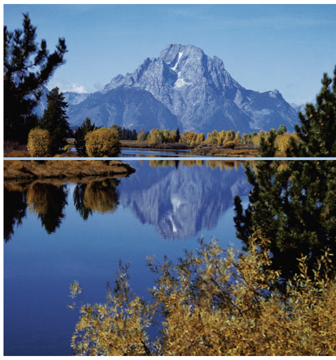
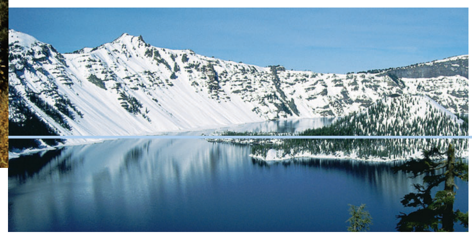


4

chapter four



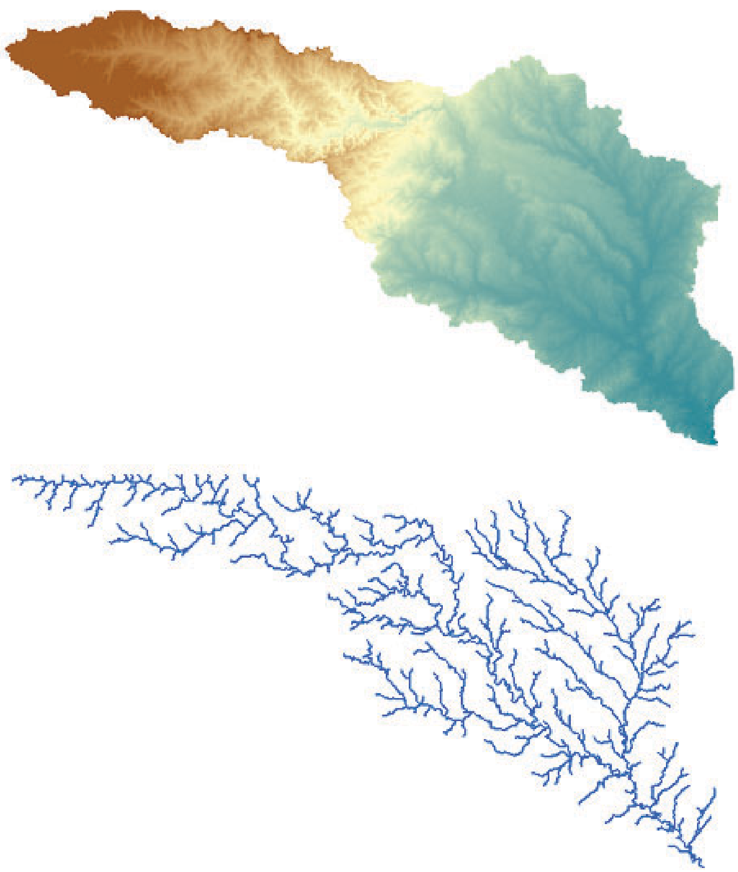
Drainage systems

Francisco Olivera, Texas A&M University
Jordan Furnans, University of Texas at Austin
David Maidment, University of Texas at Austin
Dean Djokic, ESRI
Zichuan Ye, ESRI

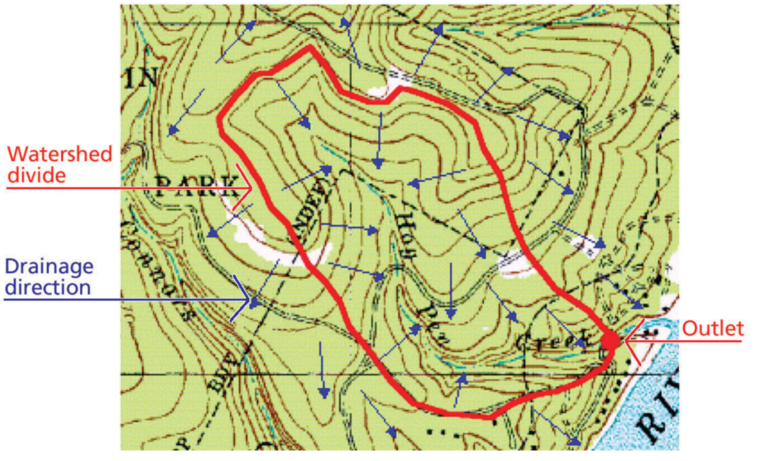
Water and land interact with one another: the shape of the land surface directs the drainage of water through the landscape, while the erosive power of water slowly reshapes the land surface. Streams, rivers, and water bodies lie in the valleys and hollows of the land surface, and drainage from the ridges and higher land areas flows downhill into these water systems. Digital elevation models are used to analyze the drainage patterns of the land-surface terrain, and drainage areas are delineated from outlets chosen either manually or automatically according to physical rules. Raster analysis using fine-resolution DEMs is practical only over limited areas, but these results may be combined with vector networks to carry out regional hydrologic studies. Drainage areas can be traced upstream and downstream, either through their attachment to the hydro network or by using area-to-area navigation, thereby identifying the region of hydrologic influence upstream and downstream of a catchment or watershed.

Drainage from the landscape

Precipitation falls on the land surface, soaks into soils, evaporates, or runs off the land surface into streams. Drainage is the flow process by which water moves from the point that it falls onto the landscape down to a stream, then to a river, and finally to the sea. Drainage flows downhill so the wetness of the land surface is a function of its shape, ridges being higher and having dryer soils and valleys being lower and having wetter soils. The shape of the landscape directs the flow of water but is in turn shaped by the erosive power of water. Gradually, over geologic time, the familiar patterns of small drainage paths leading to ditches, then to streams, and finally to rivers are etched on the landscape by flowing water as it carries away eroded sediment. There is thus an intimate relationship between the shape of the land-surface terrain and the stream network that exists within it.

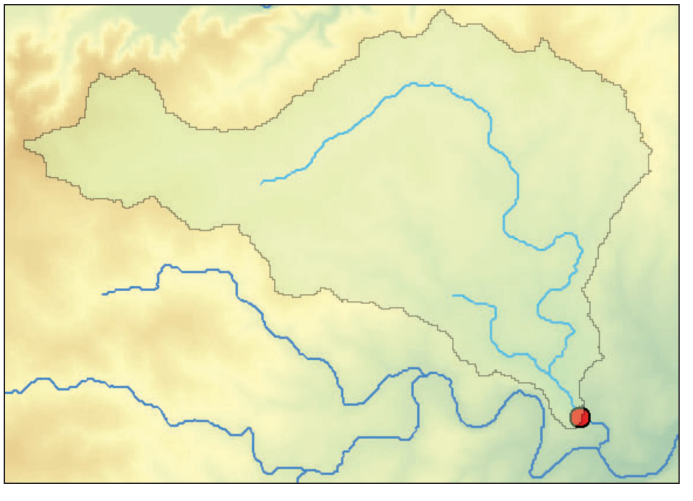


Land-surface terrain and stream network for the San Marcos basin.
The San Marcos River is a tributary of the Guadalupe River.



Manual delineation of drainage area on a topographic map

Traditionally, drainage areas have been delineated from topographic maps, where drainage divides are located by analyzing the contour lines. Arrows representing water flow direction can be drawn perpendicular to each contour, in the direction of the steepest descent. The location of a drainage divide is where flow directions diverge. The drainage area boundary is digitized by drawing a continuous line transverse to the contours, up from the outlet point to the ridgeline, along the ridgeline around the drainage area, then descending to the outlet point again.



Drainage area delineation using a digital elevation model

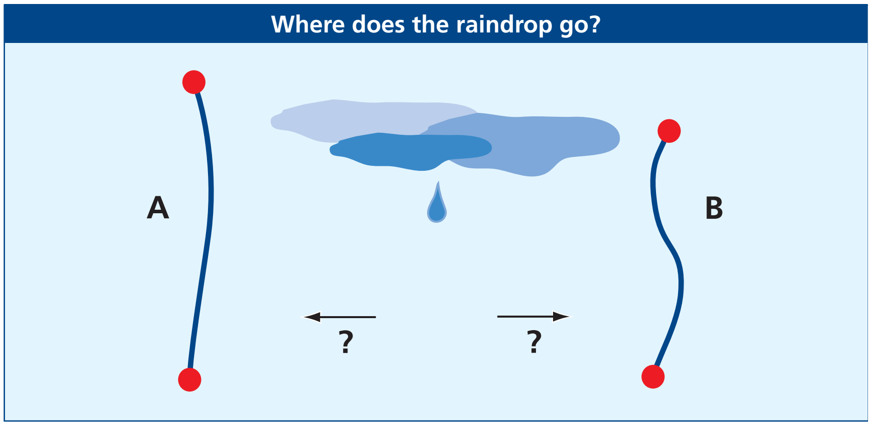
Drainage areas can also be delineated automatically using digital elevation models of the land-surface terrain. A digital elevation model is a grid of square cells, where each cell value represents the elevation of the land surface. By determining how water flows from cell to cell, the set of cells whose drainage flows through the cell at the outlet point location can be identified, and thus the drainage area determined.

The Arc Hydro toolset contains functions to accomplish automated drainage area and stream network delineation from digital elevation models, and there are many advantages to using them. Drainage patterns are complex and automated processing removes the need for the hydrologist to spend endless hours trying to interpret drainage patterns from contour lines on maps. Nevertheless, digital elevation models are only an approximate representation of land-surface terrain and manual editing of drainage boundaries may be necessary, especially in regions with very flat terrain having many constructed rather than natural drainage channels.

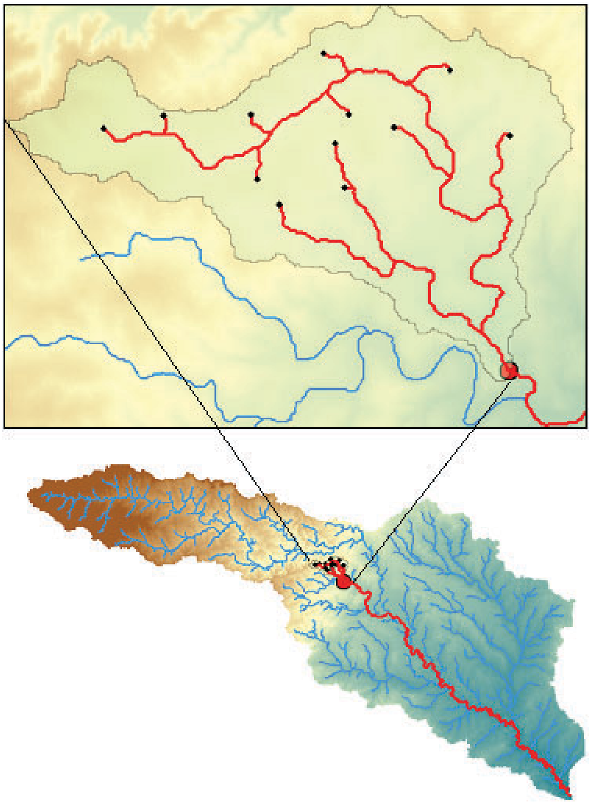
The Arc Hydro data model accepts drainage areas and connects them to the hydro network, no matter whether the areas were automatically or manually delineated, and allows for the fact that the mapped stream hydrography may not be entirely consistent with the land-surface terrain or hypsography used to determine drainage area or boundaries.

