[AM-04-066] Watersheds and Drainage Networks

Abstract

This topic is an overview of basic concepts about how the distribution of water on the Earth, with specific regard to watersheds, stream and river networks, and waterbodies are represented by geographic data. The flowing and non-flowing bodies of water on the earth's surface vary in extent largely due to seasonal and annual changes in climate and precipitation. Consequently, modeling the detailed representation of surface water using geographic information is important. The area of land that collects surface runoff and other flowing water and drains to a common outlet location defines a watershed. Terrain and surface features can be naturally divided into watersheds of various sizes. Drainage networks are important data structures for modeling the distribution and movement of surface water over the terrain. Numerous tools and methods exist to extract drainage networks and watersheds from digital elevation models (DEMs). The cartographic representations of surface water are referred to as hydrographic features and consist of a snapshot at a specific time. Hydrographic features can be assigned general feature types, such as lake, pond, river, and ocean. Hydrographic features can be stored, maintained, and distributed for use through vector geospatial databases, such as the National Hydrography Dataset (NHD) for the United States.

Keywords: analysis of surfaces, DEM, digital elevation model, hydrography, hydrology, rivers, watershed, watershed analysis

Author & citation

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Explanation

1. Definitions
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3. Drainage Networks
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1. Definitions

digital elevation model (DEM): A model representing the elevation of the land surface above mean sea level. The simplest and most used DEM is the regular grid where elevation values are assigned to points or cells uniformly distributed over a space as a two-dimensional matrix. Another type of DEM is the triangulated irregular network, which defines a flexible model with multiple resolutions for efficient representation of irregular land surface domains (de Azeredo Freitas et al., 2016).

drainage basin: A region that drains to a single outlet, which may also be called a pour point.

drainage network: A connected set of lines that represent surface-water drainage features, oriented in the direction of water flow. Drainage networks are typically extracted from a digital elevation model using a flow-accumulation model.

flow accumulation: A method of gauging contributing upstream flow by area.

flowline: A path tracing flow through a stream, river, or water body.

groundwater: All water that is below the ground surface and typically within the saturated zone of soil and rock where all the pores, cracks, and spaces are filled.

headwater: The upper reaches and source of a stream network.

hydrography: Branch of science that deals with the measurement, description, and representation of features on or near the earth's surface that contain, control, or are related to liquid or frozen water, especially the compilation of water maps.

hydrographic features: Bodies of flowing and non-flowing water on the earth's surface or features related to the control or movement of surface water. Hydrographic features include but are not limited to seas, oceans, lakes, ponds, streams, springs, glaciers, rivers, waterfalls, canals, pipelines, reservoirs, levees, bridges, dams, culverts, and gauges.

hydrologic unit: "The area of the landscape that drains to a portion of the stream network" (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/watershed-boundary-dataset).

hydrology: "the science that encompasses the occurrence, distribution, movement and properties of the waters of the earth and their relationship with the environment within each phase of the hydrologic cycle" (https://www.usgs.gov/special-topic/water-science-school/science/what-hydrology).

raster: "matrix of cells (or pixels) organized into rows and columns (or a grid) where each cell contains a value representing information" (https://desktop.arcgis.com/en/arcmap/10.3/manage-data/raster-and-images/what-is-raster-data.htm).

runoff: Stream flow contributed by precipitation.

shapefile: vector geospatial data file format that includes a shape field that stores the geographic coordinates of one or more features. The format was developed by Esri as a mostly open specification and can be used to represent point, line, and polygon features (Esri, 1998).

water cycle: The continuous movement of water above, on, and below the earth's surface. While moving through this cycle, water may change between solid, liquid, and gaseous forms. Also referred to as hydrologic cycle.

watershed: An area of land that drains toward a common outlet or pour-point location, such as the mouth of a river, or a pour-point terrain feature, such as a lake or an ocean.

2. Watersheds

A watershed is an area of land that collects precipitation, snow melt, or other surface water that drains toward a common outlet or pour-point location, such as the mouth of a river, or a pour-point terrain feature, such as a lake or an ocean. As precipitation collectors, watersheds are separated by physical barriers in the terrain like ridges, hills, and constructed dikes, levees, and dams. The physical barriers make up the watershed boundary. Precipitation is not the only means by which water enters a watershed. Water can enter or exit a watershed through groundwater flow, springs, and underground channels and rivers. Built water control structures (dams, levees, dikes, aqueducts, pipes, canals, and pumps) can have a big impact on the volume of water entering or exiting a watershed.

As can be imagined, watersheds vary dramatically in size depending on the location and type of pour-point feature. A relatively small watershed that drains the area around a single small drainage feature—such as a headwater creek or river—may be referred to as a catchment or subbasin (Figure 1). A larger watershed that drains the area around a network of streams that flows into a common river is typically referred to as a drainage basin. A drainage basin can be composed of thousands of smaller watersheds. The Mississippi River Basin flows to the mouth of the Mississippi River at the Gulf of Mexico (Figure 2). It encompasses thousands of upstream hydrologic features including rivers, lakes, ponds, constructed reservoirs, canals, dams, and pipelines. The Mississippi River Basin is one of the largest drainage basins in North America, covering over 1.1 million square miles (Kammerer, 1990).

