Watershed and Stream Network Delineation GIS in Water Resources, Fall 2011

Prepared by David Tarboton, Utah State University

Purpose

The purpose of this exercise is to illustrate watershed and stream network delineation based on digital elevation models using the Hydrology tools in the ArcGIS Geoprocessing toolbox. In this exercise, you will perform drainage analysis on a terrain model for the San Marcos Basin. The Hydrology tools are used to derive several data sets that collectively describe the drainage patterns of the basin. Geoprocessing analysis is performed to recondition the digital elevation model and generate data on flow direction, flow accumulation, streams, stream segments, and watersheds. These data are then be used to develop a vector representation of catchments and drainage lines from selected points that can then be used in network analysis. This exercise shows how detailed information on the connectivity of the landscape and watersheds can be developed starting from raw digital elevation data, and that this enriched information can be used to compute watershed attributes commonly used in hydrologic and water resources analyses.

Learning objectives

- Identify and properly execute the geoprocessing tools involved in DEM reconditioning.
- Describe and quantitatively interpret the results from DEM reconditioning as a special case of quantitative raster analysis.
- Construct profiles using 3D Analyst.
- Create and edit feature classes.
- Identify and properly execute the sequence of Hydrology tools required to delineate streams, catchments and watersheds from a DEM.
- Evaluate and interpret drainage area, stream length and stream order properties from Terrain Analysis results.
- Develop a Geometric Network representation of the stream network from the products of terrain analysis.
- Use Network Analysis to select connected catchments and determine their properties

Computer and Data Requirements

To carry out this exercise, you need to have a computer which runs ArcGIS 10 and includes the Spatial Analyst and 3D Analyst extensions. The data are provided in the accompanying zip file, Ex4.zip available at http://www.neng.usu.edu/dtarb/giswr/2011/Ex4.zip. The data files used in the exercise consist of a DEM grid for the San Marcos Basin in Texas from the National Elevation Dataset and stream and watershed data from the National Hydrography Dataset NHDPlus. If you want to do similar work in a

different location you will need to download this data from these data sources. URL's for these and other data sources were provided in Lecture 4.

Data description:

Ex4.zip should be unzipped and saved in a folder where you will do your work. In this exercise the folder C:\Users\dtarb\Scratch\Ex4 has been used. The unzipped contents of Ex4.zip are illustrated below:

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C:\Users\dtarb\Scratch\Ex4	Search Ex4		٩
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🕌 INFO	9/26/2011 6:29 PM	File folder	
\mu SanMarcos.gdb	9/26/2011 6:34 PM	File folder	
<			•
			F

The geodatabase SanMarcos.gdb contains the following data:



Raster analyses such as watershed and stream network delineation are best performed in a consistent projected spatial reference system (or projection). This is because calculation of slope, length and area are involved and these are best done in linear (not geographic) units consistent with the elevation units. In this exercise to expedite matters for you the data has all been projected into the **NAD 1983 Texas Centric Mapping System Albers.prj** spatial reference.

In the SanMarcos geodatabase the BasemapAlbers feature dataset contains the four necessary feature classes. Watershed is the set of HUC 12 watersheds within the San Marcos 8 digit HUC 12100203 extracted from the watershed boundary dataset in Exercise 2. Basin is the San Marcos 8 digit HUC 12100203 boundary obtained by dissolving the HUC 12 watersheds. Flowline is a subset of NHDPlus flowlines that cover the San Marcos Basin and surrounding area. USGSGage is a set of USGS stream gages within the San Marcos Basin, similar to what was developed in exercise 2.

There is also a raster smdem that contains the digital elevation model for this region obtained from the National Elevation dataset. This DEM is equivalent to the DEM you worked with in Exercise 3, except that it has a smaller cell size (30 m) appropriate for this analysis and has been projected to the NAD 1983 Texas Centric Mapping System Albers spatial reference being used in this exercise.

The exercise is divided in to the following activities that each comprise a sequence of steps

- 1. DEM Reconditioning
- 2. Hydrologic Terrain Analysis
- 3. Network analysis

DEM Reconditioning

DEM reconditioning is a process of adjusting the DEM so that elevations direct drainage towards the vector information on stream position, that in this case is the blue line stream features obtained from NHDPlus. DEM reconditioning is only suggested when the vector stream information is more reliable than the raster DEM information. This may not be the case here, but reconditioning is done nevertheless to illustrate the process. DEM reconditioning as done here involves a sequence of ArcGIS geoprocessing functions. The strategy is to first convert vector stream features to a raster dataset of grid cells on the streams that has exactly the same dimensions (rows, columns, cell size) as the DEM raster. This exposes you to a number of new geoprocessing tools (Feature to Raster, Greater Than, Reclassify) as well as Environment Settings to control raster cell size, extent and snapping. Then the Euclidean distance from each grid cell to the nearest stream is calculated and a Map Algebra expression used to perform the reconditioning which involved lowering the elevation of all grid cells along the streams by 20 units and grid cells near the streams by a value that tapers from 10 to 0 units based on the distance from 0 out to 500 units. The results are then visualized using 3D Analyst. By doing this you get some experience using the ArcGIS geoprocessing tools to derive new spatial data from the original DEM and vector streams and a small glimpse into the powerful geospatial analytical capability that these functions enable.

1. Feature to Raster.

Open ArcMap. Click on the **to** icon to add data. In the dialog box, navigate to the location of the data; select both the BasemapAlbers feature dataset and **smdem** raster containing the DEM for the San Marcos and click on the "Add" button. The data provided will be added to the map display.

Click on the search icon on the standard toolbar to open the ArcGIS search window. Enter **feature to raster** and click on the search magnifying glass. This is a way to find tools if you do not know which toolbox they are in. You have to however know something about their name or a word used in describing their functionality.

Search 🗜
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ALL Mass Data Teols
Search returned 40 items.
Feature to Raster (Conversion) Converts features to a raster dataset. toolboxes\system toolboxes\conversion t
Polygon to Raster (Conversion) Converts polygon features to a raster d toolboxes\system toolboxes\conversion t

Click on the Feature to Raster tool. Select Flowline as the Input features. Use Field COMID (all we need here is some unique number). For output raster designate the name FlowlineRaster in the SanMarcos.gdb. Click on the Environments button.