Raindrop model

The Arc Hydro data model represents a system of behavior. In the most simplistic sense, this system follows the drainage of a raindrop from when it hits the ground through streams and rivers to the point when it comes to its final resting place, usually in the ocean. At the beginning of its journey, we could ask the question: "If a raindrop falls between two streams, to which stream does it flow?" Fortunately, when digital elevation models are used, the cell-to-cell flow path of a raindrop is easy to trace (the Arc Hydro toolset has a function for accomplishing this), and the flow paths of raindrops falling anywhere on the land surface can be identified.



To which stream does the raindrop flow?



Following the paths of raindrops from where they fall on the land surface to streams, rivers, and all the way to the ocean.

The cell-to-cell flow paths on raster grids make it easy to define the flow path of a raindrop, but the issue is more complex when vector data is used to define drainage areas. Then, the drainage area polygon within which the raindrop falls needs to know where on the stream network this raindrop discharges. The only location that can be unambiguously identified is the drainage area outlet, that is, it can be stated certainly that the effect of a raindrop falling anywhere within a drainage area has been felt by the time the flow reaches the drainage area outlet. In Arc Hydro, the connection "areas flow to lines at points," is made and this forms the basis of building the relationship between Watershed and HydroJunction features.

It is possible, however, to associate drainage areas with streams more simply: each stream segment has one and only one drainage area associated with it. In that case, following the path of a raindrop from anywhere on the land surface to the stream network consists of identifying the stream segment lying within the drainage area where the raindrop fell. This simpler "area to line" connectivity of the land surface to the stream network is used for the Arc Hydro Catchment processing system, subdividing the landscape into a large number of elementary drainage areas, each with its own associated DrainageLine and DrainagePoint at the outlet.

Drainage areas

Drainage area boundaries are used in water-availability studies, water-quality projects, flood forecasting programs, as well as many other engineering and public policy applications. So far in this book, the terms drainage area, catchment, watershed, and basin have been used interchangeably without defining the distinctions between them. Indeed in normal language there is little distinction between these terms. In the United States, watershed is the standard term for a drainage area, while in Britain and Europe, catchment is considered the standard term. Basin is understood to be a larger drainage area associated with a major river, such as for the Mississippi or Missouri River basins.

In Arc Hydro, the following definitions apply:

- Basin—A set of administratively chosen drainage areas that partition a region for purposes of water management. Basins are usually named after the principal rivers and streams of a region. Basins may serve as spatial packaging units for Arc Hydro data sets.
- Watershed—A tessellation or subdivision of a basin into drainage areas selected for a particular hydrologic purpose. Watersheds may drain to points on a river network, to river segments, or to water bodies.
- Catchment—A tessellation or subdivision of a basin into elementary drainage areas defined by a consistent set of physical rules.

A distinction is drawn between catchments, whose layout can be automatically determined using a set of rules applied to a digital elevation model, and watersheds, whose outlets are chosen manually to serve a particular hydrologic purpose. Watershed outlet points may lie anywhere, and are not necessarily coincident with catchment outlet points. Drainage area is used in this book as a generic term for a catchment, watershed, or basin, and also to specify the physical area within the drainage basin boundary. The context in which the term is used serves to distinguish these two meanings of drainage area.

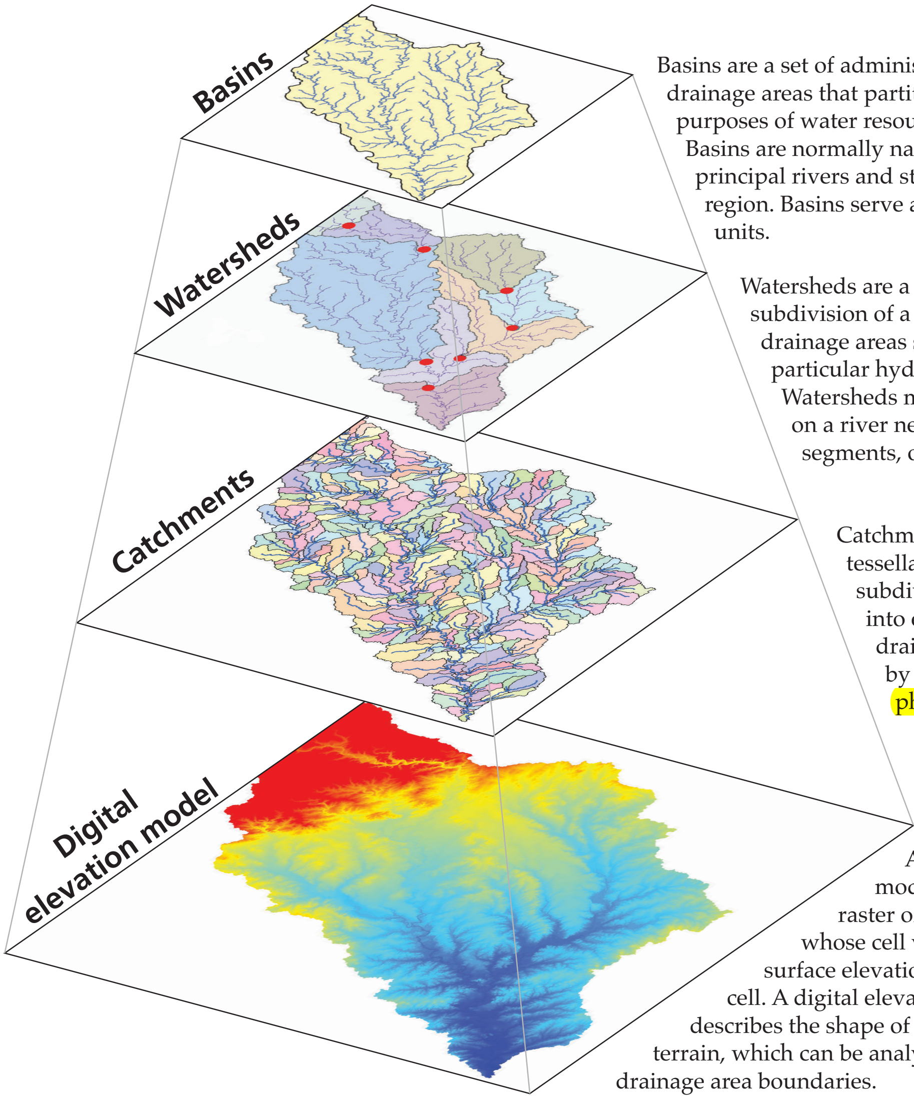
Catchments

Catchments are elementary drainage areas defined by a consistent set of physical rules. The approach most often used is to define the beginning of a stream using a threshold upstream drainage area, then delineate catchments from the confluences of all the stream segments thus created. The analysis is carried out on a digital elevation model, so a catchment is defined by a zone of raster cells, a stream segment is defined by a line of raster cells, and an outlet is defined by a single cell. When converted from raster to vector features, these cells form the Arc Hydro feature classes Catchment, DrainageLine, and DrainagePoint, respectively. The advantage of the threshold drainage area approach to defining catchments is that the tessellation of the landscape into elementary drainage areas is readily automated. The disadvantage is that this approach takes no account of the presence of water bodies in the landscape (they are treated as if they are large, flat land surfaces), and it cannot produce catchments draining directly to the coastline rather than to a stream.

An alternative approach to defining catchments is to take a hydro network with reach codes defined for all of its segments, and use a digital elevation model to delineate an elementary drainage area for each reach. This approach allows for catchments to be defined for coastline

Scales of representation of drainage systems

At the highest level are Basins, which may be subdivided into Watersheds or Catchments. Digital Elevation Models may be used to define drainage area boundaries for Catchments, Watersheds, and Basins.



Basins are a set of administratively chosen drainage areas that partition a region for purposes of water resources management. Basins are normally named after the principal rivers and streams of the region. Basins serve as data packaging units.

Watersheds are a tessellation or subdivision of a basin into drainage areas selected for a particular hydrologic purpose. Watersheds may drain to points on a river network, to river segments, or to waterbodies.

Catchments are a tessellation or subdivision of a basin into elementary drainage areas defined by a consistent set of physical rules.

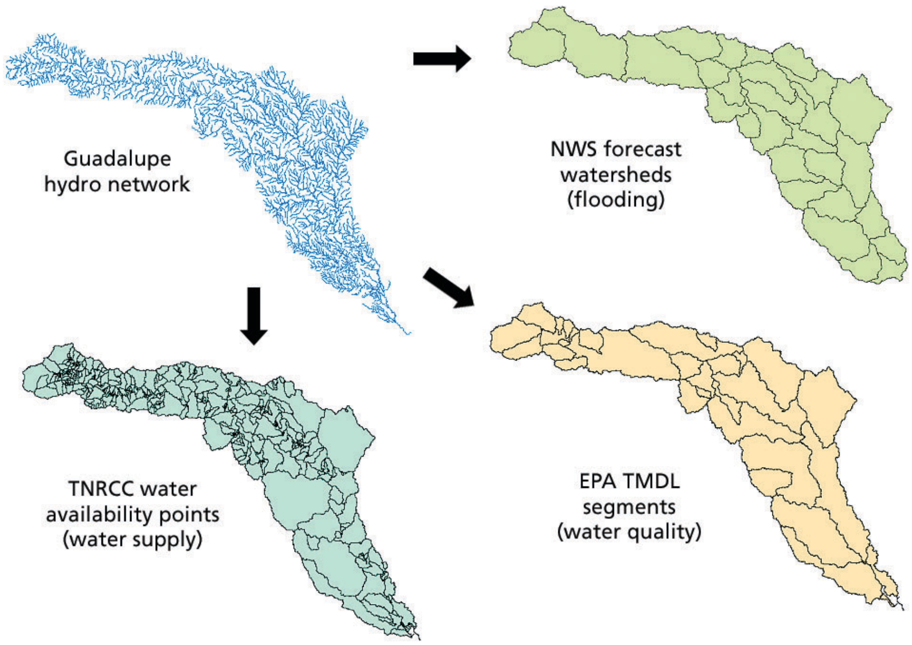
A digital elevation model is a grid or raster of square cells whose cell value is the land surface elevation in the center of cell. A digital elevation model describes the shape of the land surface terrain, which can be analyzed to define drainage area boundaries.

