segments for
further analysis, resulting in a new Stream Link Grid. Finally, the “Drainage Line Processing” function converts the Stream Link Grid into a vector stream coverage.

The next step in the Terrain Preprocessing is the “Catchment Grid Delineation.” This uses the Flow Direction Grid and the Stream Link Grid to delineate a drainage area (subbasin) for each of the stream segments in the network, resulting in a Catchment Grid. This Catchment Grid is then converted to a vector polygon data file using the “Catchment Polygon Processing” function. Lastly, the stream and catchment vector files are used by the “Adjoint Catchment Processing” function to aggregate the upstream subbasins at each stream confluence to improve computational performance in later procedures.

The final result of this Terrain Preprocessing is six grids (Hydro DEM, Flow Direction, Flow Accumulation, Stream, Stream Link, and Catchment) and two vector data files (Catchment and Drainage Line) that will be used in the following steps.

3.2 HMS Project Setup

The next step in the overall process is the HMS Project Setup, part of the HEC-GeoHMS Main View toolbar, which defines the project area (in my case the Guadalupe River Basin). While the Terrain Preprocessing was performed for the entire DEM, the rest of the work will only be completed for this specific project area. The first step in the Project Setup is the “Start New Project” function in which the user specifies the Project Name, Extraction Method, and Project Data Location. The “Add Project Point” tool is then used to specify the outlet location for the desired study area, resulting in a project area of all land draining to this Project Point. After this is complete, the “Generate Project” function is applied and a new data frame is created with the appropriate data being automatically imported. All further data analysis will be performed in this data frame.

3.3 Basin Processing

The remainder of the analysis process uses functions from the HEC-GeoHMS Project View Toolbar, with the first of these analysis procedures being the Basin Processing. This step can be used to adjust the layout of the watershed and subbasins to be analyzed. The first function that can be performed is “Basin Merge.” This function will merge several smaller subbasins together into one larger subbasin. The opposite can also be done with the “Subbasin Subdivision” tool by specifying a point on a stream segment for which a new subbasin is desired, or the subbasin can be divided into several smaller subbasins using the “Split Basin at Confluences” function. Another option is to further divide a subbasin based on the location of specified points (such as stream gauges) using the “Import Batch Points” and “Delineate Batch Points” functions. This same process can be repeated for the stream segments. Several river segments can be joined using the “River Merge” function and a profile of a stream segment can be created using the “River Profile” tool. To divide a stream reach into smaller segments, the Split Tool of the ArcGIS Editor Toolbar can be used, which has the ability to split a line at a specified point, distance, or percentage of its length.
3.4 Stream and Subbasin Characteristics

The next step in the analysis process is to determine the hydrologic characteristics of the modified subbasins and stream segments from the previous step. The first two functions under this category are “River Length” and “River Slope.” These populate the River attribute table with the length, upstream elevation, downstream elevation, and slope of each stream segment feature. The average slope can also be calculated for each subbasin using the “Basin Slope” function; however, before this can be done a slope grid must first be created using the “Slope” function under Terrain Preprocessing. The Subbasin attribute table will then be populated with the average subbasin slope based on this slope grid.

The next part of this process incorporates the “Longest Flow Path” function. This uses the DEM and Flow Direction grids created in the Terrain Preprocessing step to determine the longest flow path for each subbasin. This function results in the creation of a new vector polyline data file.

Subsequently, the centroid of each subbasin can be located using the “Basin Centroid” function. There are three different methods to determine the location of the centroid. The first is a Center of Gravity Method, which places the centroid at the center of gravity of each subbasin. The next is a Longest Flow Path Method, which places the centroid at the midpoint of the longest flow path of each subbasin. The final option is the 50% Area Method, which places the centroid at the point that has a contributing area equal to 50% of the area of the entire subbasin. Furthermore, the user can always move the centroid points using the ArcGIS Editor Toolbar if so desired. This function results in the creation of a new vector point data file. The elevation of the centroids can then be calculated and added to the attribute table using the “Centroid Elevation” function. Finally, the “Centroidal Flow Path” function can be used to trace the flow from the centroid to the outlet of the subbasin. This function projects the centroid onto the longest flow path at a 90 degree angle and then traces the longest flow path to the subbasin outlet. This function results in the creation of a new vector polyline data file.