√ Feature to Raster	CAP	
Input features	^	Feature to Raster
Flowline	- 🖻	
Field		Converts features to a raster dataset.
COMID	•	
Output raster		
C:\Users\dtarb\Scratch\Ex4\SanMarcos.gdb\FlowlineRaster	6	
Output cell size (optional)	_	
1044.62691255806		
	Ŧ	
OK Cancel Environments	<< Hide Help	Tool Help

In Environment Settings expand Output Coordinates and select Same as Layer "smdem". Expand Processing Extent and select Extent same as "smdem" and Snap Raster as "smdem". Click OK

😤 Environment Settings		×
* Workspace		Environment Settings
Courbut Coordinates Output Coordinate System Same as Layer "smdem" NAD_1983_Texas_Centric_Mapping_System_Albers Geographic Transformations		Environment settings specified in this dialog box are values that will be applied to appropriate results from running tools. They can be set hierarchically, meaning that they can be set for the application you are working in, so they apply to all tools; for a model, so they apply to all processes within the model; or for a particular process within a model. Environments set for a process within a model will overrride all other setting, and environments set for all processes in a model will override those set in the application.
Geographic Transformations Names	II	Changing the default settings that will be used is a prerequisite to performing geoprocessing tasks. You may only be interested in analyzing a small piece of a geographic area, such as changing the extent for results, or you may want to write all results to a specific location (for example, changing the current workspace or the scratch workspace).
Processing Extent Extent Same as layer smdem Top 7343279.299336		
Left Right 1621751.870791 Bottom 7261439.299336 Snap Raster smdem		
 XY Resolution and Tolerance M Values Z Values 	Ŧ	~
OK Cancel << Hide Help		Tool Help

Notice that back on the Feature to Raster tool the output cell size now inherits the value 30 from the snap raster. Click OK on the Feature to Raster tool.

Feature to Raster	
Input features	Feature to Raster
Flowline 💌 🖻	
Field	Converts features to a raster dataset.
COMID	
Output raster	
C: \Users \dtarb \Scratch \Ex4 \SanMarcos.gdb \FlowlineRaster	
Output cell size (optional)	
30	
v	T
OK Cancel Environments	Tool Help

The result is a FlowlineRaster that represents the flowlines as a raster with value corresponding to their COMID. The particular field used was somewhat arbitrary as we really just need a value by which to identify stream grid cells.



2. Threshold using Greater Than to obtain stream raster.

To identify whether a grid cell is part of a stream or not, we use the greater than function to obtain a binary (0, 1) raster of stream cells. Locate the **Greater Than** tool (using the search window) and enter the following input, click OK.

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Input raster or constant value 1	Greater Than
FlowlineRaster 🗾 🖻	Deferre a Deletional constantion anostica an
Input raster or constant value 2	two inputs on a cell-by-cell basis
1 🗹 🔁	two inputs on a cen by cen basis.
Output raster	Returns 1 for cells where the first raster is
C: \Users\dtarb\Scratch\Ex4\SanMarcos.gdb\BinaryRaster	greater than the second raster and 0 for cells if
	it is not.
	-
OK Cancel Environments << Hide Help	Tool Help

The result is a raster with value 1 for stream cells and no data elsewhere.



To use in calculations below, we need 0's not no data off the streams, so let's reclassify this. Locate the **Reclassify** tool (using the search window) and enter the following input, click OK. (It does not matter

which of Reclassify (3D Analyst) or Reclassify (Spatial Analyst) tools you select. They are functionally the same, just associated with different extension licenses)

* Reclassify		
Input raster		Reclassify
BinaryRaster	- 🖻	
Reclass field		Reclassifies (or changes) the values in a raster.
Value	▼	
Reclassification		
Old values New values	Classifi	
	Classify	
	Unique 🗧	
	Add Entry	
-	Delete Entries	
Load Save Reverse New Values	Precision	
Output raster		
C:\Users\dtarb\Scratch\Ex4\SanMarcos.cdb\FlowlineReclas		
		v
OK Cancel Environmen	nts	Tool Help
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The result is a raster where NoData values have been replaced by 0's.

3. Distance to streams

Search on distance and open the Euclidean Distance tool. Set Flowline as the input feature and designate distance as the output raster in the SanMarcos.gdb.

🔨 Euclidean Distance		_ D X
Input raster or feature source data	*	Euclidean Distance
Flowline 💽 🖻		
Output distance raster		Calculates, for each cell, the Euclidean
C:\Users\dtarb\Scratch\Ex4\SanMarcos.gdb\distance		distance to the closest source.
Maximum distance (optional)		
Output cell size (optional)		
30		
Output direction raster (optional)		
	~	-
OK Cancel Environments << Hide He	lp	Tool Help

Click on Environments and as before set Output Coordinates same as smdem and Processing Extent same as smdem and Snap Raster to smdem.

🛠 Environment Settings				•/ = = • • • • • • •	٢
¥ Workspace			Â	Environment Settings	^
Output Coordinates Output Coordinate System Same as Laver "smdem"		- -		Environment settings specified in this dialog box are values that will be applied to	
NAD_1983_Texas_Centric_Mapping_S	ystem_Albers			can be set hierarchically, meaning tools. They they can be set for the application you are	
Geographic Transformations				working in, so they apply to all tools; for a model, so they apply to all processes within the model; or for a particular process	
Geographic Transformations Names			Ш	within a model. Environments set for a process within a model will overrride all other setting, and environments set for all processes in a model will override those set in the application.	
* Processing Extent	III	•		Changing the default settings that will be used is a prerequisite to performing geoprocessing tasks. You may only be interested in analyzing a small piece of a geographic area, such as changing the extent for results, or you may want to write	
Same as layer smdem		-	ч	all results to a specific location (for example, changing the current workspace	
Left 1621751.870791	Top 7343279.299336 Bottom 7261439.299336	Right 1751771.870791		or the scratch workspace).	
Snap Raster smdem		_			
 XY Resolution and Tolerance M Values 			-		-
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The result is a grid giving distances to the streams that looks a bit like the inside of an intestine (sorry!).