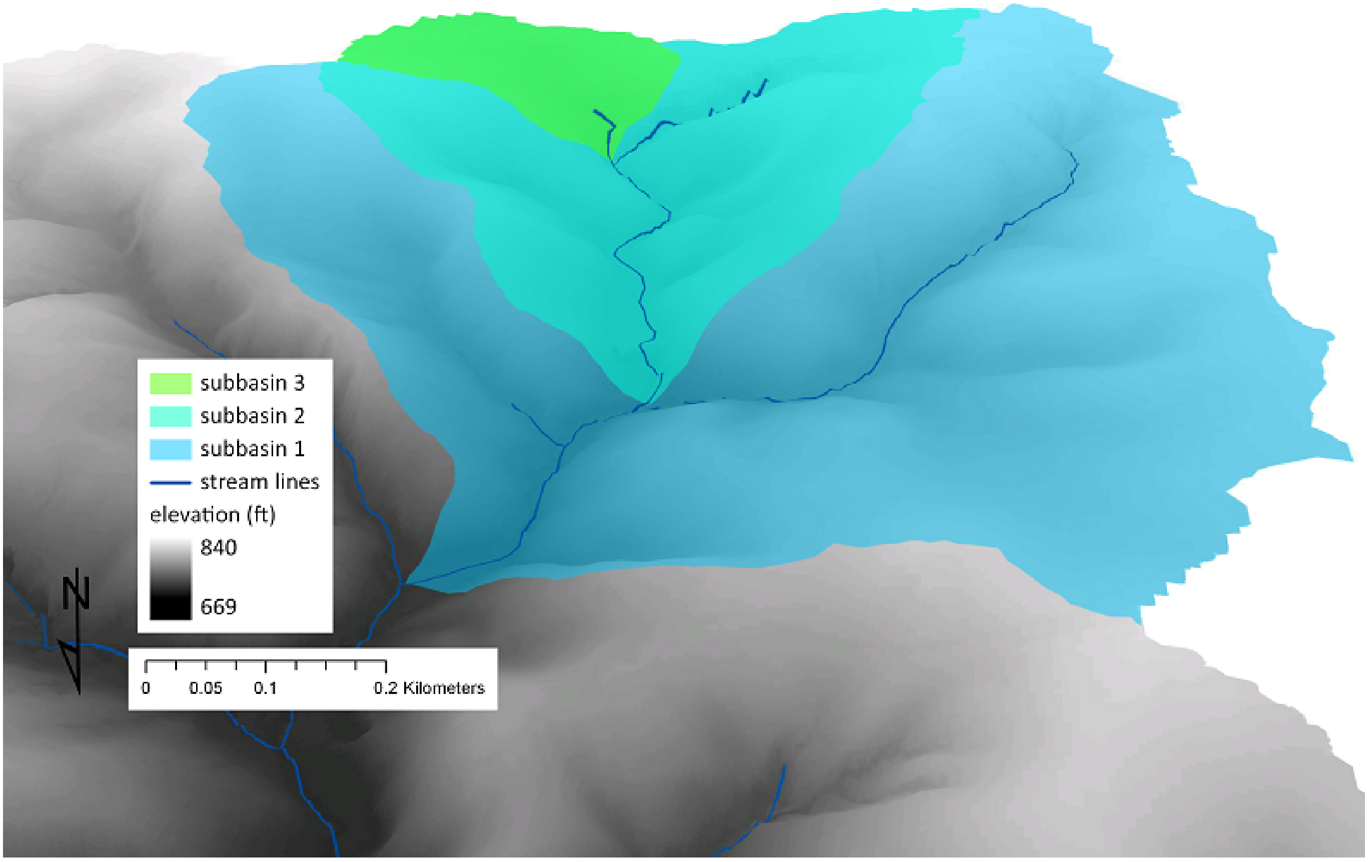


Figure 1. Hierarchy of subbasin watersheds derived from an elevation model. Subbasin 3 watershed drains to the mouth (pour point) of a single headwater stream feature. Subbasin 3 is part of the larger watershed, subbasin 2, that drains three stream sections and forms part of larger subbasin 1. Source: authors.

Figure 2. Figure 2. Mississippi River Basin. Source: Wikipedia Commons. (Image from Wikipedia Commons. https://en.wikipedia.org/wiki/en:GNU_Free_Documentation_License)

Watersheds are naturally arranged in a hierarchy based upon surface water drainage patterns. Examples of headwater drainage channels and associated watersheds are shown in Figure 1. Watersheds that drain headwater features are smaller than watersheds formed for downstream features because downstream watersheds encompass all headwater and other subbasins that are upstream (Figure 1).

2.1 Watershed Boundaries

The delineation of drainage areas, watersheds, or basin boundaries is an important process that can impact investigations of local and regional ecology, epidemiology, hydrology, flood modeling, urban planning, and political boundaries (Griffin, 1999). Various techniques and strategies exist for delineating watershed boundaries (Eash et al., 2018; Lindsay, 2005). Historically, boundaries were defined by traditional field surveys and by deriving watershed divides from other bisecting ridges, saddles, and contour lines of equal elevation (Berelson et al., 2004).

Presently there are numerous open source and proprietary GIS tools for generation of drainage area boundaries using a digital elevation model (DEM). A DEM may be a raster with evenly spaced symmetrical cells or a triangulated irregular network (TIN), and researchers argue that each has merits in hydrologic modeling (de Azeredo Freitas et al., 2016). In addition to options for DEM type, there is a wide range of DEM spatial resolutions currently available. Therefore, care should be taken in selecting the input data for generating drainage basin features. A DEM with a resolution of 30m or greater may be ideal for region- and continent-scale basin definition while 1-10 m resolution is generally beneficial for smaller subbasins. Yet even within a range of resolutions such as 1-10 m, it has been shown that the resulting drainage basin boundaries can vary a great deal (Woodrow, Lindsay, and Berg, 2016).

The choice of resolution can aid in obtaining appropriate feature complexity and processing time. Production artifacts, sinks, waterbodies, and culvert-type flow obstructions in the DEM should also be addressed before watershed boundary delineation. To address the presence of sinks, or low points that would catch surface water, a pit-fill algorithm is often applied to the DEM before generating the drainage area boundaries. The resulting “filled” DEM will more accurately depict the contributing surface area to an outlet point because cells within and contributing to a sink will not be counted as contributing to a downstream flow accumulation for a watershed. Another DEM conditioning step that may be useful is channel burning, that is, lowering the DEM surface where channels are known to exist, such as under bridges. Smoothing may also be used as a preprocessing step to simplify the topography and generalize the flow patterns. It must be noted that any alteration of a DEM adds potential error and generally makes the DEM less accurate (Woodrow, Lindsay, and Berg, 2016; Jasiewicz and Metz, 2011).