Four spatial scales for representation of a basin: digital elevation model, catchment, watershed, and basin segments and for water bodies, as well as for river reaches, but it is more difficult to implement than the simple definition of catchments based on threshold drainage area.

Watersheds

How water resources agencies subdivide a given landscape into drainage units may vary significantly from one agency to another, or even within the same agency when different kinds of analyses are undertaken. In the United States, the National Weather Service forecasts floods on all the major rivers. For that purpose the nation is divided into watersheds, each watershed being a model unit in the agency's river forecast system. The Environmental Protection Agency manages water pollution using Total Maximum Daily Loads defined on watersheds draining to selected river segments or water bodies, a different watershed layout than that used by the National Weather Service. The Texas Natural Resource Conservation Commission uses yet another watershed layout to determine the availability of water supply, where watersheds are delineated to outlet locations on streams and rivers where permits have been issued for water withdrawal. All of these watershed delineations serve legitimate but different purposes. There are an infinite number of ways to subdivide the landscape into watersheds, and no unique way serves all purposes.

What all these watershed layouts have in common is that they share the same hydro network. In other words, it does not matter how the landscape is subdivided into watersheds once the water reaches the stream and river system. Arc Hydro is designed to allow any set of watersheds



Four different views of the Guadalupe basin to be relationally connected to the hydro network using the "area flows to a point on a line" concept to establish relationships between watersheds and hydro junctions at their outlet locations. This approach works regardless of whether the watersheds are derived from digital elevation models or from manual delineation. The flexibility of being able to combine watershed data sets derived from one map source with stream and river networks derived independently is a strength of Arc Hydro. This is a significant advance over previous approaches to working with watersheds and stream networks in GIS that have been almost entirely based on raster analysis of digital elevation models. Indeed, some countries in the world do not have publicly available digital elevation models and their GIS data sets are entirely based on vector watershed and stream networks. Such vector data can readily be incorporated into the Arc Hydro data model.

Basins

Although there is no unique way of defining a watershed layout, many agencies have a standardized set of watersheds that have been worked out over the years, and that serve as reference units for water resources management. In Arc Hydro, these standardized watersheds are called Basins, and they serve as reference units for data management and data packaging. In particular, in applying Arc Hydro, it may be convenient to develop an Arc Hydro geodatabase for each basin. Later in this chapter a method of regionalizing the HydroID is presented. This enables geodatabases defined for a set of basins to be merged to form a geodatabase for a water resource region.

Information sources

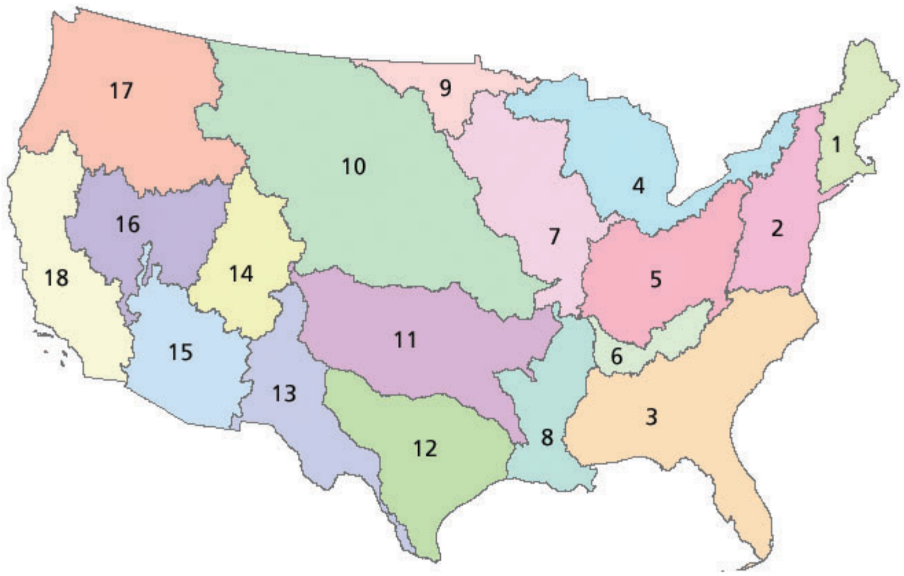
Hydrologic units of the United States

In the United States, a standard set of basins called hydrologic units has been developed by the U.S. Geological Survey and indexed by a Hydrologic Unit Code. Hydrologic units are arranged in a hierarchy. At the highest level, the United States is divided into 20 two-digit water resource regions.

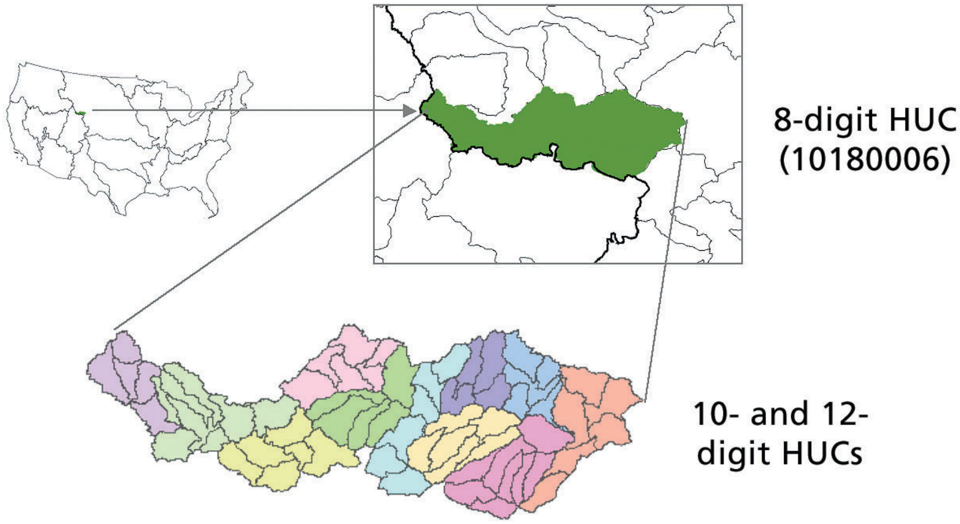
Within the two-digit water resource regions are defined four-digit subregions, six-digit basins, and eight-digit subbasins. The eight-digit Hydrologic Unit Code subbasins, popularly known as the "HUCs" or "cataloging units," have become the standard geospatial units for packaging GIS data for water resources in the United States. The eight-digit cataloging units have an average area of 3,700 square kilometers, and there are 2,156 of them within the continental United States, about the same number as the number of counties. Thus the cataloging units can be thought of as "hydrologic counties." They serve some of the same purposes that counties do, namely for archiving and indexing spatially distributed data across the country.

The Guadalupe basin is comprised of four eight-digit cataloging units: the Upper Guadalupe (12100201), Middle Guadalupe (12100202), San Marcos (12100203), and Lower Guadalupe (12100204). The illustrations presented in this chapter focus on the San Marcos subbasin, which is subbasin 12100203 within basin 121002 within subregion 1210 within region 12 in the Hydrologic Unit Cataloging system.

Eight-digit hydrologic cataloging units. The four cataloging units making up the Guadalupe basin are highlighted in red. The colored backgrounds delineate the water resource regions.



Water resource regions of the contiguous United States

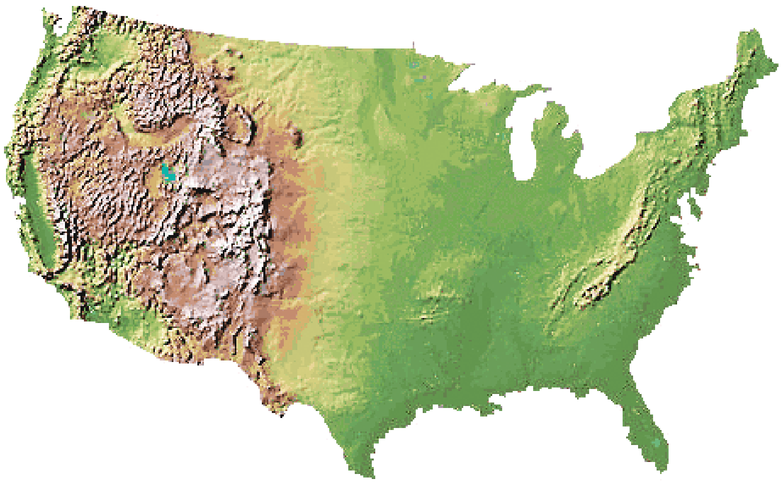


The Watershed Boundary Dataset for Wyoming subdivides eight-digit HUCs into 10-digit HUCs (colored) and then into 12-digit HUCs (outlined).

For water resources management, an area of 3,700 square kilometers is considered large, so there is an ongoing effort by the U.S. Department of Agriculture and the U.S. Geological Survey to create a Watershed Boundary Dataset that further subdivides the eight-digit cataloging units into 10-digit and 12-digit units, called watersheds and subwatersheds, respectively.

Elevation derivatives for national applications

The standard digital elevation model of the United States is called the National Elevation Dataset (NED). It provides a seamless coverage of the nation using one arc-second cells, corresponding on the land surface to a cell size of approximately 30 meters. The illustrations derived from digital elevation models presented in this chapter were developed using this data set. The EROS Data Center, located in Sioux Falls, South Dakota, is presently undertaking a project in collaboration with the National Severe Storms Laboratory in Norman, Oklahoma, to process the National Elevation Dataset into a fine-scale set of catchments. This data set is called the Elevation Derivatives for National Applications, popularly known as EDNA. The name EDNA was chosen in part to emphasize the relationship between terrain information and catchments derived from it, or between NED and EDNA. A five-thousand-cell threshold drainage area (4.5 square kilometers) is used to define the beginning of a stream segment, and catchments are delineated for each stream segment. This threshold drainage area was chosen so that the resulting catchments would be roughly the same size as the standard spatial units for the National Weather Service's Nexrad radar rainfall. In this way Nexrad radar rainfall could readily be mapped onto catchments for flood warnings. The Arc Hydro time series data storage and capacity for downstream



National Elevation Dataset of the United States

accumulation of catchment properties may facilitate the processing of storm rainfall information for this purpose.