Overall, this step populated the attribute tables for the River and Subbasin layers with their respective lengths and slopes and created three new vector data files (Longest Flow Path, Centroid, and Centroidal Flow Path) for further use.

3.5 Hydrologic Parameter Estimation

The final step in the analysis process is the Hydrologic Parameter Estimation, which uses the data created in previous steps to determine the hydrologic parameters of the subbasins that can then be exported into HEC-HMS for further hydrologic analysis. The first step in this process is to “Select HMS Processes” which specifies the methods to be used in HEC-HMS. The next steps are the “River Auto Name” and “Basin Auto Name” which populate the respective attribute tables with a field which contains a default name for each feature. The river names start with “R” followed by a number which increases
moving downstream, and the subbasin names follow the same pattern but start with “W.” The names can be changed using the ArcGIS Editor Toolbar if desired.

The next function that will be used is “Subbasin Parameters from Raster.” However, before this step can be completed a Curve Number, Percentage Impervious, Initial Abstraction and 2-Year Rainfall Grid must each be developed. A Percentage Impervious Grid can be obtained directly from USGS data. A Curve Number Grid must be calculated based on land use and soil type data using the “Generate CN Grid” function under the Utility menu on the HEC-GeoHMS Project View Toolbar. However, the land use and soil type grids must first be combined using the Union function in ArcGIS and a Lookup Table must be created to specify the curve numbers for each land use type and corresponding hydrologic soil groups. A Curve Number Grid will then be created by assigning a curve number to each polygon in the new land use-soil type layer based on the lookup table. An Initial Abstraction Grid can be developed based on the Curve Number grid using the Raster Calculator in ArcGIS and the following NRCS formulas:

\[ I_\alpha = 0.2S \]
\[ S = \frac{1000}{CN} - 10 \]

A Rainfall Grid for a 2-year Return Period, 24-hour Duration Rainfall can be calculated using the appropriate coefficients (b, d, and e) for each county from the TXDOT Hydraulic Design Manual and the following formulas:

\[ i = \frac{b}{(t + d)^c} \]
\[ P = i \times t \]

Once the precipitation is calculated for each county and put in a tabular format, the resulting table can be joined to the Texas Counties attribute table. This joined layer can then be converted into a grid based on the precipitation values using the Polygon to Raster function in ArcGIS.

Once these four grids are created, the “Subbasin Parameters from Raster” function can be used to populate the PctImp, InitAbst, BasinCN, and Rain2Yr fields of the Subbasin attribute table.

The next procedure is to calculate the time of concentration and lag time for each subbasin using the NRCS TR-55 Method. This procedure is completed in three steps. The first step uses the function “TR55 Flow Path Segment” to divide the longest flow path for each subbasin into three segments by placing two points on the longest flow path. The first point is located 100 feet from the subbasin divide by default and represents the point at which flow changes from overland flow to concentrated flow. The second point is placed at the point where the longest flow path first intersects the stream segment, which represents the point at which concentrated flow changes to channelized flow. The second
step uses the function “TR55 Flow Segment Parameters” to calculate the length and slope of each of the three segments created in the previous step and populate the Longest Flow Path attribute table. The final step uses the “Export TR55 Data” function to export the data into a predefined Excel Spreadsheet that calculates the time of concentration for each of the three segments and adds them together to get the total time of concentration for each subbasin. The users can modify the data in the Excel Spreadsheet to better reflect field conditions for the three segments, such as their Manning’s Roughness Coefficient and Cross Sectional Flow Area values. After any desired changes are made, the data is exported back into ArcGIS and will populate the LagMethod, Tc, and BasinLag fields of the Subbasin Attribute Table. The Basin Lag is simply calculated using the formula:

\[ t_L = \frac{3}{5} t_C \]

However, the Basin Lag Time can also be calculated using the “CN Lag Method” function. This directly calculates the lag time based on the subbasin hydraulic length (L), curve number (CN), and average slope (Y) according to the formulas:

\[ t_L = \frac{L^{0.8} (S + 1)^{0.7}}{1900Y^{0.5}} \]
\[ S = \frac{1000}{CN} - 10 \]

If this method is used the BasinLag and LagMethod fields of the Subbasin attribute table will be repopulated, but the Tc field will remain unchanged.