4. AGREE Reconditioning with Map Algebra.

The distance and FlowlineReclas grids contain the information required to do an AGREE like (see Lecture 9 slide 33 and <u>http://www.ce.utexas.edu/prof/maidment/GISHYDRO/ferdi/research/agree/agree.html</u>) reconditioning of the DEM to burn in the streams. Open the Raster Calculator on Map Algebra and construct the following expression

🐔 Raster Calculator	1			
Map Algebra expression			^	Map Algebra expression
Layers and varia distance FlowlineRedas BinaryRaster FlowlineRaster smdem	7 8 9 / == != & 4 5 6 * > >= 1 2 3 - < <= ^	Conditional		The Map Algebra expression you want to run. The expression is composed by specifying the inputs, values, operators, and tools to use. You can type in the expression directly or use the buttons and controls to help you create it.
Output raster C:\Users\dtarb\Scratch	\Ex4\SanMarcos.gdb\smrecon		Ŧ	 The Layers and variables list identifies the datasets available to use in the Map Algebra expression. The buttons are used to enter numerical values and operators
	OK Cancel Environ	ments << Hide Help		Tool Help

The output is saved in a raster named **smrecon** (San Marcos reconditioned) in the SanMarcos.gdb. The Map algebra expression is interpreted as follows



5. 3D Analyst

Let's use Raster calculator and 3D Analyst to see what this has produced.

Use raster Calculator to evaluate the following expression

* Raster Calculator	
Map Algebra expression	Map Algebra expression
Layers and varia \bigcirc smrecon \bigcirc distance \bigcirc FlowlineRedas \bigcirc FlowlineRaster \bigcirc FlowlineRaster \bigcirc smdem \bigcirc	The Map Algebra expression you want to run. The expression is composed by specifying the inputs, values, operators, and tools to use. You can type in the expression directly or use the buttons and controls to help you create it.
"smdem" - "smrecon" Output raster C: \Users \dtarb \Scratch \Ex4\SanMarcos.gdb \diff	 The Layers and variables list identifies the datasets available to use in the Map Algebra expression. The buttons are used to enter numerical values and operators into the conditional sectors.
OK Cancel Environments << Hide Help	Tool Help

The worm like result shows how the DEM has been altered to reduce values along the streams.



Select Customize → Extensions

Customize		Windows	Help		
Toolbars			•		
Extensions					
Add-In Manager					

Select the 3D analyst extension.

Extensions	? ×
Select the extensions you want to use. Image: Select the extensions you want to use. Image: ArcScan Image: ArcScan Image: Geostatistical Analyst Image: Maplex Image: Maplex	
Description:	
3D Analyst 10.0 Copyright ©1999-2010 ESRI Inc. All Rights Reserved	
Provides tools for surface modeling and 3D visualization.	
About Extensions	Close

Select **Customize → Toolbars → 3D Analyst** to display the 3D Analyst toolbar

	3D Analyst
Customize Windows Help	Advanced Editing
Toolbars 🕨	Animation
Extensions	ApUtilities
3D Analyst	· · · · · · · · · · · · · · · · · · ·
3D Analyst - Layer: 餐 smreco	n 🔽 🖓 🗞 🐝 🚣 🔁 🖴 🕂 🚳 🗐
Set the target layer in the tool	bar to smrecon and click on the interpolate line button I . Draw a line



Repeat the procedure with target layers "smdem" and "diff". It seems that you have to redraw the line each time, but with a bit of fiddling you can illustrate the effect of reconditioning on the DEM.



To turn in:

1. Screen captures that illustrate the effect of DEM Reconditioning. Show the location where you made a cross section as well as the DEM cross sections with and without reconditioning.

Open the attribute table of **FlowlineReclas** and find the number of grid cells that were mapped as stream cells. Given that the size of each grid cell is 30 m estimate the length of channels in the area defined by the smdem grid as this number of cells times 30 m. Actually this is an over estimate because FlowlineReclas approximates the Flowline feature class using a stair step approach. Nevertheless the result is a rough estimate useful for cross checking. Use the total number of grid cells in the FlowlineReclas raster dataset, and grid cell area to estimate the total area and take the ratio to estimate the drainage density (Length of Channels/Total Area).

To turn in:

2. Number of stream grid cells in FlowlineReclas and estimates of channel length and drainage density.

Open the Layer Properties of the diff raster and find the average amount of "earth" removed by the reconditioning process. Multiply this by the total area to get the total volume of "earth" removed. The cross section of "earth" removed was a swath 1000 m wide along the streams with triangular cross section (illustrated in a profile graph) going down to 10 m and a spike 30 m wide going down to 20 m. Calculate the area of this cross section and multiply it by the length of channels to get another estimate of the volume of "earth" removed by this reconditioning.



To turn in:

3. Volumes of earth removed estimated from (a) layer properties of diff and (b) from estimates of channel length and cross section area. Comment on the differences.

Hydrologic Terrain Analysis

This activity will guide you through the initial hydrologic terrain analysis steps of Fill Pits, calculate Flow Direction, and calculate Flow Accumulation (steps 1 to 3). The resulting flow accumulation raster then allows you to identify the contributing area at each grid cell in the domain, a very useful quantity fundamental to much hydrologic analysis. Next an outlet point will be used to define a watershed as all points upstream of the outlet (step 4). Focusing on this watershed streams will be defined using a flow

accumulation threshold within this watershed (step 5). Hydrology functions will be used to define separate links (stream segments) and the catchments that drain to them (steps 6 and 7). Next the streams will be converted into a vector representation (step 8) and more Hydrology toolbox functionality used to evaluate stream order (step 9) and the subwatersheds draining directly to each of the eight stream gauges in the example dataset (step 10). The result is quite a comprehensive set of information about the hydrology of this watershed, all derived from the DEM.

1. Fill

This function fills the sinks in a grid. If cells with higher elevation surround a cell, the water is trapped in that cell and cannot flow. The Fill function modifies the elevation value to eliminate these problems.

Select **Spatial Analyst Tools** \rightarrow **Hydrology** \rightarrow **Fill**. Set the input surface raster as smrecon and output surface raster as fel in SanMarcos.gdb.

🔨 Fill			x
Input surface raster	^	Fill	*
smrecon	- 🖻	-	
Output surface raster		Fills sinks in a surface raster to remove	
C:\Users\dtarb\Scratch\Ex4\SanMarcos.gdb\fil		smail imperiections in the data.	
Z limit (optional)			
1	$\overline{\nabla}$		Ŧ
OK Cancel Environments.	. << Hide Help	Tool Help	

Press **OK**. Upon successful completion of the process, the "fil" layer is added to the map. This process takes a few minutes.

In work to date we have specifically set the location of each output dataset. ArcGIS provides the capability to set the location where geoprocessing data is saved by default, and this saves a little bit of clicking in setting up the inputs. Let's do this. Click on **Geoprocessing** \rightarrow Environments on the main menu.



Then expand Workspace and set the Current and Scratch Workspace to the geodatabase where you are working.