The EDNA catchments are classified into a hierarchy of larger to smaller catchment units using the Pfaffstetter classification system. In this system, the highest level drainage areas are subdivided using a set of rules into 10 subdrainage areas, each of which is similarly subdivided into 10 further subdrainage areas, and so on (Verdin n.d.).

Watersheds and stream networks in cities

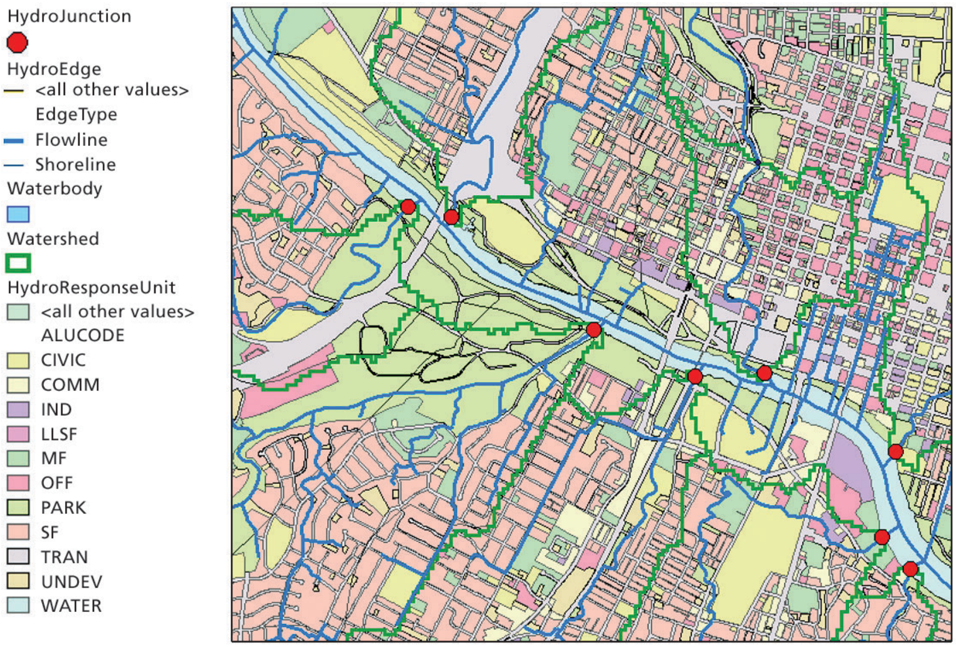
The techniques and data sets described up to this point apply to regional or national information. Yet, the same concepts can be used to apply Arc Hydro within a city or other urban jurisdiction. The Arc Hydro framework data set is simple enough that it can be applied directly to existing digitized streams, watershed boundaries, water bodies, and monitoring points. Achieving a greater degree of detail requires building Arc Hydro data using aerial photogrammetry to identify vector features such as buildings, roads, and streams. Defining stream networks in cities is complicated by the fact that water flows along curbs and drainage ditches, that empty into underground storm sewers, that discharge into streams; not all the segments of the urban hydro network are visible on the land surface. Another complication arises where water flow paths intersect with major highway interchanges, and a significant effort is required to define what happens under the highways.

As an aid to its water-quality management program, the Drainage Utility of Austin, Texas, has developed a complete, digitized stream network for the city and all areas draining through the city at a scale of 1 inch to 100 feet, based on interpretation of aerial photogrammetry. This network is coupled with drainage areas derived from the National Elevation Dataset for regional analysis of water quality over the whole city. LIDAR mapping is used to define the terrain surface more precisely for flood damage reduction projects.

International watershed and stream network data

The EROS Data Center has compiled data sets similar to NED and EDNA for the whole earth. The digital elevation model is called GTOPO30, and represents the terrain surface of the earth in 30 arc-second cells (approximately 1 kilometer on the ground surface). The corresponding drainage area and stream network data set is called Hydro1K Derivatives, and like EDNA, it arranges drainage areas in a hierarchy according to the Pfaffstetter system. In addition to catchment and basin boundaries, the Hydro1K data set provides a set of raster data products derived from GTOPO30 to facilitate reprocessing the data to derive watershed boundaries at chosen points in any region of the earth.

The ability provided by GTOPO30 and Hydro1K to delineate drainage areas for any location on the earth is remarkable, and supports the concept that hydrologic models can be applied using GIS data consistently in any country.



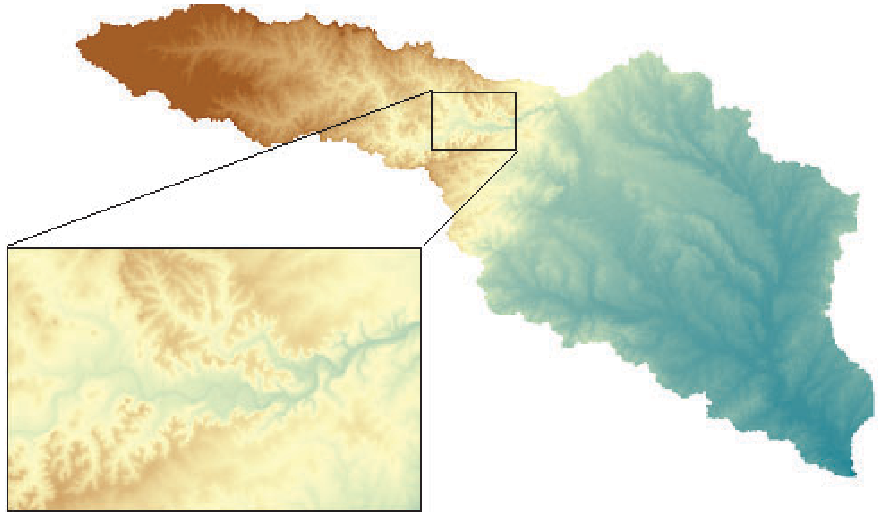
Arc Hydro geodatabase for the city of Austin. Hydro response units are based on the land-use map.

Pfaffstetter Level 1 Basins of North America from the Hydro1K data set

Drainage analysis using digital elevation models

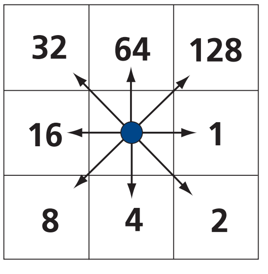
Automated delineation of drainage areas is carried out using a model of the land-surface terrain. This model can be a raster digital elevation model (DEM) or a triangulated irregular network (TIN). TIN data consists of irregularly spaced elevation points in x,y,z values derived from land surveying or aerial mapping that precisely represent the terrain surface. Such data is necessary for floodplain mapping, as described in chapter 5, but currently it is cumbersome to edit TIN data for large regions, so that water will everywhere flow downhill over the TIN surface. DEMs more approximately represent the land surface as compared to TINs, and processing DEMs to properly define drainage flow paths is much simpler because of its regular cell structure. Hence DEMs are the most widely used terrain model for drainage delineation. DEMs are digital records of terrain elevations for ground positions at regularly spaced horizontal intervals. This gridded data is derived from the contour information on standard topographic quadrangle maps, or interpolated from irregularly spaced x,y,z points or contours derived from aerial mapping.

All ArcGIS raster operations involved in watershed delineation are derived from the premise that water flows downhill, and in so doing will follow the path of steepest descent. In a DEM grid structure, there exist at most eight cells adjacent to each individual grid cell (cells on the grid boundary are not bounded by cells on all sides). Accordingly, water in a given cell can



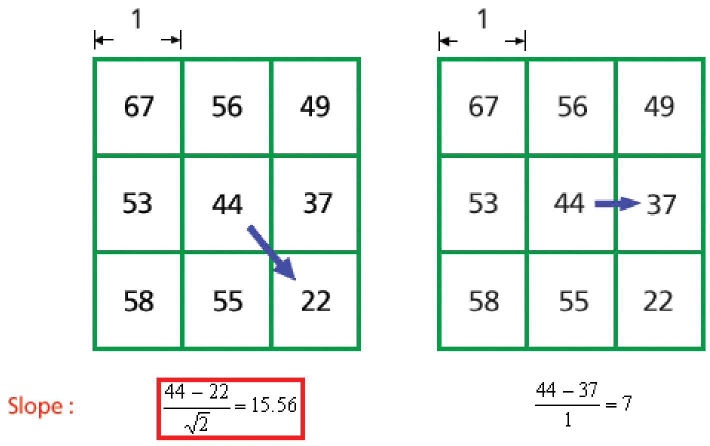
Digital elevation model of the San Marcos subbasin from the National Elevation Dataset

flow to one or more of its eight adjacent cells according to the slopes of the drainage paths. This concept is called the eight-direction pour point model. There are several variants of the eight-direction pour point model, but the simplest, and the one used in ArcGIS, allows water from a given cell to flow into only one adjacent cell, along the direction of steepest descent. The resulting flow direction is encoded 1 for east, 2 for southeast, 4 for south, and so on, to 128 for northeast, a numbering scheme that is derived from the series, which is written in the binary representation used by computers as 00000001, 00000010, 00000100, and so on, to 10000000.



Flow directions in the eight-direction pour point model

Watershed delineation with the eight-direction pour point model is best explained with an illustration. For demonstration purposes, assume a section of a sample DEM grid is provided as shown. The numbers in each grid cell represent the cell elevation.



Slope calculations with the eight-direction pour point model. On the left-hand grid, slope is calculated for diagonal cells. On the right, slope is calculated for cells with common sides.

Flow direction grid

The first important grid derived from the digital elevation model grid is the flow direction grid. In the center cell of the illustration (elevation = 44), only two of the eight adjacent cells contain elevations less than 44. This limits the possible flow directions since water will not flow to a cell at a higher elevation. Water will flow in the direction of steepest descent, where slope is defined by elevation decrease per unit travel distance. There are two cases: (1) along the diagonal, where the slope is calculated by subtracting the destination cell elevation from the origin cell elevation, and dividing the result by 1.41 times the cell size, and (2), which applies to water flow in the rectilinear directions through the sides of the cell, where the slope is calculated simply as the elevation difference divided by the cell size. In the case illustrated, the slope along the diagonal is greatest, and water flows to the southeast, so the center cell is assigned a flow direction value of 2. This process is repeated for each of the cells in the DEM grid, thereby creating the flow direction grid whose cell values are the flow directions defined by the eight-direction pour point model. In flat areas, where all surrounding cells have the same elevation as the cell being processed, the search width is expanded until a direction of steepest descent is found. It is important to note that the DEM must have enough precision of elevation measurement to support correct flow direction determination. Large extents of flat areas might produce unnatural drainage patterns. In those cases, a better resolution DEM needs to be used to get satisfactory results.