Many drainage basin delineation tools require two inputs, a flow direction raster and a data source that represents the outlet of a drainage area. A flow direction algorithm estimates the direction of flow from each cell within a DEM. Although several flow routing algorithms are available (Wilson et al., 2008), two common flow direction algorithms described here are D8 and D-infinity. Generally speaking, the D8 method directs cell flow to the lowest elevation cell of the surrounding 8 cells (O’Callaghan and Mark, 1984), while the D-infinity method distributes flow between up to two cells using the direction of steepest downward slope on a surface triangulated from the 9-cell patch centered on the given pixel (Tarboton, 1997). Flow direction values may be generated in a dedicated tool or as a step in a flow accumulation tool. Flow accumulation algorithms generate a raster with cell values representing the number, area, or weighted value of cells that flow into each cell based on flow direction. Thus, cells along a ridge will have very low or zero accumulation, while valley cells will have increasing accumulation values with increasing up-slope area (Figure 3). Flow accumulation rasters are often used to model stream networks. Typically, a drainage area is specified as the minimum contribution to the formation of a stream. All accumulation cells with values greater than the threshold are considered within the stream network.

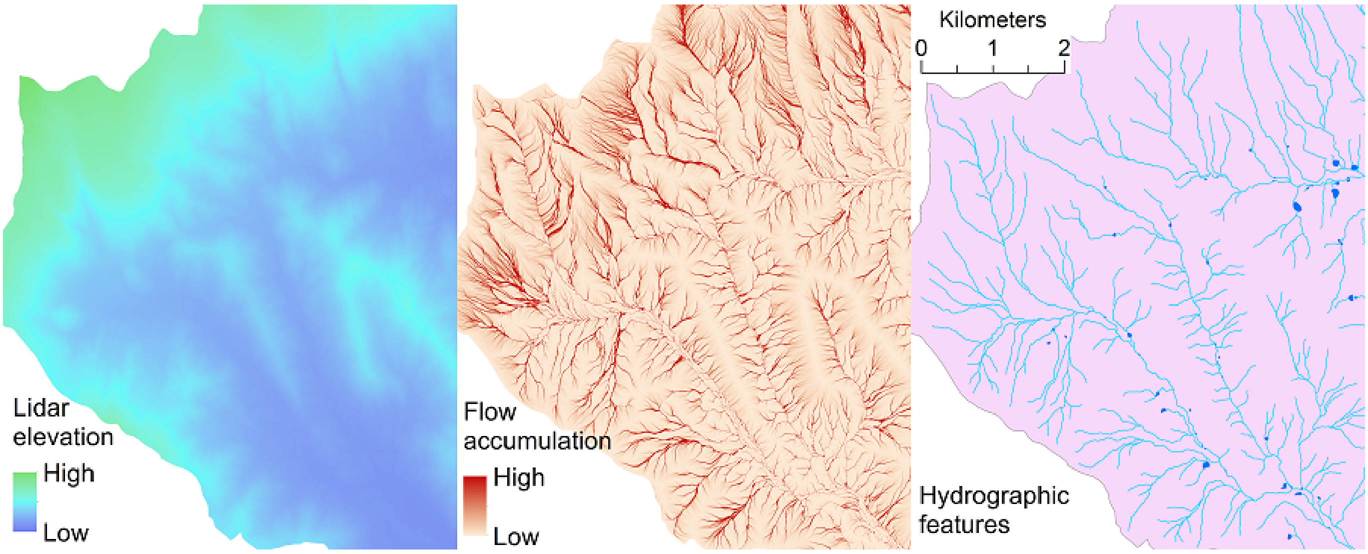


Figure 3. Display of elevation model derived from lidar and the associated flow accumulation raster data and hydrographic features for a section of the Covington River watershed in Virginia. Source: authors.

Stream network features are commonly used to designate watershed outlets, and thereby identify contributing areas that drain to each outlet. As explained in the next section, tools exist to automatically derive a stream network and identify outlet points from the network structure. Alternatively, a channel or stream network can be interpreted from historic maps or image data. The junctions of the channel network may be used as outlet points for the delineation of catchments (Figure 4b). In other cases, individual point features may be used as pour points to delineate specific catchments, or to determine flow estimates related to unique locations such as stream gauges or culverts. Other techniques simply designate the lowest elevation point as an outlet point for a defined section of a DEM. Once raster drainage areas are defined, it is a simple process to convert them to vector polygonal features for further analyses or display.

3. Drainage Networks

The complex interaction of water with diverse terrain conditions forms a wide variety of drainage environments that give rise to various arrangements of surface water features. Water flowing over the terrain erodes a network of drainage channels onto the surface, which transports water and sediments downhill. A drainage network is a connected set of surface-water drainage channels that are oriented in the downhill direction with the flow of water. The level of connectedness in a drainage network depends on terrain conditions. The pattern of a drainage network is largely a reflection of the type and arrangement of subsurface bedrock, sediment characteristics, and hydrologic character (Muller and Oberlander, 1978). Understanding drainage patterns can assist in the proper classification and management of land resources (Clubb, Bookhagen, and Rheinwalt, 2019).