🛠 Environment Settings		×
 Workspace Current Workspace C: \Users\dtarb \Scratch \Ex4\SanMarcos.gdb Scratch Workspace C: \Users\dtarb \Scratch \Ex4\SanMarcos.gdb Output Coordinates Processing Extent 		Environment Settings Environment settings specified in this dialog box are values that will be applied to appropriate results from running tools. They can be set hierarchically, meaning that
 XY Resolution and Tolerance M Values 	Ţ	they can be set for the application you are working in, so they apply to all tools: for a model, so they
↓ Z Values	OK Cancel << Hide Help	Tool Help

Click OK. Now the default outputs will be in this location.

2. Flow Direction

This function computes the flow direction for a given grid. The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell.

Select Spatial Analyst Tools → Hydrology → Flow Direction.

Set the inputs as follows, with output "fdr".

K Flow Direction				x
Input surface raster		^	Output flow direction raster	*
fil Output flow direction raster C:\Users\dtarb\Scratch\Ex4\SanMarcos.gdb\fdr			The output raster that shows the flow direction from each cell to its steepest downslope neighbor.	
Force all edge cells to flow outward (optional)				
Output drop raster (optional)	e	-		~
OK Can	Environments << Hide Help		Tool Help	

Press OK. Upon successful completion of the process, the flow direction grid "fdr" is added to the map.



To turn in:

4. Make a screen capture of the attribute table of fdr and give an interpretation for the values in the Value field using a sketch.

3. Flow Accumulation

This function computes the flow accumulation grid that contains the accumulated number of cells upstream of a cell, for each cell in the input grid.

Select Spatial Analyst Tools → Hydrology → Flow Accumulation.

Set the inputs as follows

The Accumulation	
Input flow direction raster Input flow direction raster Output accumulation raster C: \Users\dtarb\Scratch\Ex4\SanMarcos.gdb\fac Input weight raster (optional) Output data type (optional) FLOAT	Flow Accumulation Creates a raster of accumulated flow into each cell. A weight factor can optionally be applied.
OK Cancel Environments << Hide Help	Tool Help

Press OK. Upon successful completion of the process, the flow accumulation grid "fac" is added to the map. This process may take **several minutes** for a large grid, so take a break while it runs! Adjust the symbology of the Flow Accumulation layer "fac" to a classified scale with multiplicatively increasing breaks that you type in, to illustrate the increase of flow accumulation as one descends into the grid flow network.

Layer Properties		? ×
General Source Extent	Display Symbology	
Show: Unique Values Classified	Draw raster grouping values into cla	sses Import
Stretched Discrete Color	Fields <u>V</u> alue <value> ~ No</value>	ormali <u>z</u> ation ~
	Classification Manual	<u>C</u> lasses 8 ▼ Classif <u>y</u>
	Color Ramp	▼
	Symbol Range	Label
	0 - 100	0 - 100 100.0000001 - 300
	300 - 1,000	300.0000001 - 1,000
	1,000 - 3,000	1,000.000001 - 3,000
	10,000 - 30,000	10,000.00001 - 10,000 10,000.00001 - 30,000
	Show class breaks using cell values	Display <u>N</u> oData as
		OK Cancel Apply

After applying this layer symbology you may right click on the "fac" layer and Save As Layer File

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ß	Сору
X	Remove
	Open Attribute Table
	Joins and Relates
💻 🔁	Zoom To Layer
	Zoom To Make Visible
	Zoom To Raster Resolution
🖃 🗹 fdr	Visible Scale Range
	Data 🔸
_1	Edit Features
	Save As Layer File
	Create Layer Package
	Properties

The saved Layer File may be imported to retrieve the symbology definition and apply it to other data.

Add the SanMarcos **Basin** feature class. This shows the outline of the San Marcos basin. Change the symbology so that this is displayed as hollow and zoom in on the outlet in the South West corner. Use

the identify tool to determine the value of "fac" at the point where the main stream exits the area defined by the San Marcos Basin polygon. This location is indicated in the following figure.



The value obtained represents the drainage area in number of 30×30 m grid cells. Calculate the drainage area in km².

Also examine the edges of the San Marcos Basin as represented by the Basin feature class. Note the consistency between this basin boundary and streams as represented by flow accumulation. Notice also how, apart from cutting off a number of meanders, there is generally good agreement between the Flowline feature class and flow accumulation grid. This is a result of the DEM reconditioning that was performed.

To turn in:

5. Report the drainage area of the San Marcos basin in both number of 30 m grid cells and km² as estimated by flow accumulation.

Add the SanMarcos **Watershed** feature class. This shows the outline of the HUC 12 subwatersheds in the San Marcos basin. Change the symbology so that this is displayed as hollow and zoom in on the outlet in the South West corner. Use the identify tool to find the HU_12_NAME of the subwatershed right at the outlet of the San Marcos Basin.



Use the identify tool to determine the value of "fac" at the point where the main stream enters and exits the area defined by this most downstream subwatershed. Subtract the entering fac value from the exiting fac value to determine the area of this subwatershed. Compare your result to the area reported in the ACRES and Shape_Area attributes of this feature. The Shape_Area attribute was calculated automatically by ArcGIS when this feature class was created and is in the units consistent with the Linear Unit of this feature class, meters in this case, so area is m².

To turn in:

6. Report the name of the most downstream HUC 12 subwatershed in the San Marcos Basin. Report the area of the most downstream HUC 12 subwatershed determined from flow accumulation, from the ACRES attribute and from Shape_Area. Convert these area values to consistent units. Comment on any differences.

4. Isolating our Watershed

Rather than working with the whole grid, we now want to focus only on the area of the San Marcos Watershed upstream of where flow leaves the Basin feature class. Lets define an outlet point there to help us.

Open Catalog and right click on SanMarcos\BaseMapAlbers → New → Feature Class

SanMarcos			
	Þ	Сору	
🗉 🏢 diff	ß	Paste	L
🗉 🎆 distance	×	Delete	N
🗄 🇱 fac	~		
🗄 🇰 fdr		Rename	
🗉 🏢 fil	2	Refresh	
🗉 🇱 FlowlineRast		A 1	
🗉 🏼 FlowlineRecl		Analyze	
🗄 🇱 smdem		New 🕨	Feature Class
🗄 🎬 smrecon			

Set the Name as **Outlet** and Type as **Point Features**. Click Next.