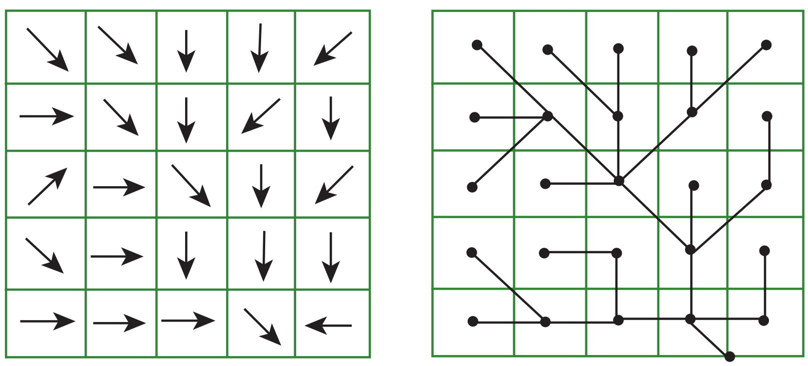
The flow direction grid can also be graphically symbolized by arrows drawn over each cell, or by a flow network drawn between the cell centers. Even though this grid network is not formally defined by a set of lines in Arc Hydro, raster DEM processing does follow an implied network concept.

67	56	49	46	50
53	44	37	38	48
58	55	22	31	24
61	47	21	16	19
53	34	12	11	12

2	2	4	4	8
1	2	4	8	4
128	1	2	4	8
2	1	4	4	4
1	1	1	2	16

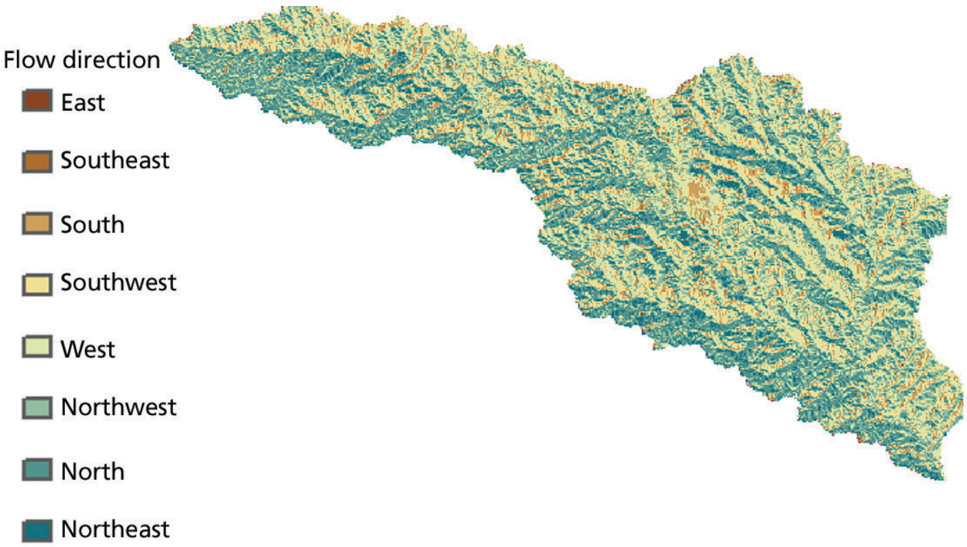
Grid operations. On the left is a DEM grid. The right is a flow direction grid. The areas in red are from the grids on the previous page.

It is necessary to consider the possibility that flow might accumulate in a cell or set of cells in the interior of the grid, and that the resulting flow network may not necessarily extend to the edge of the grid. An example of such a situation is in the Great Salt Lake in Utah, an inland lake with no outlet to the ocean. A second potential problem arises, moreover, where the DEM grid itself contains artificial pits in the terrain, due to errors in elevation determination or grid development. These artificial sinks must be eliminated in order to accurately delineate watersheds. A pit is where a set of one or more cells is surrounded on all sides by cells of higher elevation.



Physical representation of flow direction grids. The left grid has directional arrows, and the right shows a flow network.

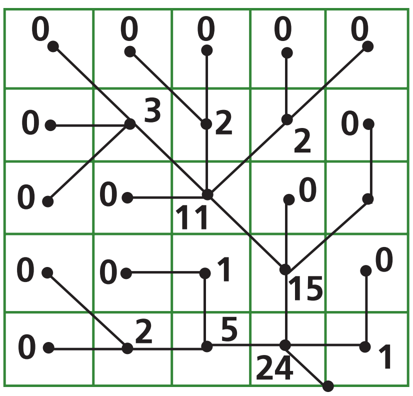
Pits in the DEM are removed through the use of a sink-filling function in ArcGIS. This raises the elevation of all the cells in a pit to the minimum elevation of the surrounding cells so that water can flow across the terrain surface.



The flow direction grid of the San Marcos subbasin

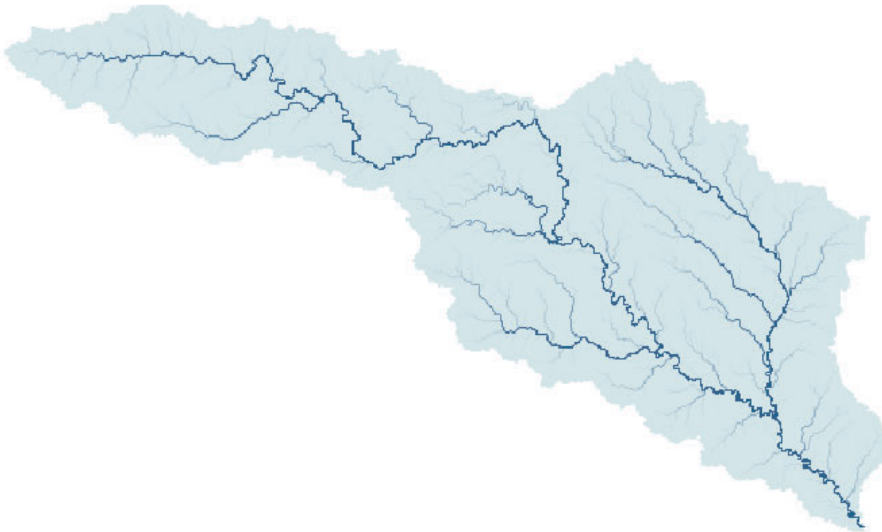
Flow accumulation grid

Flow accumulation is calculated from the flow direction grid. The flow accumulation grid records the number of cells that drain into an individual cell in the grid. Note that the individual cell itself is not counted in this process. From the physical point of view, the flow accumulation grid is the drainage area measured in units of grid cells. The flow accumulation grid for the San Marcos subbasin clearly shows how drainage area accumulates above the principal rivers and streams of the basin.



0	0	0	0	0
0	3	2	2	0
0	0	11	0	1
0	0	1	15	0
0	2	5	24	0

Flow accumulation: number of cells draining into a given cell along the flow network

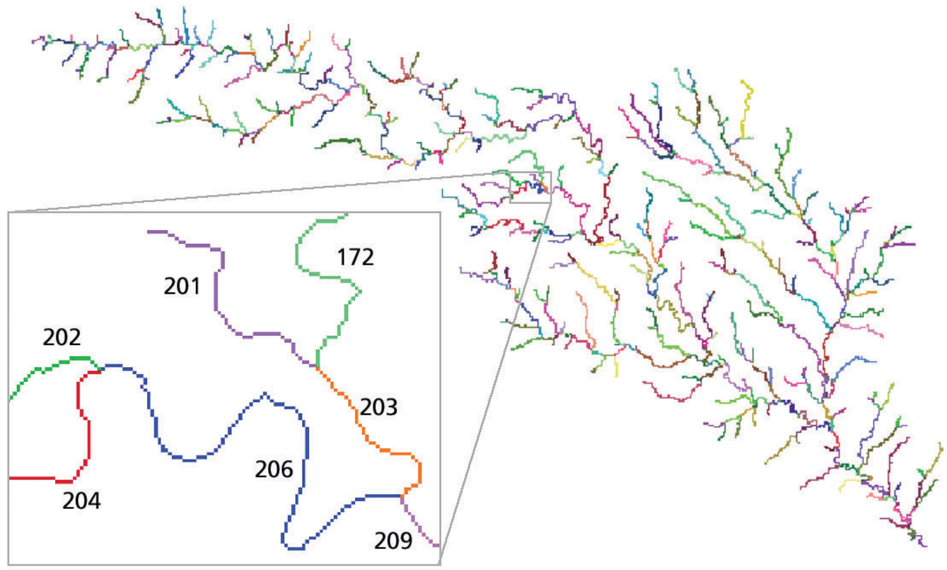


Flow accumulation grid of the San Marcos subbasin.

Stream definition using a threshold drainage area

With a flow accumulation grid, streams may be defined through the use of a threshold drainage area or flow accumulation value. A typical value to use with the National Elevation Dataset is 5,000 cells, which means that all cells whose flow accumulation is greater than 5,000 cells are classified as stream cells, while the remaining cells are considered the land surface draining to the streams. The cell values are assigned 1 where there is a stream and NODATA elsewhere. NODATA is a standard ArcGIS raster notation for a cell with an undefined value. Of course, any cell threshold value may be used, but below a threshold of 1,000 cells the resulting catchment area delineation becomes more questionable, especially in regions of flat terrain. A threshold flow accumulation of 5,000 cells with a 30-meter cell size means that it takes a drainage area of 5,000 x 30 x 30 = 4,500,000 m^2 or 4.5 km^2 to generate a stream.

At this point all the stream cells are labeled identically with a value of 1. The next step is to divide the stream network into distinct stream segments or links. In other words, instead of all the stream cells being 1,1,1,1, etc., for the first link they are labeled 1,1,1, etc., for the second link, 2,2,2, etc., and so on for succeeding links. Links are defined between stream confluences.