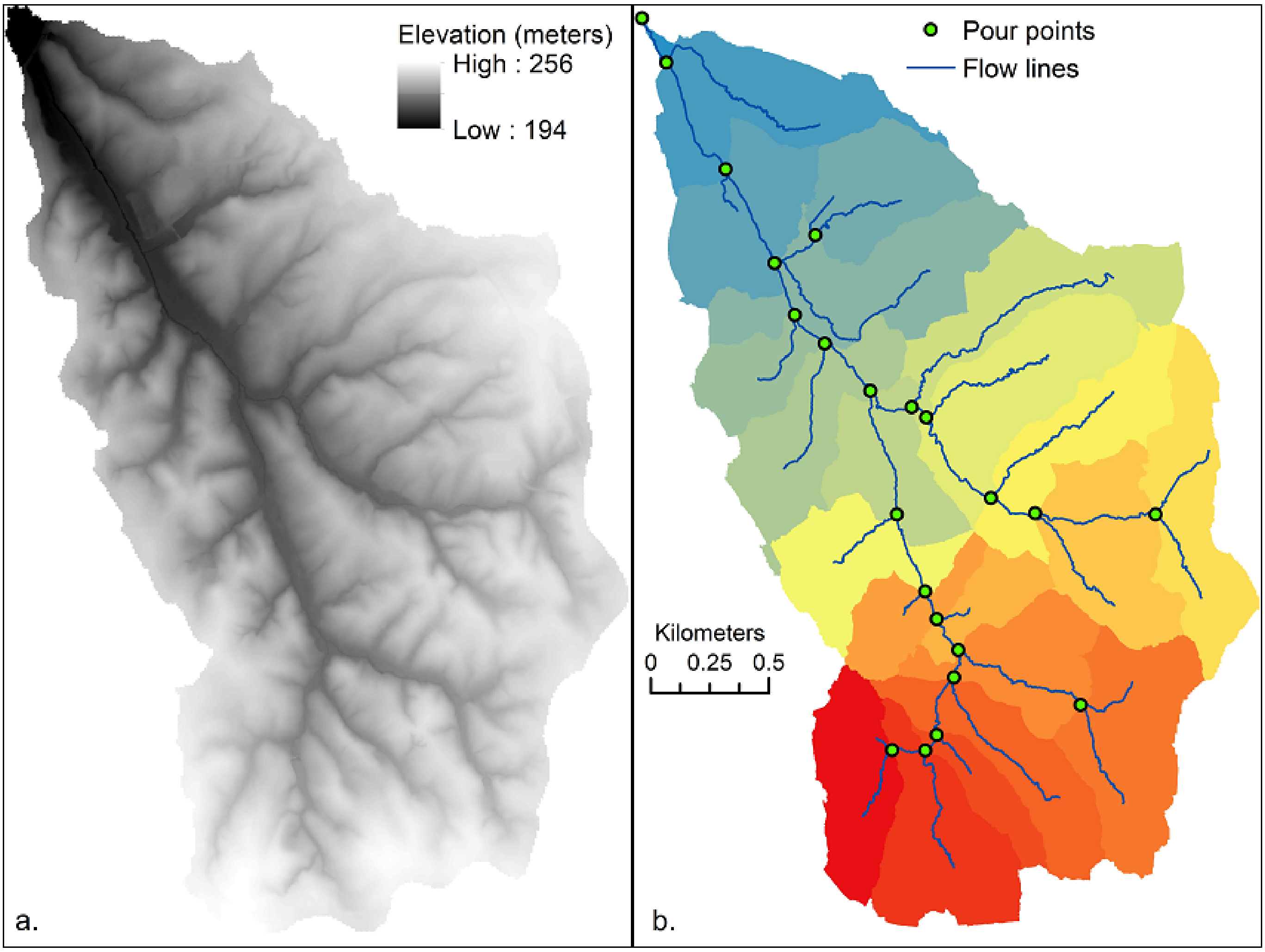


Figure 4. A digital elevation model (a) and flow lines with pour points at channel intersections (b). The pour points were used to delineate the subbasins of different colors. Source: authors.

A drainage network of linear features can be extracted from a DEM (Figure 4a) using a flow-accumulation model. Numerous hydrologic analysis and geographic information system (GIS) tools are available to assist with the process of deriving a drainage network from a raster DEM (Tarboton and Ames, 2001; Wilson et al., 2008). As described in the previous section, a common approach involves conditioning a DEM, and then generating flow direction and flow accumulation information for each cell in the DEM. Conditioning an elevation model fills spurious depressions that may obstruct continuous downhill flow over the surface, where spurious depressions are relatively small anomalous depressions. A threshold value for flow accumulation, or upstream drainage area, can be designated as the minimum contributing area to form a stream pixel (raster cell). All flow accumulation pixels with values greater than the threshold are considered part of the stream network, which subsequently may be converted to vector features (Figure 4b). Threshold values for stream formation must be tailored to local geomorphic conditions. The least-cost path algorithm is another effective approach for routing flow, generating flow accumulation, and extracting drainage networks from elevation models (Ehlschlaeger, 1989; Metz, Mitasova, and Harmon, 2011). The least-cost path method does not require DEM conditioning, and some cases have shown the method can generate more accurate drainage networks than other approaches that condition the DEM (Metz, Mitasova, and Harmon, 2011; Jasiewicz and Metz, 2011).

All automated methods to form stream networks require subsequent verification of the features, which typically involves interpretation of high-resolution image data, or more rarely may be completed through costly field surveys. Subbasin watersheds associated with the drainage network features can also be automatically generated using existing tools (Jenson and Domingue, 1988; Sathyamoorthy, 2008; Lindsay, 2016) as shown in Figure 4b.