	155
Nam <u>e</u> :	Outlet
Alias:	
Туре	
Type of	f features <u>s</u> tored in this feature class:
Point F	Features 🔹
Geometry P	roperfies
-Geometry Pr	roperties ates include <u>M</u> values. Used to store route data.
Geometry Pr	roperties ates include <u>M</u> values. Used to store route data. ates include <u>Z</u> values. Used to store 3D data.
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Geometry Pr	roperties ates include <u>M</u> values. Used to store route data. ates include <u>Z</u> values. Used to store 3D data.

Leave the coordinate system as default (inheriting from the Feature Dataset it is going in to) and click Next. Click Finish at the last screen without changing any of the fields.

Now let's use the Editor to create an outlet point in this feature class. Click on the Editor Toolbar button

on the standard toolbar to activate the Editor toolbar

Editor									- X
Editor 🕶 📄 🛌	$ h_A \geq$	Ľ	4.		÷	Х	\mathcal{D}	\land	

Click on **Editor** \rightarrow **Start Editing.** Zoom right in on the outlet at the bottom right where flow accumulation exits the area. Make sure that the outlet layer is turned on so that it appears in the Create Features list. Using the Create Features button on the Editor Toolbar with Outlet clicked carefully place a point at the desired outlet location



Click **Editor** → **Stop Editing**. Respond Yes to the Save Edits prompt.



You should now have a new outlet point feature at your designated outlet.

Select Spatial Analyst Tools \rightarrow Hydrology \rightarrow Watershed. Set the inputs as follows and click OK.

Natershed				
Input flow direction raster		^	Watershed	^
fdr	- 🖻			
Input raster or feature pour point data			Determines the contributing area above a	
Outlet	- 🖻		set of cells in a faster.	
Pour point field (optional)				
OBJECTID	•			
Output raster				
C: \Users \dtarb \Scratch \Ex4\SanMarcos.gdb \wshed				
	_			
		-		-
OK Cancel Environments	<< Hide Help		Tool Help	

The result should be a Watershed grid that has the value 1 over the area upstream from the outlet point as evaluated from the flow direction field.

5. Stream Definition

Let's define streams based on a flow accumulation threshold within this watershed.

Select **Spatial Analyst Tools** \rightarrow **Map Algebra** \rightarrow **Raster Calculator** and enter the following expression, using the name **Str** for the output raster.

Raster Calculator	
Map Algebra expression	Map Algebra expression
$\begin{array}{c c} Layers and & & \\ $	The Map Algebra expression you want to run. The expression is composed by specifying the inputs, values, operators, and tools to use. You can type in the expression directly or use the buttons and controls to help you create it. • The Layers and variables list identifies the datasets available to use in the Map Algebra expression. • The buttons are used to enter numerical values and operators into the expression. The (and) buttons
	can be used to apply parentheses to the expression.
OK Cancel Environments << Hide Help	Tool Help

The result is a raster representing the streams delineated over our watershed.

6. Stream Links

This function creates a grid of stream links (or segments) that have a unique identification. Either a link may be a head link, or it may be defined as a link between two junctions. All the cells in a particular link have the same grid code that is specific to that link.

🔨 Stream Link	
Input stream raster Str Input flow direction raster fdr Output raster C: \Users\dtarb\Scratch\Ex4\SanMarcos.gdb\StrLnk	Stream Link Assigns unique values to sections of a raster linear network between intersections.
OK Cancel Env	Tool Help

The result is a grid with unique values for each stream segment or link. Symbolize StrLnk with unique values so you can see how each link has a separate value.



7. Catchments

The Watershed function also provides the capability to delineate catchments upstream of discrete links in the stream network.

Select **Spatial Analyst Tools** \rightarrow **Hydrology** \rightarrow **Watershed.** Set the inputs as follows. Notice that the Input raster pour point data is in this case the StrLnk grid. Click OK.

🔨 Watershed	
Input flow direction raster	Pour point field (optional)
fdr Input raster or feature pour point data	Field used to assign values to the pour
StrLnk Pour point field (optional)	If the pour point dataset is a raster, use
Value Value Output raster Cull loggeddach/SanMarcon odb/Catchmente	Value.
	If the pour point dataset is a feature, use a numeric field. If the field contains floating-point values, they will be truncated into integers.
OK Cancel Environments << Hide Help	Tool Help

The result is a Catchments grid where the subcatchment area draining directly to each link is assigned a unique value the same as the link it drains to. This allows a relational association between lines in the StrLnk grid and Area's in the Catchments grid. Symbolize the Catchments grid with unique values so you can see how each catchment has a separate value.



8. Conversion to Vector

Let's convert the raster representation of streams derived from the DEM to a vector representation.

Select **Spatial Analyst Tools** \rightarrow **Hydrology** \rightarrow **Stream to Feature.** Set the inputs as follows. Note that I put the output in the BaseMapAlbers feature dataset.

🔨 Stream to Feature	1			x
Input stream raster StrLnk Input flow direction raster fdr Output polyline features C:\Users\dtarb\Scratch\Ex4\SanMarcos.gdb\BaseMapAlbers\DrainageLine	- C	*	Stream to Feature Converts a raster representing a linear network to features representing the linear network.	*
OK Cancel Environments	<< Hide Help	Ŧ	Tool Help	Ŧ

Note here that we uncheck the Simplify polylines option. The simplification can cause streams to "cut corners" that will result in errors when they are later on matched up with values an underlying stream order grid during the process of determining stream order.

The result is a linear feature class "DrainageLine" that has a unique identifier associated with each link.

Select Conversion Tools \rightarrow From Raster \rightarrow Raster to Polygon. Set the inputs as follows

🔨 Raster to Polygon		
Input raster	*	Raster to Polygon
Catchments	- 🖻	
Field (optional)		Converts a raster dataset to polygon features.
Value	-	
Output polygon features		
C:\Users\dtarb\Scratch\Ex4\SanMarcos.gdb\BaseMapAlbers\CatchPoly	6	
Simplify polygons (optional)		÷
OK Cancel Environments	<< Hide Help	Tool Help

The result is a Polygon Feature Class of the catchments draining to each link. The feature classes DrainageLine and CatchPoly represent the connectivity of flow in this watershed in vector form and will be used later for some Network Analysis, that is enabled by having this data in vector form.



To turn in:

7. Describe (with simple illustrations) the relationship between StrLnk, DrainageLine, Catchments and CatchPoly attribute and grid values. What is the unique identifier in each that allows them to be relationally associated?

9. Strahler Stream Order

Run Spatial Analyst Tools \rightarrow Hydrology \rightarrow Stream Order with inputs as follows.