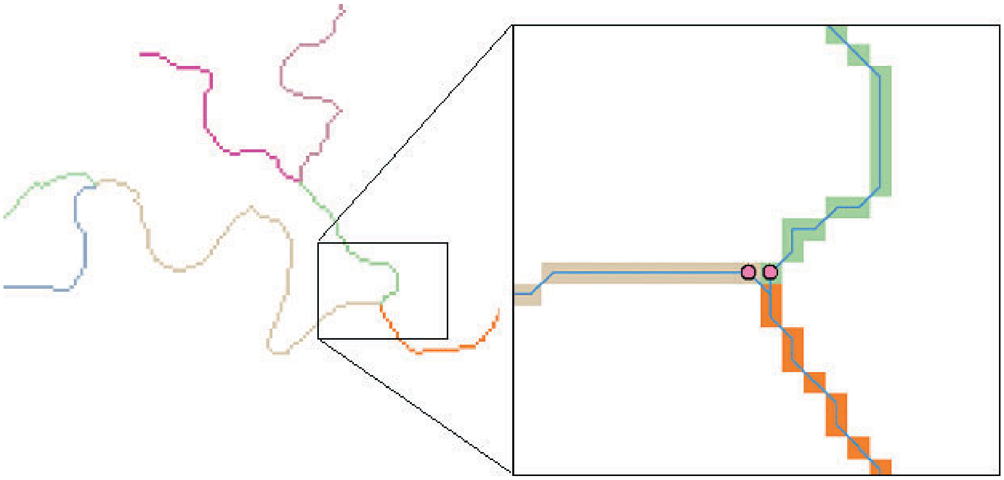


Stream links grid for the San Marcos subbasin. Each link has a unique identifying number.

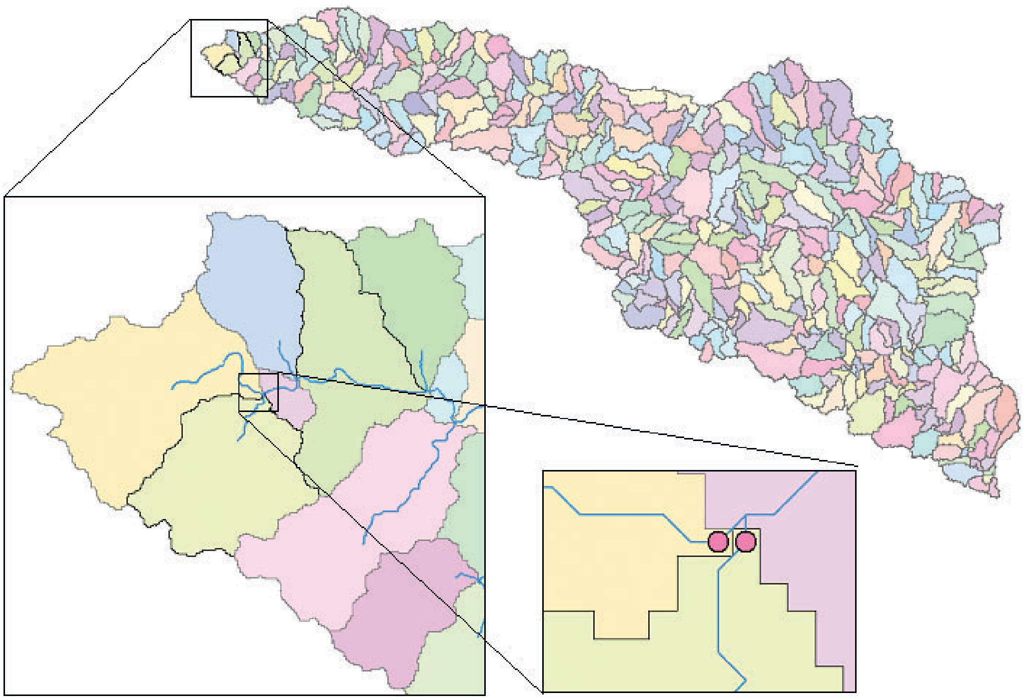
Catchments

To define catchments for each stream link, we use the flow direction grid to define the zone of cells whose drainage flows through each stream link. The results of the delineation are stored in a catchment grid, whose values are 1,1,1, and so on for cells flowing through the stream link 1 then 2,2,2, and so on for cells flowing through the stream link 2, continuing in this pattern for all links. In the Arc Hydro terrain processing functions, this number is carried forward through the grid operations and is called the GridID. The GridID serves to relate the catchments with the stream links from which they were created. This is the basis of the simple "area flows to line" concept of linking the land surface to the water flow system.

Once the catchment grid is defined, it can be converted into a set of catchment polygons using standard ArcGIS raster-to-vector conversion functions. This process may generate "spurious polygons," which are isolated single cells or small groups of cells connected along a diagonal flow direction with the rest of the catchment. The Arc Hydro toolset contains an automated procedure to detect the existence of such polygons and eliminate them by "dissolving" them into the correct parent catchment polygon. The stream links are also vectorized to form DrainageLines, and the outlet cells are vectorized to form DrainagePoints. The Catchment, DrainagePoint, and DrainageLine feature classes in Arc Hydro store the vector products resulting from terrain analysis using a digital elevation model.



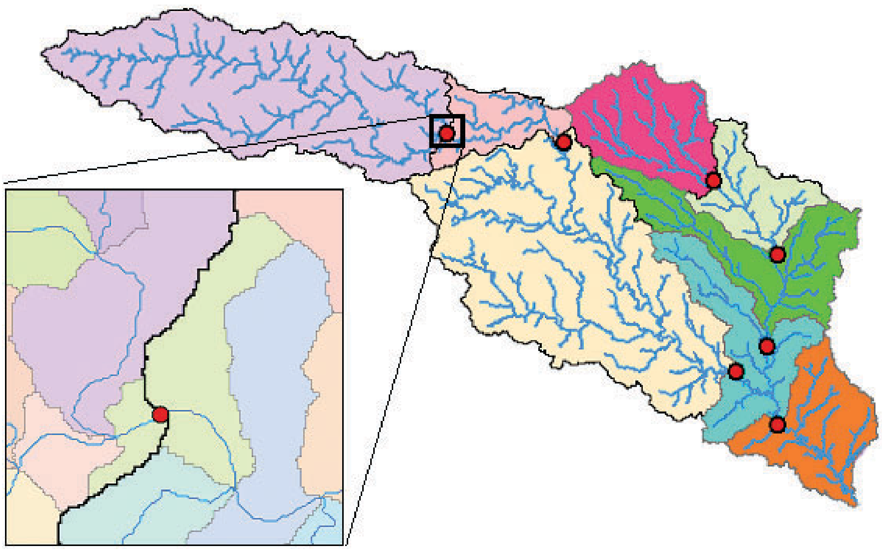
DrainageLines (blue) are drawn through the centers of cells on the stream links. DrainagePoints (magenta dots) are located at the centers of the outlet cells of the catchments.



Catchments, DrainageLines, and DrainagePoints of the San Marcos basin

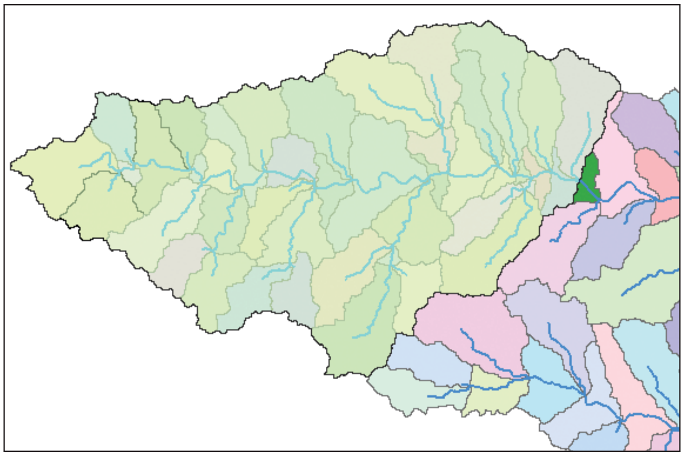
Watershed delineation

Catchment processing from a digital elevation model is a preliminary or preprocessing step to watershed delineation using the Arc Hydro watershed processing tools. The standard application for watershed delineation is to identify a series of points on the hydro network as watershed outlets, then divide and merge the underlying catchments to produce a watershed layout. There are two alternatives: to produce watersheds or to produce subwatersheds. When producing watersheds with the Arc Hydro toolset, the result is a watershed polygon for each outlet point that covers its entire upstream drainage area. Producing subwatersheds results in a polygon for each outlet point that covers only the incremental drainage area upstream of this outlet point and downstream of all others. The subwatershed polygon set is what most people think of when they see a watershed map, and this is what is contained in the Arc Hydro Watershed feature class.



Watersheds delineated from each USGS stream-gaging site within the San Marcos subbasin. Watershed outlet points may lie within the interior of a catchment. The most downstream watershed is the portion of the basin below the most downstream gaging station.

For any set of drainage areas, there exists three maps that can be produced: the total drainage area upstream of each outlet point, the subdrainage area upstream of this point and downstream of all other outlet points, and what is called in Arc Hydro the adjoint drainage area, which means the difference between the total drainage area upstream and the local subdrainage area. During Arc Hydro processing of catchments, the adjoint catchment is produced for each catchment, to simplify the later processing of watersheds.

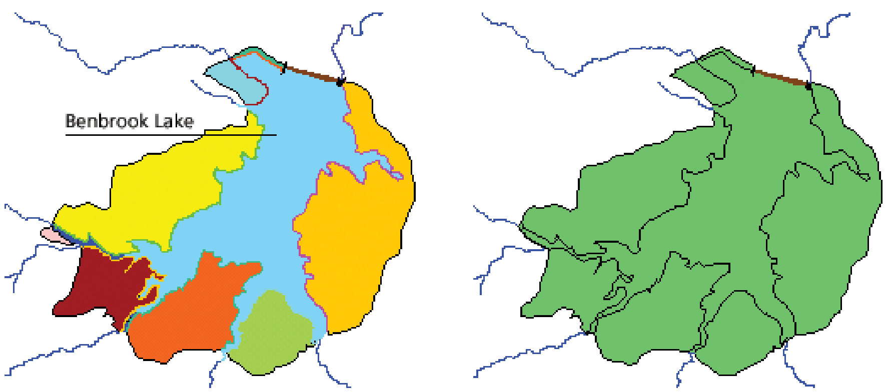


Adjoint catchment: the catchment colored dark green has an adjoint catchment shaded in light green. Together, these features define the total area draining to the catchment outlet.

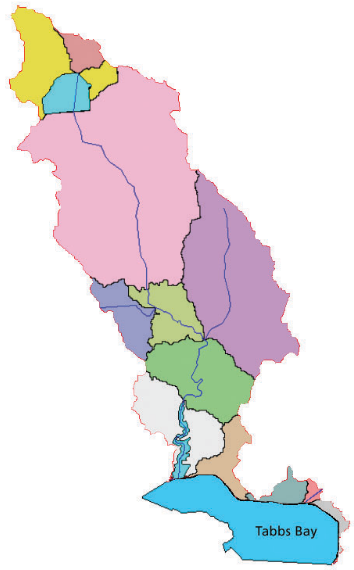
Watersheds draining to water bodies

The conventional method of delineating catchments and watersheds is to define their outlets by points on a stream network and delineate the area upstream of that point. Similarly, there may be a need to delineate the catchment or watershed of a lake or of a coastal bay segment. These tasks can be accomplished with ArcGIS, but they require special processing. For a lake, shoreline catchments can be delineated for each HydroEdge shoreline segment around the lake. If necessary, these shoreline catchments can be merged with the lake itself to form a single water body catchment.