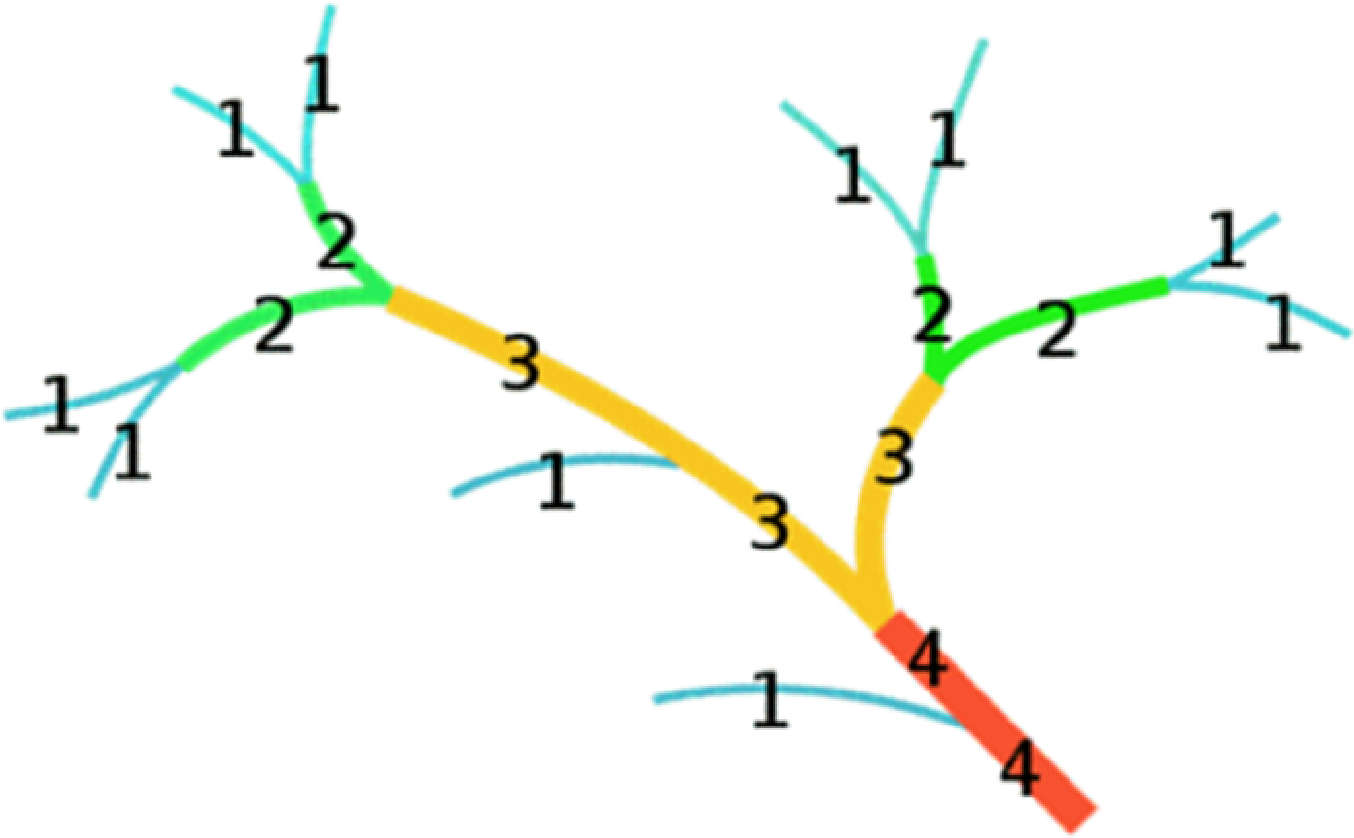


Figure 5. An example of the Strahler ordering of streams. Source: U.S. Geological Survey (2020a).

Drainage networks have inherent attributes like length, sinuosity (path length divided by end-to-end distance), flow accumulation values, and slope (drop in elevation over length of feature). Another inherent attribute is stream order, yet this is not so easily defined as slope. Order refers to placement in a sequence. With complex stream networks, sequence can be hard to determine yet holds important information such as upstream complexity and likelihood of flow presence. The most common stream ordering method is the Strahler order (Figure 5) (Strahler, 1952). The Strahler order assumes a fixed, connected network of streams and begins the order at the headwaters or smallest streams making up the periphery of the network closest to the catchment boundary. Headwater streams, where flow initiates in a channel, are designated 1st order. Successive designations are identified at confluences, where channels come together. If two streams of the same order converge, the downstream channel is designated with the next higher order as in Figure 5. The above-mentioned attributes can be calculated in a GIS environment (Neteler and Mitasova, 2013), though stream order is more involved than other calculations and requires several steps. There are many other attributes that may be associated with a stream feature such as average width, discharge, permanence (likelihood of water being present in a channel), or riparian structure. Such attributes often require ancillary data, like field observations, to be determined, and are functions of numerous landscape factors and therefore complicated to constrain. A more thorough treatment of the subject can be found in the work of Vieux (2001).

4. Hydrography and Watershed Datasets and Representation

Water is continuously moving around the planet and changing between gas, liquid, and solid forms. The constant movement of water above, on, and below the earth's surface is referred to as the water cycle, or the hydrologic cycle (Figure 6). A variety of factors control how water is distributed on the earth in different storage compartments (surface water, soil, groundwater, etc.). The flowing and non-flowing bodies of water on the earth's surface vary in spatial extent largely due to seasonal and annual changes in climate and precipitation. The cartographic representations of these features are referred to as hydrographic features and consist of a snapshot of the surface-water features at a specific time. Hydrographic features form an important reference for hydrologic studies, where hydrology is "the science that encompasses the occurrence, distribution, movement and properties of the waters of the earth and their relationship with the environment within each phase of the hydrologic cycle" (https://www.usgs.gov/special-topic/water-science-school/science/what-hydrology).

The types of hydrographic features (e.g., lake, pond, river, creek) that form in different landscapes depend on the slope of the terrain and interaction of available water with the earth's surface. A soil's characteristics, such as type, depth, and saturation, control the volume of water that flows over (as runoff), drains through, or is absorbed by the soil. Bedrock geology, depth, and configuration also affect the volume of water that can infiltrate the soil to the bedrock and be stored in an aquifer. In addition, vegetation type and density can impact runoff volume and the amount of water that plants absorb and transpire. In general, surface water from precipitation or snow-melt flows over the terrain following gravity to accumulate in drainage channels and further downhill to form rills, creeks, and eventually streams and rivers where larger watersheds support larger volumes of water flow. Large rivers are often found in relatively flat areas where flood plains have formed over thousands of years of erosion and deposition from streams and rivers meandering over the landscape. In humid environments wetlands, swamps, and marshes may exist at lower elevations where the water table is near the ground surface and where the terrain is relatively flat. Likewise, estuaries may exist in similar conditions in and around coastal areas. Lakes and ponds form in terrain depressions where conditions favor accumulation and retention of surface or groundwater.