🔨 Stream Order				<
Input stream raster	_	^	Stream Order	*
Str	2			
Input flow direction raster			Assigns a numeric order to segments of a raster	
fdr 🗸	6		representing branches of a linear network.	
Output raster				
C:\Users\dtarb\Scratch\Ex4\SanMarcos.gdb\StrahlerOrder	2			
Method of stream ordering (optional)	_			
STRAHLER	-			
		-		Ŧ
OK Cancel Environments << Hid	le Help		Tool Help	

The result is a Raster StrahlerOrder that holds Strahler Order values for each grid cell. Let's now associate these with the streams represented by DrainageLine.

Locate the Zonal Statistics as Table (Spatial Analyst) tool and run it with inputs as follo	ool and run it with inputs as follows
--	---------------------------------------

🔨 Zonal Statistics as Table			
Input raster or feature zone data	_	^ 0	utput table
DrainageLine	- 🖻		
Zone field		0	utput table that will contain the summary of the
grid_code	-	Va	alues in each zone.
Input value raster		=	
StrahlerOrder	- 🖻		
Output table			
C:\Users\dtarb\Scratch\Ex4\SanMarcos.gdb\OrderTable			
Ignore NoData in calculations (optional)		•	Ψ.
OK Cancel Environments	<< Hide Help		Tool Help

Grid_code was chosen as the Zone field because there is a unique grid_code for each DrainageLine link. The result is a Table "OrderTable". Open the DrainageLine attribute table. Select **Table Options** \rightarrow **Add Field.** Specify the name StrahlerOrder and leave other properties at their default. (Strahler Orders are small integer numbers that should fit in a Short Integer data type)

Table	Add Field
🔚 ▾ 🖶 靴 🖾 🖓 💥 🗶 Market Karlet 👬 🕅 🕅 🕅 🕅 🕅 🕅 🕅 🕅 🕅 🕅 🕅	Name: Strahler/Order
 Select By Attributes Clear Selection Switch Selection Select All 	Type: Short Integer Field Properties Alias
Add Field Turn All Fields On	Allow NULL Values Yes Default Value Domain
	OK Cancel

Select Table Options \rightarrow Joins and Relates \rightarrow Join, then specify the Join data as follows



Respond No to the prompt about indexing.

The DrainageLine table now displays many more columns because it has included all the columns from OrderTable. Which of these contains the Strahler Stream order that we need. It may initially be puzzling as to why the MIN and MAX are different, because each link is supposed to have a single Strahler Order. However, when you recognize that a link extends at its junction into the grid cell represented by the downstream link, the reason becomes apparent. Given this it seems best to select the MIN field from OrderTable to assign values for StrahlerOrder. If you appear to be getting unexpected results, check your DrainageLine polygon. If at step 8 you forgot to uncheck the simplify polylines setting, the simplification can result in this process picking up some unexpected stream orders.

Right Click on the StrahlerOrder field header and select Field Calculator, then double click on the OrderTable.MIN field so that the Field Calculator displays as follows and click OK.

	StrahlerOrde	r	OBJECTID* GRID CODE	(
j	<null></null>	A .	Sort Ascending	Ī
2	<null></null>	=	Sort Descending	
3	<null></null>		solebestellung	L
3	<null></null>		Advanced Sorting	ľ
)	<null></null>		Summarize	
)	<null></null>			
2	<null></null>	Σ	Statistics	ľ
2	<null></null>		Field Calculator	
3	<null></null>			L
2	<null></null>		Calculate Geometry	Ī
3	<null></null>		Turn Field Off	
•	-Mulls			Γ

eld Calculator			? 🕳 🗙
Parser VB Script Python			
Fields:		Type:	Functions:
OrderTable.GRID_CODE OrderTable.COUNT OrderTable.AREA OrderTable.MIN OrderTable.MAX OrderTable.RANGE OrderTable.MEAN OrderTable.STD ∢ Show Codeblock		 Number String Date 	Abs () Atn () Cos () Exp () Fix () Int () Log () Sin () Sqr () Tan ()
DrainageLine.StrahlerOrder =			* / & + - =
[OrderTable.MIN]			•
	<u>C</u> lear	<u>L</u> oad	Save Help
			OK Cancel

Notice that the StrahlerOrder field is now populated with the minimum OrderTable.MIN values. Remove all Joins from the DrainageLine table.

Symbolize the DrainageLine feature class using Strahler Stream Order for color and line width.



Use **Options** \rightarrow **Select by attributes** and **Statistics** in the DrainageLine table to obtain the number of stream links and total length of streams of each order. Use a similar approach applying joins to the CatchPoly table to determine the stream order of the stream associated with each catchment polygon. Use **Options** \rightarrow **Select by attributes** and **Statistics** to obtain the total area of catchments draining directly to streams of each order.

To turn in:

- 8. A table giving the number of stream links, total stream length and total catchment area draining directly to streams of each order.
- 9. A layout showing the stream network and catchments attractively symbolized with scale, title and legend. The symbology should depict the stream order for each stream.

10. Stream Gauge Subwatersheds

It is often necessary to delineate watersheds draining to specific monitoring points on the stream network, such as stream gages. Let's do this. If necessary add the USGSGage feature class. This is a stream gauge feature class similar to that used in previous exercises. Zoom in close to one of the gages. You will see that although close, the gages do not lie exactly on the streams.

Use **Spatial Analyst Tools** → **Hydrology** → **Snap Pour Point** with the following input

Snap Pour Point	2	
Input raster or feature pour point data	*	Snap Pour Point
USGSGage 🗾 🖻		
Pour point field (optional)		Snaps pour points to the cell of
OBJECTID 🗸		nignest flow accumulation within a
Input accumulation raster		specified distance.
🖌 🖌 📩 🔁		
Output raster		
C:\Users\dtarb\Scratch\Ex4\SanMarcos.gdb\GageSnap		
Snap distance		
50		
	-	-
OK Cancel Environments << Hide Help		Tool Help

This results in a raster of pour points close to each gage but on the stream as defined by flow accumulation.

Use Spatial Analyst Tools \rightarrow Hydrology \rightarrow Watershed with the following input

Natershed	-			×
Input flow direction raster		•	Watershed	*
fdr	- 🖻			
Input raster or feature pour point data			Determines the contributing area above a set of cells	
GageSnap	- 🖻		in a faster.	
Pour point field (optional)				
Value	-			
Output raster				
C: \Users \dtarb \Scratch \Ex4\SanMarcos.gdb \wshedG				
	-			Ŧ
OK Cancel Environments	<< Hide Help]	Tool Help	

This results in subwatersheds delineated to each stream gage. These may be used with zonal functions to evaluate properties of the subwatersheds draining to these gauges.