The overall result of this step is the population of the Name, PctImp, InitAbst, BasinCN, Rain2Yr, Tc, LagMethod, and BasinLag fields of the Subbasin Attribute Table. These hydrologic parameters, along with the previously calculated BasinSlope and Area, can then be exported into HEC-HMS for further hydrologic analysis.
4.0 Application, Results, and Discussion

The watershed chosen for analysis was that of the Guadalupe River in South Central Texas. The Guadalupe River Basin is a very large and diverse watershed covering over 5,800 square miles and portions of 21 counties and ranging in elevation from over 700 feet in the Texas Hill Country north and west of San Antonio to mean sea level where it empties into San Antonio Bay near the town of Seadrift. Mean annual precipitation in this area ranges from around 22 to 34 inches. The watershed covers mainly rural areas with the exception of some areas near the cities of San Antonio and Victoria. Figure 2 below displays this study area overlaid on a Google Earth image.

Figure 2: Project Study Area

The data collected for this project area included digital elevation models (DEMs) from the USGS National Elevation Dataset (NED), land cover and impervious surfaces from the USGS 2001 National Land Cover Dataset (NLCD), hydrologic data from the USGS National Hydrography Dataset (NHD), gauging station locations from the USGS National Water Information Service (NWIS), soil data from the NRCS SSURGO database, HUCs from the Texas Water Development Board (TWDB), and 2-yr 24-hr precipitation coefficients from the TXDOT Hydraulic Design Manual.
This data was utilized as described in the Methodology section above to delineate the Guadalupe River Watershed and calculate the hydrologic parameters of its subbasins and stream network. The first step in the analysis was the Terrain Preprocessing, which resulted in Figure 3 below, delineating the subbasins and stream segments for the entire DEM.

**Figure 3: Result of Terrain Preprocessing**

The second step in the analysis was the HMS Project Setup, which extracted the Guadalupe River Basin project area from the overall area shown above. This area was then compared to HUC data from the TWDB and found to be nearly identical, resulting in the acceptance of delineated project area with no need for any modifications. The result is shown in Figure 4 on the following page.
Basin Processing was then performed to adjust the layout of the above watershed and subbasins to be analyzed, with the result being shown in Figure 5 below.

The next step in the analysis process was to determine the hydrologic characteristics of the newly modified subbasins and stream segments shown above using the Stream and Subbasin Characteristics functions. The results of the Longest Flow Path and Centroid functions are shown on the map in Figure 6 on the next page. Also included in Figure 6 is the Rivers attribute table which was populated with the length, upstream elevation, downstream elevation, and slope of each stream segment feature. The Subbasin attribute table was also populated with the average slope of each subbasin feature which can be seen in the overall result in Figure 7.
Figure 6: Results of Stream and Subbasin Characteristics
The final step in the analysis process was the Hydrologic Parameter Estimation, which populated the Name, PctImp, InitAbst, BasinCN, Rain2Yr, Tc, LagMethod, and BasinLag fields of the Subbasin Attribute Table as shown in Figure 7 below. This is the final result of the Guadalupe River Watershed analysis. Also shown in Figure 7 is a map with the corresponding subbasin names to help identify trends in the hydrologic parameters based on subbasin location. The basin slope increases and the rainfall decreases as you move upstream, which is to be expected since the upstream subbasins cover part of the Hill Country, which is very undulating and has a drier climate, and the land near the coast has a wetter climate and is much flatter. The subbasins with the highest values for percentage impervious and curve number are those near the cities of San Antonio and Victoria while the lower values are in the Hill Country above San Antonio. Also, the time of concentration and lag time are greater for the larger, oblong subbasins as to be expected. Overall these results seem quite reasonable; therefore these hydrologic parameters can now be exported into HEC-HMS to perform further hydrologic analyses as desired.

Figure 7: Results of Hydrologic Parameter Estimation
5.0 Conclusions

I believe that this project has been successful in my gaining knowledge of the ArcGIS and HEC-GeoHMS computer programs and their various functions relating to water resources objectives, specifically watershed delineation and analysis. I have learned how and where to obtain the required data and how to prepare the data to be analyzed. I also learned how to utilize the data to delineate watersheds, as well as the various techniques and methods available to adjust the layout of the watersheds and calculate the desired watershed parameters. Furthermore, not only have I learned the steps to follow in the analysis but I have also developed an understanding of how the functions work so that I can better understand the software processes and their results. Both ArcGIS and HEC-GeoHMS are powerful tools that are regularly used by water resources engineers and having the knowledge of how they work and how to utilize them will be a great benefit for me in the future.