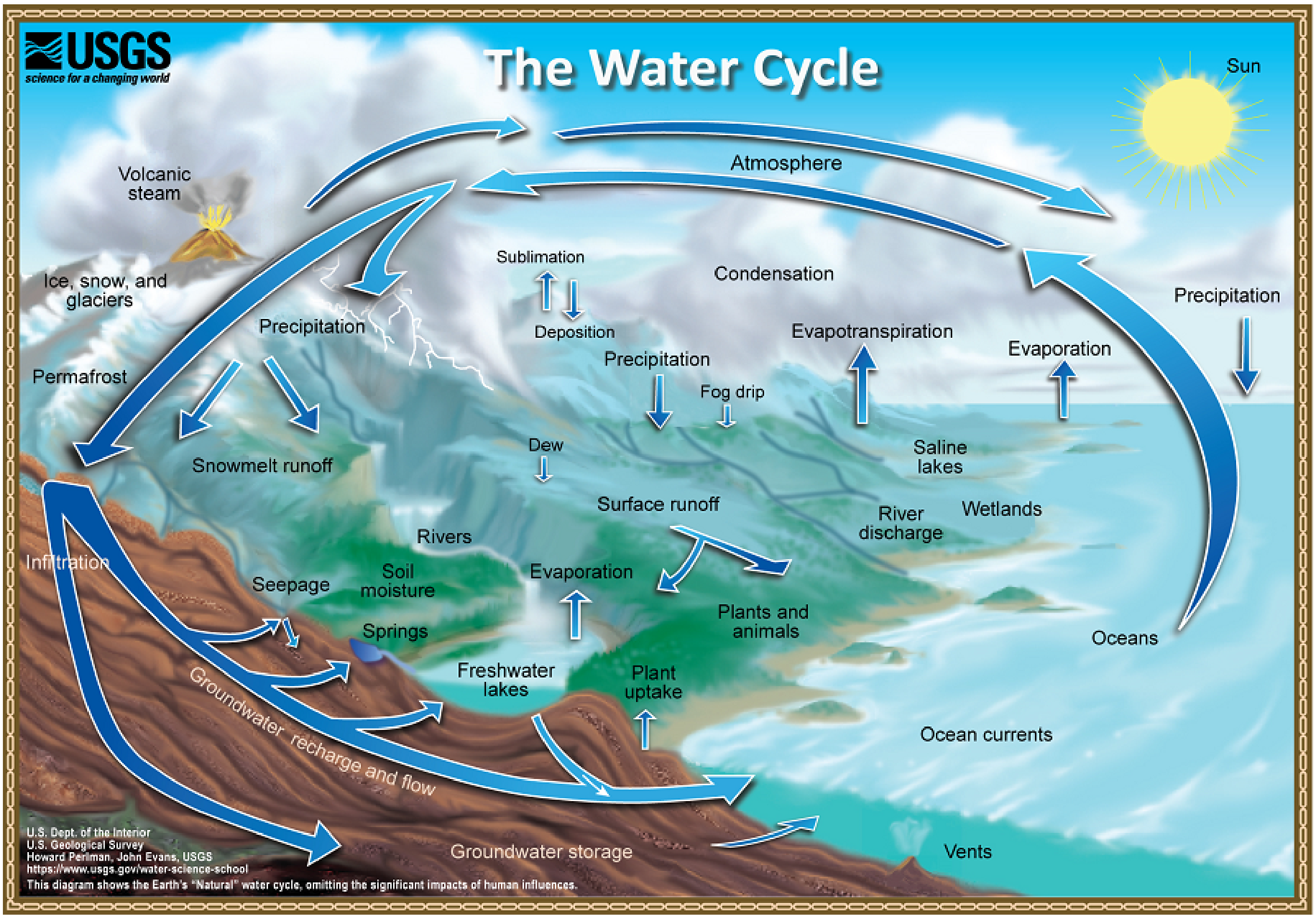


Figure 6. The natural water cycle. Source: U.S. Geological Survey, https://www.usgs.gov/special-topic/water-science-school/science/fundamentals-water-cycle.

The importance of water to society and ecology makes cataloging and mapping of surface hydrography important. Resulting data can be used to understand costs and benefits of development or forecast future availability or risks (Simley and Carswell, 2009; Wright et al., 2012; Poppenga, Gesch, and Worstell, 2013; Maidment, 2016; Schultz et al., 2017; Terziotti et al., 2018). Examples of cataloging hydrology in a GIS-compatible format include the Canadian National Hydrographic Network (NHN), the India Water Resources Information System (India-WRIS), the European Catchments and Rivers Network System (ECRINS), and the United States' National Hydrography Dataset (NHD).

Hydrographic data can be represented in many ways. One goal of the above-mentioned databases is to represent hydrographic data in a uniform manner to facilitate repeat analysis of the data in a standard way. Important factors for standardized data structure are feature type such as polygon vs line, metadata structure such as reference system tables and feature identifiers, and feature-related semantics. Examples of systems developed for broad hydrographic feature representation standards include Arc Hydro (Maidment, 2002), Open Geospatial Consortium (OGC) Hydrology Domain Working Group, and the Global Runoff Data Centre (GRDC) HY Features framework.

4.1 United States Hydrography Datasets

The National Hydrography Dataset (NHD) is a comprehensive vector database of hydrographic features for the United States that is managed by the U.S. Geological Survey (USGS) and partner organizations (U.S. Geological Survey, 2020b). Within the conterminous United States, the NHD High Resolution (HR) is a multi-scale dataset of hydrographic features compiled from the best available data sources having scales of 1:24,000 or larger (1:63,360 or larger in Alaska). Features are separated into five feature classes – NHDArea, NHDFlowline (flowline), NHDWaterbody (waterbody), NHDLine, and NHDPoint – each containing a subset of NHD feature types represented with the same geometrical shape type. All polygonal features are stored in the NHDWaterbody and NHDArea feature classes. NHDWaterbody represents features such as lakes, ponds, and reservoirs. The NHDArea feature class includes, among other features, broad river features that are not suitably represented as a single-line feature. The flowline feature class contains features of type artificial path, canal/ditch, coastline, connector, pipeline, stream/river, and underground conduit. An artificial path represents a flow path through a polygonal water feature that is connected to other flowline features, and a connector represents a path where surface flow is known to exist but was not included in the source material (Figure 7). Each flowline feature is represented as a polyline, which is a shape object defined by a series of line segments that can be stored in a shapefile. A visibility attribute allows users to filter NHD HR feature content to eight scales (1:24,000; 1:50,000; 1:100,000; 1:250,000; 1:500,000; 1:1,000,000; 1:2,000,000; and 1:5,000,000) for cartographic or analysis purposes (U.S. Geological Survey, 2020c).