To generate the total water body watershed, the shoreline catchments are merged with the catchments defined for all the HydroEdge flowlines draining into the water body.



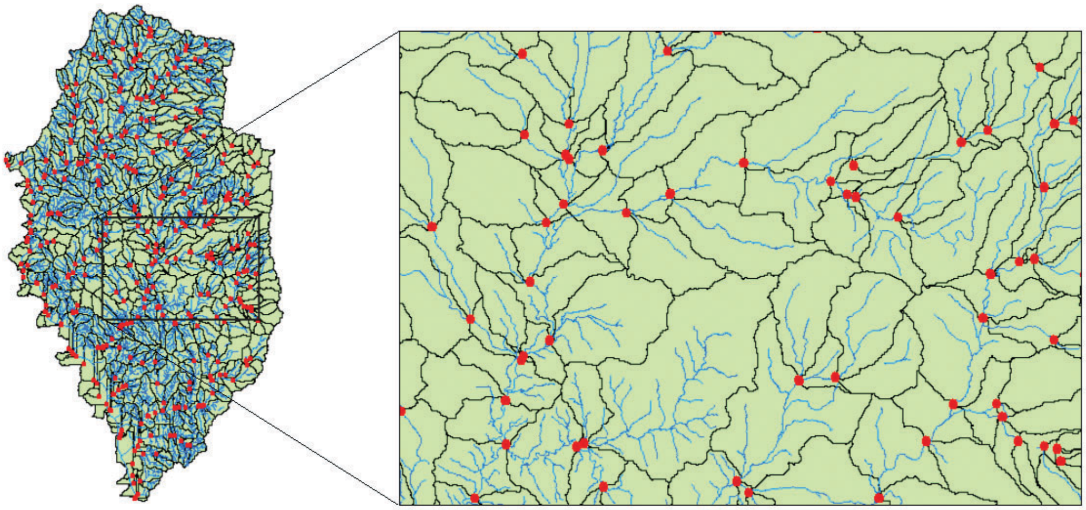
Drainage to a water body. The left map shows catchments of each shoreline segment. The right shows a water body catchment formed by merging the shoreline catchments with the water body.



Watershed draining to a bay segment formed by merging the shoreline catchments with catchments draining tributary streams

Store area outlets

One of the key challenges in assembling disparate data sets in an Arc Hydro geodatabase is that there may be one or several watershed or catchment layouts that the hydrologist wants to connect to the hydro network. These drainage areas may have been developed from a digital elevation model using the Arc Hydro tools, or they may have come from independent sources. In particular, it is a challenge to be able to combine raster-based catchment data sets with vector-based stream networks produced as part of standard hydrographic data sets. Each hydrographic reach may be associated with one catchment or sections of several catchments. Each catchment may have one, many, or even no reaches within it. The Arc Hydro toolset has a Store Area Outlets tool that facilitates linking drainage areas with the hydro network, and contains special provisions for dealing with the complications of combining raster and vector data.



These maps were created using the Arc Hydro Store Area Outlets tool to connect 646 DEM-based catchments with an independently derived vector-based stream hydrography through the use of hydro junctions at catchment outlets.

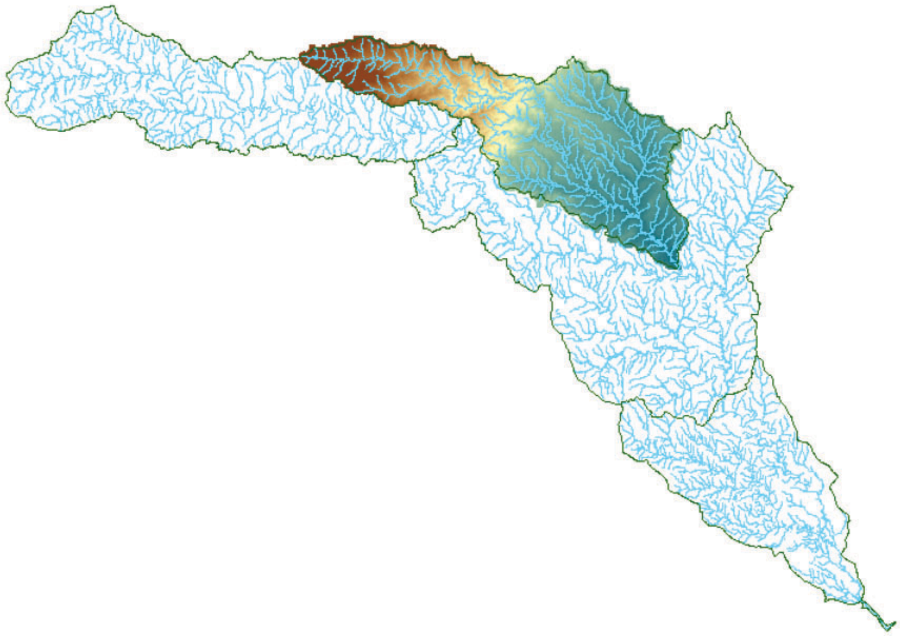
Regional analysis

As the precision of digital elevation models increases, their cell size decreases and the number of cells needed to cover a study region increases. The size of the digital elevation model may become so large that it is cumbersome or even impossible to process as a single data set. One solution to this dilemma is to resample the DEM so that it has larger cells, but this would reduce the precision of the watershed delineation.

The San Marcos basin requires a grid of 2,500 x 4,300 or about 11 million cells to cover it with the 30-meter cell size of the National Elevation Dataset. This is a reasonable number of cells for raster processing functions to operate efficiently. Typically, a digital elevation model covering one eight-digit hydrologic cataloging unit is reasonable (the San Marcos basin is one such unit). For the Guadalupe basin as a whole (four cataloging units), the required grid size is 70 million cells, which is still workable with a single grid but more cumbersome and time consuming, particularly if an analysis has to be repeated several times because of local changes to the data in one small area of the basin.

The Trinity basin in Texas requires a grid of 237 million cells to be covered, and that size is beyond the realm of reasonable processing times. In fact, completing the data development for a water availability modeling study of the Trinity basin using a single terrain grid required 11 continuous days of processing, and it was not clear if somewhere in the middle of this activity the processing had stopped for some unknown reason. Then there were a few changes to the input data and the whole exercise had to be repeated. This is completely impractical!

The solution to this problem is to combine the Arc Hydro vector and raster processing tools into a regional analysis where the study area is subdivided into subbasins, each of which is

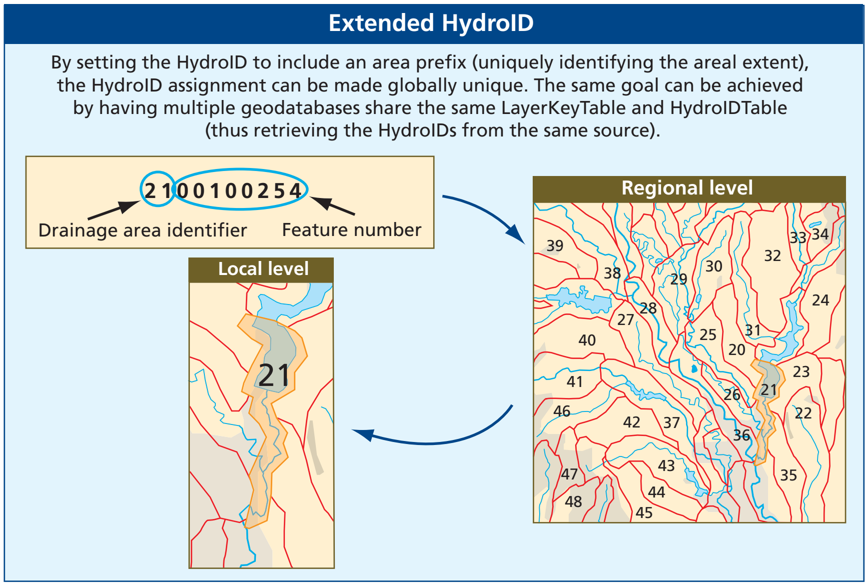


To do regional analysis, the terrain for each subbasin is analyzed separately, and the results are combined by linking them to the hydro network for the whole region.

processed separately with its own smaller digital elevation model. The results are combined to create a regional database.

The process of merging subbasin Arc Hydro geodatabases into a regional Arc Hydro geodatabase is facilitated by special treatment of the HydroID assignment to the features in each subbasin. If, in addition to the feature class number and the object number, the HydroID includes a subbasin number, all features within a subbasin will be uniquely identified within the subbasin geodatabase, and also within the merged regional geodatabase. Relationships between HydroJunctions and Watersheds, Waterbodies and MonitoringPoints formed at the subbasin level will still be valid at the regional level, since the HydroID values used to populate them stay the same.

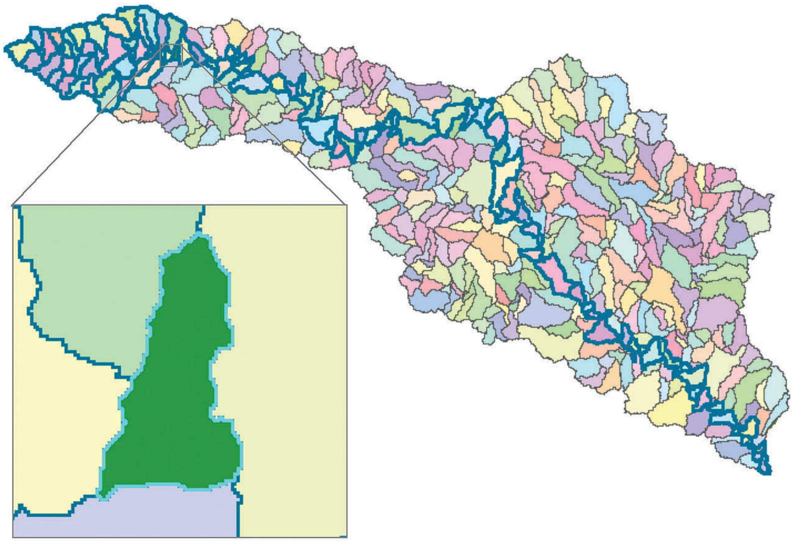
Combining a regional hydro network with locally delineated drainage areas is a powerful device for regionalization. For determining the upstream drainage area of a particular location within a subbasin, a trace is run upstream on the regional database using the hydro network to select all the upstream catchments for all subbasins, not just the ones in the local subbasin. The properties of the selected catchments can be accumulated downstream across hydro networks so that valid results are obtained both locally within the subbasin and also regionally. For the Trinity basin case, a total of 12 subbasins was used, one for each of the eight-digit hydrologic cataloging units in the basin. The results for the combined network–raster analysis were just as accurate as those obtained by using the laborious method of applying a single digital elevation model grid to the whole Trinity basin.