To turn in:

10. Indicate the field in the gages table that is associated with values in the wshedG. Give the area in number of grid cells and km² of each gauge subwatershed. Add these as appropriate to give the total area draining to each gauge and compare to the DA_SQ_MILE values from the USGS for these gauges.

Network Analysis

Some of the real power of GIS comes through its use for Network Analysis. A Geometric Network is an ArcGIS data structure that facilitates the identification of upstream and downstream connectivity. Here we step through the process of creating a geometric network from the vector stream network representation obtained above, and then use it to determine some simple aggregate information.

Locate the Feature Vertices to Points tool (using the search window) and run it with the following input.

Input Features				Feature Vertices To F	Points
DrainageLine Output Feature Class		⊥ 🖻		Creates a feature class	containing points
C:\Users\dtarb\Scratch\Ex4\SanMarco	os.gdb\BaseMapAlbers\DrainageLineS	ourceSinks 🛛 🔁		generated from specifie the input features	d vertices or locations of
Point Type (optional)				the input leatures.	
DANGLE		•			
				LINE INPUT	POLYGON INPUT
				× ,	•
			-	•	

This creates vertices at each "dangling" end of the stream network. This was done so as to be able to identify the vertex that is the outlet to set as a sink in the Geometric Network creation procedure, so that flow direction can be determined.

Zoom in on the bottom right and select the vertex that is right at the outlet. Use the Select Features tool on the Tools toolbar



Right click on **DrainageLineSourceSink** \rightarrow **Data** \rightarrow **Export Data** and save the selected point as OutletSink.

Export Data									
Export: Selected features									
Use the same coordinate system as:									
🔿 this layer's source data									
🔘 the data frame									
 the feature dataset you export the data into (only applies if you export to a feature dataset in a geodatabase) 									
Output feature class:									
Jsers\dtarb\Scratch\Ex4\SanMarcos.gdb\BaseMapAlbers\OutletSink									
OK Cancel									

Now open the Catalog window and right click on **BaseMapAlbers** \rightarrow **New Geometric Network**

BaseManA	lbers	-	
	Сору		
<u>- </u> 말 🖻	Paste		
	Delete		
FI	Rename		
😳 Gi 🥭	Refresh		<u>ک</u>
⊡ о	Analyze		\sim
:: o	New 🕨		Feature Class
tr Se tr Se	Import +	뮵	Relationship Class
E Binan	Export >	*	Terrain
🗄 🏢 Catch	Compress File Geodatabase	謵	Network Dataset
Gatch Gatch Gistar	Uncompress File Geodatabase	RI	Topology
± # fac	Upgrade Spatial Reference	82	Parcel Fabric
± 🎆 fdr	Add Global IDs	ġ	Geometric Network

Click Next on the New Geometric Network screen. Enter the name **SanMarcosNet**, then click Next.

Sarina cosiver			
Snap features within :	pecified tolerance:		
<u>Y</u> es 0.001		Meters	
Line ends and junc connect. If they d of the snap tolera of the feature dat	tions must match up o not match up they nce, The default val aset,	precisely for featur can be moved withi ue is based on the X	es to n the limits Y tolerance

Select the features **DrainageLine** and **OutletSink**. These will be used to create a Geometric Network. Click Next.

New Geometric Network	? ×
Select the <u>f</u> eature classes you want to build your network fro	m:
TrainageLine	Select All
Gages	Clear All
	Unavailable
V 🖸 OutletSink	
< <u>B</u> ack Next	> Cancel

At the prompt to Select roles for the network feature class switch the role under Sources and Sinks for OutletSink to Yes. This will be used as a Sink for the network. This is a location that receives flow. Click Next.

lew Geometric Network	A ROT	? <mark>×</mark>
Select <u>r</u> oles for the the netwo	ork feature classes:	
Feature Class Name	Role	Sources & Sinks
🛨 DrainageLine	Simple Edge	The ex
OutletSink	Simple Junction	Yes
	< <u>B</u> ack	Next > Cancel

Do not add any weights at the prompt about weights, just click Next. Click Finish at the summary prompt. The result is a Geometric Network SanMarcosNet that can be used to perform network operations

-	SanMarcos.gdb	
	🗉 둼 BaseMap	
	BaseMapAlbers	
	CatchPoly	
	🛨 DrainageLine	
	😳 DrainageLineSourceSink	s
	🛨 Flowline	
	😳 Gages	
	😳 Outlet	
	Concetoine	
	🗟 SanMarcosNet	
	SanMarcosNet_Junction	s
	(1997) (1997)	

Select **Customize** \rightarrow **Toolbars** \rightarrow **Utility Network Analyst** from the main menu to activate the Utility Network Analyst toolbar

Utility Network Analyst		- X
Network: SanMarcosNet	🗕 Flow 🕶 🖧 Analysis 🕶 🏒 🕶	Trace Task: Find Common Ancestors

Click on **Flow** → **Display Arrows** on the Utility Network Toolbar

Network: SanMarcosNet	→ F	Flow 🗝 🖕 🛛 Analysis 🔻 🏒 👻
		Display Arrows For
4	<u> </u>	🖌 🛛 Display Arrows
	5	Properties

The result is a set of black dots on each network link. These indicate that flow direction for the network is not assigned.



To assign network flow direction the OutletSink needs to have a property called AncillaryRole set to be the encoding for Sink.

Open the Editor toolbar and select Start Editing (Click Continue at the warning). Use the Editor Edit Tool to select the point at the outlet in the OutletSink Feature Class for editing.



Click on the Attributes button on the Editor Toolbar to open the attributes display panel.



The panel should show that the AncillaryRole for this point is "None".

Attributes	Ψ×
🖃 🚸 OutletSink	
613	
	\left\left\left\left\left\left\left\left
OBJECTID	1
arcid	613
grid_code	429
from_node	612
to_node	614
ORIG_FID	613
DANGLE_LEN	3768.74675
Enabled	True
AncillaryRole	None

Open the attribute table for OutletSink and edit the encoding for the Field AncillaryRole from 0 to 2.