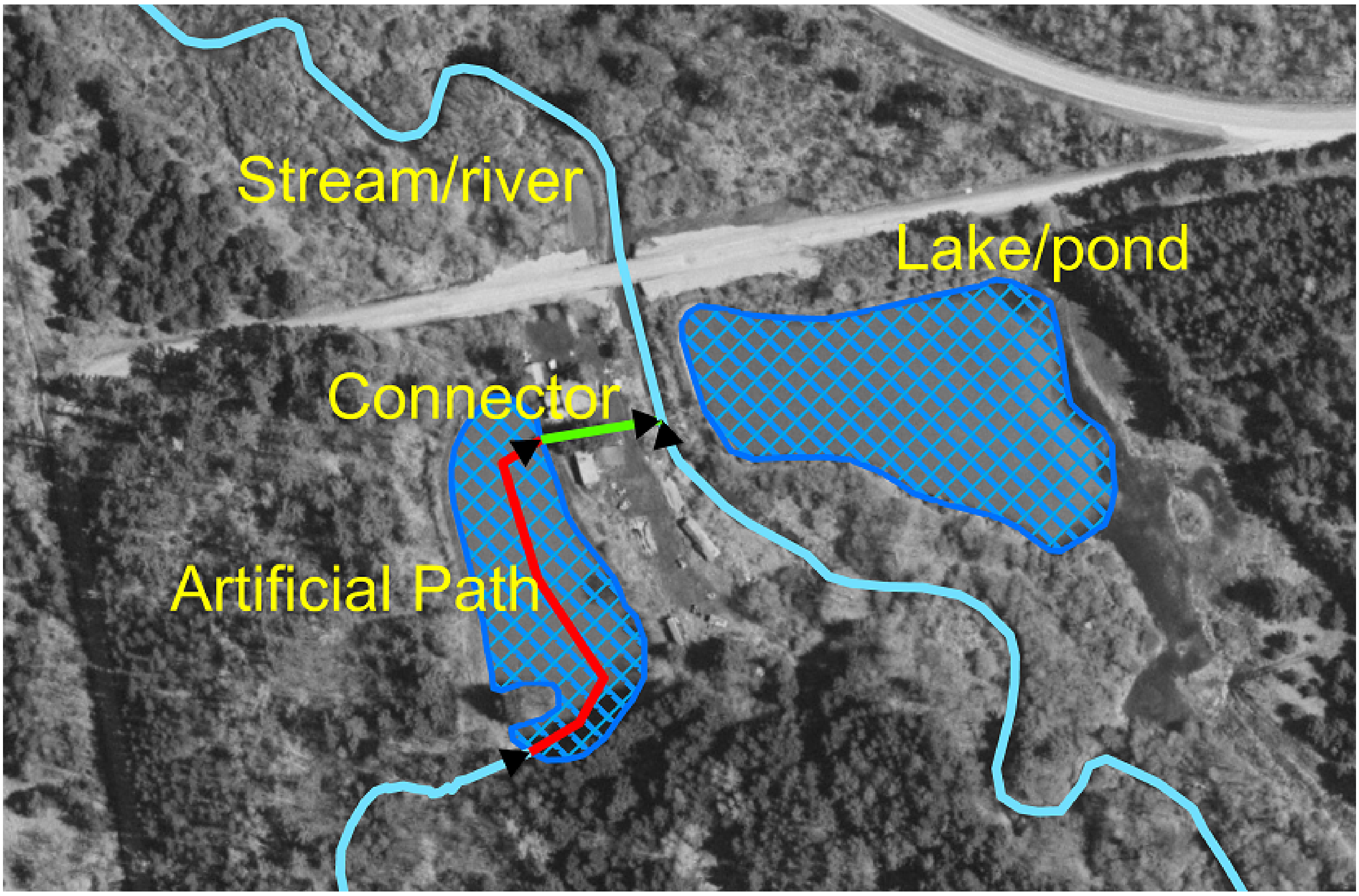


Figure 7. Example of hydrographic feature types stored in the National Hydrography Dataset. Source: authors.

In addition, NHDPlus HR, which is available for much of the country, provides a model for the flow of water across the landscape based on the streams from the NHD HR flowline network, and elevation features from the USGS 1/3 arcsecond DEM (approximately 10 m resolution). See U.S. Geological Survey (2020d). Drainage catchments and flow volume estimates are furnished for all flowline features within the NHDPlus HR, along with many other data that can assist hydrologic and science investigations.

The Watershed Boundary Dataset (WBD) for the United States is a companion dataset to the NHD HR that subdivides the nation into hydrologic unit (HU) watersheds. In general, a hydrologic unit is a drainage area or basin delineated to nest in a multi-level, hierarchical drainage system. The WBD forms a standardized system for collecting and managing hydrologic information for the nation (U.S. Geological Survey, 2020e). Development and maintenance of the WBD has been an ongoing effort since the mid 1970s, and guidelines and procedures for the collection and delineation of the WBD are now available (U.S. Geological Survey and U.S. Department of Agriculture, 2013). In general, the WBD provides a nested hierarchy of watersheds that are subdivided into smaller and smaller HUs. As seen in Figure 8, the country is subdivided into the largest watersheds that are assigned unique 2-digit codes, referred to as HU2 codes, of which 22 exist. HU2 watersheds are subdivided into smaller watersheds and assigned unique 4-digit HU4 codes, which adopt the first two digits from the parent HU2. For instance, HU2 region 06 is subdivided into four HU4 subregions: 0601, 0602, 0603, and 0604. HU watersheds have been delineated up to the HU12 level, which are available for the entire country. Table 1 shows the different levels of HU watersheds that are available for the country, along with the average area and approximate number of watersheds at each level. Over 100,000 watersheds exist at the HU12 level.