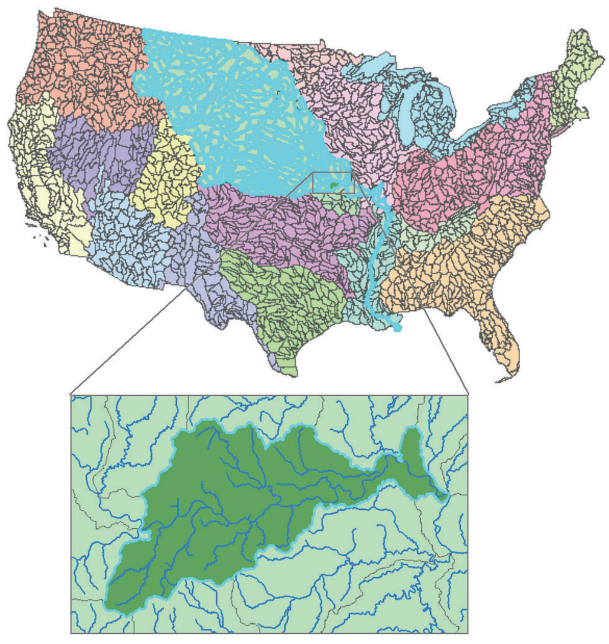
An extended HydroID to support regional watershed analysis

Watershed analysis

Once an Arc Hydro geodatabase has been developed, it may be used to analyze watershed and stream network properties and perform a limited number of hydrologic analyses. A key task for hydrologists is to summarize the properties of catchments or watersheds. This involves in some cases considering the properties of all the drainage areas upstream. Likewise, the outflow from any catchment or watershed affects all the downstream streams and rivers. An elegant capability has been built into Arc Hydro to do area-to-area navigation across drainage areas without having to use the hydro network tracing capabilities. This capability requires that each drainage area possess a NextDownID attribute, which is the HydroID of the next downstream drainage area. Then, using NextDownID on the drainage area, a trace can be run upstream or downstream for a selected drainage area, or the two traces can be combined to identify the "region of hydrologic influence" of a given drainage area, namely the set of upstream and downstream areas that either influence this area or are influenced by it.



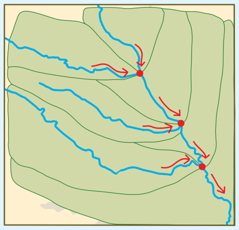
The region of hydrologic influence of a selected catchment in the San Marcos basin



Area-to-area tracing using Arc Hydro USA identifies a region of hydrologic influence for a selected hydrologic unit code watershed in the Missouri basin.

Consolidate

The goal of the Consolidate function is to summarize the properties of features in one class as attributes of features in a related class. For example, when one or several drainage areas flow to a particular HydroJunction, Consolidate summarizes the properties of the contributing areas as attributes of the HydroJunction.



Consolidate

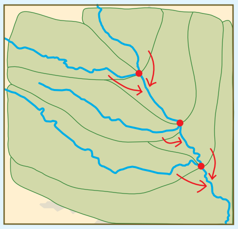
Suppose a given drainage area contains a number of components, such as Nexrad radar rainfall cells or land-use polygons, and we want to summarize their properties and attach the result to the drainage area as a new attribute. For example, we may want to find the total area of each particular land use within the drainage area. The Arc Hydro Consolidate function carries out this task. It assumes that the features to be summarized are connected by a formal relationship between them, for example by using the HydroID of the drainage area as the DrainID of all features in that area.

The Consolidate function uses the operators Average, Sum, Maximum, Minimum, Median, Count, Mode, and Standard Deviation to allow statistics of the selected features to be summarized if necessary. Area-weighted averages of the features can also be consolidated.

Another way to use the Consolidate function is to summarize the properties of all the drainage areas related to a HydroJunction as attributes of that HydroJunction. These might include the local drainage area, runoff, or pollutant loads from that area.

Accumulate

Drainage area properties are accumulated going downstream.



Accumulate

One of the most useful functions in the raster hydrology tools for GIS is the FlowAccumulation function. It sums up, going downstream, the number of cells upstream of each cell, or applies a weight, in which case the weights are summed for all upstream cells. For example, if mean annual precipitation is defined on each cell, it can be treated as a weight and summed using FlowAccumulation, so that for each downstream cell, the total volume of annual precipitation falling upstream of that cell can be determined. In this way the flow to be expected in the stream can be estimated.

In Arc Hydro, the catchments play the same role in the vector domain as cells do in the raster domain. Each catchment has one and only one downstream catchment. Hence, catchment properties can be accumulated downstream using the Arc Hydro Accumulate function, in the same manner as the FlowAccumulation function operated on a raster grid. Indeed, properties can be accumulated going downstream on any feature class for which a NextDownID is defined. This is how the DrainArea attribute of HydroJunctions is populated: the areas of all catchments or watersheds attached to upstream junctions are consolidated onto the junctions, then accumulated going downstream through the junctions to find total drainage area. This function is very useful for doing steady-state hydrologic analysis, in particular for defining maps of mean annual runoff and pollutant loadings for rivers and water bodies, which are needed for Total Maximum Daily Load analysis of water quality.

For more complex watershed analyses involving attributes varying through time, the Arc Hydro time series component and modeling methods using Visual Basic should be used. For more details, see chapters 7 and 8.

Data dictionary

These diagrams summarize the object and feature classes in the Drainage component of Arc Hydro, and their interrelationships. All the classes shown are available for loading data because they have inherited all the attributes from classes located above them in the UML hierarchy. The attributes shaded in blue are ESRI standard attributes, while those shaded in white are Arc Hydro attributes. The terms used here are defined in the glossary at the back of this book.

Simple feature class
Basin

Geometry *Polygon*
Contains M values *No*
Contains Z values *No*

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	
OBJECTID	OID							
Shape	Geometry	Yes						
HydroID	Integer	Yes			0			Unique feature identifier in the geodatabase
HydroCode	String	Yes					30	Permanent public identifier of the feature
DrainID	Integer	Yes			0			HydroID of the reference drainage area feature
AreaSqKm	Double	Yes			0	0		Area in square kilometers
JunctionID	Integer	Yes			0			HydroID of the HydroJunction at drainage outlet
NextDownID	Integer	Yes			0			HydroID of the next downstream basin
Shape_Length	Double	Yes			0	0		
Shape_Area	Double	Yes			0	0		

Basins are a set of administratively selected standard drainage areas usually named after the principal streams and rivers of a region.

See network features

Simple junction feature class
HydroJunction

Field name	Data type
OBJECTID	OID
Shape	Geometry
AncillaryRole	Small Integer
Enabled	Small Integer
HydroID	Integer
HydroCode	String
NextDownID	Integer
LengthDown	Double
DrainArea	Double
FType	String

Relationship class
HydroJunctionHasWatershed

Type *Simple*
Cardinality *One To Many*
Notification *None*

Forward label *Watershed*
Backward label *HydroJunction*

Origin feature class
Name *HydroJunction*
Primary key *HydroID*
Foreign key *JunctionID*

Destination feature class
Name *Watershed*

No relationship rules defined.

Simple feature class
Watershed

Geometry *Polygon*
Contains M values *No*
Contains Z values *No*

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length
OBJECTID	OID						
Shape	Geometry	Yes					
HydroID	Integer	Yes			0		
HydroCode	String	Yes					30
DrainID	Integer	Yes			0		
AreaSqKm	Double	Yes			0	0	
JunctionID	Integer	Yes			0		
NextDownID	Integer	Yes			0		
Shape_Length	Double	Yes			0	0	
Shape_Area	Double	Yes			0	0	

Watersheds are drainage areas defined by subdividing the landscape into units convenient for a particular analysis.

Unique feature identifier in the geodatabase
Permanent public identifier of the feature
HydroID of the reference drainage area feature
Area in square kilometers
HydroID of the HydroJunction at drainage outlet
HydroID of the next downstream watershed

Simple feature class
Catchment

Geometry *Polygon*
Contains M values *No*
Contains Z values *Yes*

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length
OBJECTID	OID						
Shape	Geometry	Yes					
HydroID	Integer	Yes			0		
HydroCode	String	Yes					30
DrainID	Integer	Yes			0		
AreaSqKm	Double	Yes			0	0	
JunctionID	Integer	Yes			0		
NextDownID	Integer	Yes			0		
Shape_Length	Double	Yes			0	0	
Shape_Area	Double	Yes			0	0	

Catchments are elementary drainage areas defined by subdividing the landscape according to a set of physical rules.

Unique feature identifier in the geodatabase
Permanent public identifier of the feature
HydroID of the reference drainage area feature
Area in square kilometers
HydroID of the HydroJunction at drainage outlet
HydroID of the next downstream catchment

Simple feature class
DrainagePoint

Geometry *Point*
Contains M values *No*
Contains Z values *No*

Field name	Data type	Allow nulls	Default value	Domain	Prec-ision	Scale	Length
OBJECTID	OID						
Shape	Geometry	Yes					
HydroID	Integer	Yes			0		
HydroCode	String	Yes					30
DrainID	Integer	Yes			0		
JunctionID	Integer	Yes			0		

A point at the center of a DEM cell which is the outlet of a DEM-derived drainage area.

HydroID: Unique feature identifier in the geodatabase
HydroCode: Permanent public identifier of the feature
DrainID: HydroID of the reference drainage area feature
JunctionID: HydroID of the HydroJunction at drainage outlet

Simple feature class
DrainageLine

Geometry *Polyline*
Contains M values *No*
Contains Z values *No*

Field name	Data type	Allow nulls	Default value	Domain	Prec-ision	Scale	Length
OBJECTID	OID						
Shape	Geometry	Yes					
HydroID	Integer	Yes			0		
HydroCode	String	Yes					30
DrainID	Integer	Yes			0		
Shape_Length	Double	Yes			0	0	

A line drawn through the center of cells on a DEM-derived drainage path.

HydroID: Unique feature identifier in the geodatabase
HydroCode: Permanent public identifier of the feature
DrainID: HydroID of the reference drainage area feature