Г	Tab	le			-								OBJECTID	1
I	Tab			_	-		-					4	arcid	613
I	□ - 1 電 - 1 幅 🔞 🖸 💩 ×										grid_code	429		
ł	OutletSink								:	from_node	612			
L		OBJECTID *	Shape *	arcid	grid_code	from_node	to_node	ORIG_FID	DANGLE_LEN	Enabled	AncillaryRole		to_node	614
I		1	Point	613	429	612	614	613	3768.74675	1	2		ORIG_FID	613
I	Þ												DANGLE_LEN	3768.74675
I													Enabled	True
l													AncillaryRole	Sink
I														

When you make this change you should see the Ancillary Role designation switch from None to Sink.

Click on the Set Flow Direction Tool on the Utility Network Analysts toolbar.

Utility Network Analyst	\sim				- ×
Network: SanMarcosNet	▼ Flow 원	Analysis 🕶 🏒 🕶	Trace Task:	Find Common Ancestors	- X
-	3	et Flow Direction]		

You should see the black dots switch to arrows indicating that Flow in the network is now set towards the designated Sink at the outlet. This network is now ready for Analysis. Stop Editing, saving edits.



Zoom to the vicinity of one of the USGS stream gauges and place an edge flag near the gauge using the Utility Network Analyst Add Edge Flag Tool.



Set the Trace Task to Trace Upstream and press Solve.

D 1 U 1	Ŧ		-
Network: SanMarcosNet	💌 Flow 🔻 🚑 Analysis 🕶 🔀 🕶 Trace Task	Trace Upstream 🔹 🔀 👳	
Jor (Solve	I
	•		

The result is a highlighting of the link that has the edge flag and all links upstream.



Select Analysis \rightarrow Options



Switch the Results format to Selection. Select Analysis Clear Results and run the trace again.

Analysis Options	Flow • 🖕 Analysis • • 🕻 • Trace Ta Disable Layers 🕨
General Weights Weight Filter Results Results format Return results as: Drawings Draw individual elements of complex edges Trace task result color Selection	Clear Flags Clear Barriers Clear Results Options
Results content Results include: Image: Peatures stopping the trace Of these results include: Image: Peatures Image: Peatures stopping Image: Peatures stopping	

Now the upstream features are selected. Open the Drainage Line feature class attribute table and show selected records

T	Table 🛛										
Γ	Ξ - 🖶 - 🖫 🚱 🖸 🐠 🗙 🗞 🗠 🗶										
[DrainageLine									×	
I	Τ	OBJECTID *	Shape *	arcid	grid_code	from_node	to_node	Shape_Length	StrahlerOrder	Enabled	A
١Ľ	۲	78	Polyline	78	70	66	89	2934.777054	1	True	E
		80	Polyline	80	63	57	89	4890.29004	1	True	
		89	Polyline	89	84	81	102	2909.92424	1	True	
		90	Polyline	90	100	99	102	1082.756493	1	True	
		119	Polyline	119	96	95	134	5100.29004	1	True	
		120	Polyline	120	123	121	134	1409.741341	1	True	
		123	Polyline	123	105	107	138	4585.142853	1	True	
		124	Polyline	124	99	89	138	6951.686143	2	True	
		131	Polyline	131	137	138	145	591.837662	2	True	
		132	Polyline	132	147	144	145	932.756493	1	True	
		137	Polyline	137	140	105	149	5829.884194	1	True	
		142	Polyline		151	152	149	1491.396103	1	True	*
	14 4 1 ► ► 1 = 1 = 1 (87 out of 437 Selected)										
l	DrainageLine										

Right click on column header Shape_Length → Statistics



Record the total length and number of stream links upstream of each USGS gauge. Note that there is a small error in these results due to the gauge being part of the way along the flagged link which is included in the calculations. The link could be split to make this analysis more precise but that will not be done here (it would add another 5 pages and few hours to this already long assignment). Switch the Trace Task to **Trace Downstream** and press **Solve** again. Notice how the selected stream links switch to those downstream from the flag. Determine the total length of these links as an estimate of the distance along the rivers from each gauge to the downstream outlet. Join the CatchPoly attribute table to the DrainageLine table. This provides access to the area draining directly to each stream link. Evaluate the total area upstream of each using **Shape_Area** → **Statistics**. You can also, by placing a flag at an upstream link determine the flow path (and its length) from any distant link to the outlet. Evaluate the length of the longest flow path by choosing a link that appears to have the longest flow path (a bit of trial and error may be necessary). Prepare a layout that illustrates the longest flow path in the San Marcos watershed.



To turn in:

- 11. A table giving for each USGS gauge the number of upstream stream links, the total length of upstream stream links, the total upstream area, drainage density (total length/total area), number of downstream links along path to outlet, distance to outlet along the streams.
- 12. A layout illustrating the longest flow path in the San Marcos watershed and giving the length in *km*.

OK. You are done!

Summary of Items to turn in.

- 1. Screen captures that illustrate the effect of DEM Reconditioning. Show the location where you made a cross section as well as the DEM cross sections with and without reconditioning.
- 2. Number of stream grid cells in FlowlineReclas and estimates of channel length and drainage density.
- 3. Volumes of earth removed estimated from (a) layer properties of diff and (b) from estimates of channel length and cross section area. Comment on the differences.
- 4. Make a screen capture of the attribute table of fdr and give an interpretation for the values in the Value field using a sketch.
- 5. Report the drainage area of the San Marcos basin in both number of 30 m grid cells and km² as estimated by flow accumulation.
- 6. Report the name of the most downstream HUC 12 subwatershed in the San Marcos Basin. Report the area of the most downstream HUC 12 subwatershed determined from flow accumulation, from the ACRES attribute and from Shape_Area. Convert these area values to consistent units. Comment on any differences.
- 7. Describe (with simple illustrations) the relationship between StrLnk, DrainageLine, Catchments and CatchPoly attribute and grid values. What is the unique identifier in each that allows them to be relationally associated?
- 8. A table giving the number of stream links, total stream length and total catchment area draining directly to streams of each order.
- 9. A layout showing the stream network and catchments attractively symbolized with scale, title and legend. The symbology should depict the stream order for each stream.
- 10. Indicate the field in the gages table that is associated with values in the wshedG. Give the area in number of grid cells and km² of each gauge subwatershed. Add these as appropriate to give the

total area draining to each gauge and compare to the DA_SQ_MILE values from the USGS for these gauges.

- 11. A table giving for each USGS gauge the number of upstream stream links, the total length of upstream stream links, the total upstream area, drainage density (total length/total area), number of downstream links along path to outlet, distance to outlet along the streams.
- 12. A layout illustrating the longest flow path in the San Marcos watershed and giving the length in km.