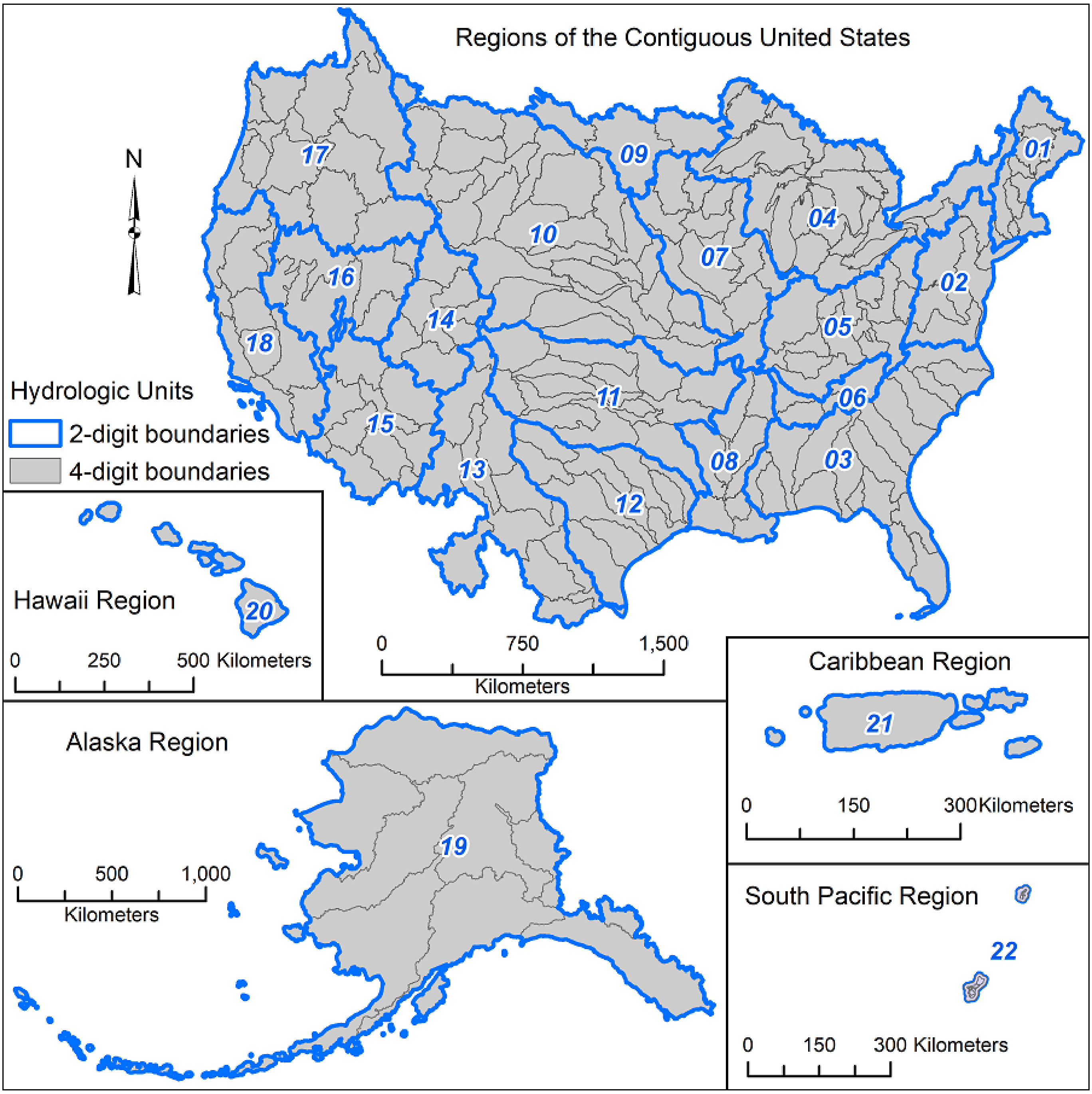
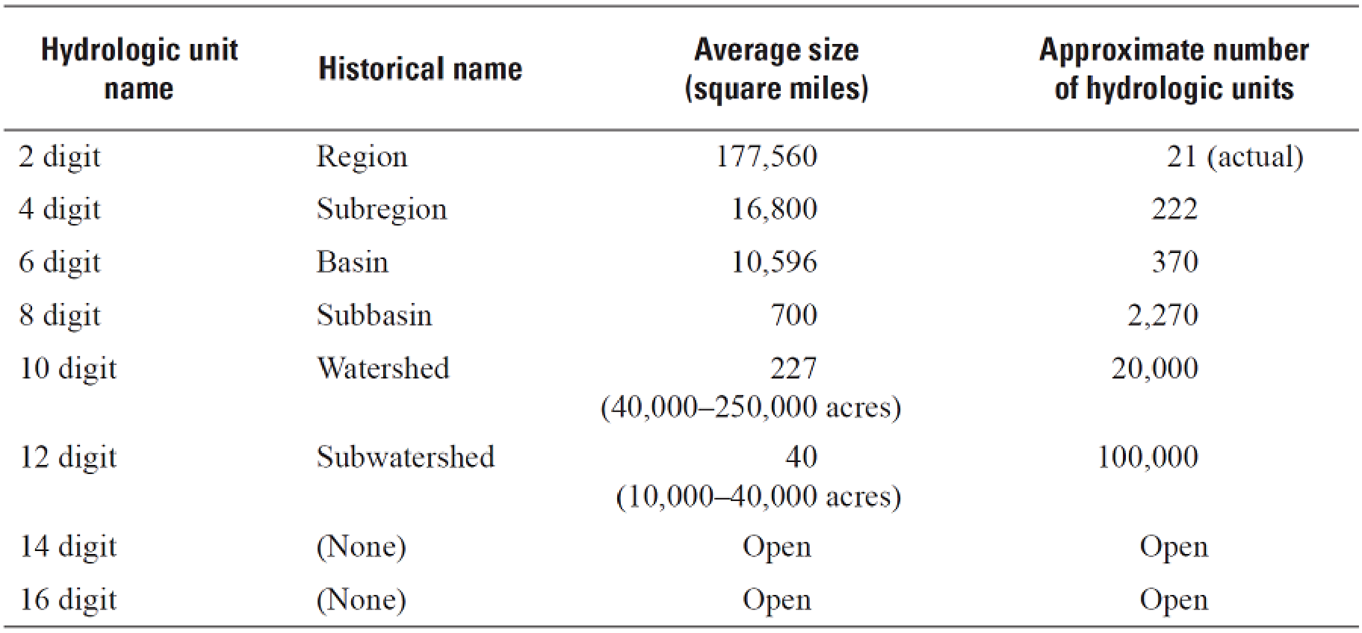


Figure 8. Hydrologic Unit (HU) watershed boundaries for the United States from the Watershed Boundary Dataset (WBD). The first two levels of the nested hierarchy of HU watersheds are shown with the 2-digit region (blue) and 4-digit subregion (gray) boundaries. Full watershed boundaries are displayed, including where they overlap international borders. Source: authors.

Table 1. Levels, sizes, and numbers of hydrologic units in the U.S. Geological Survey Watershed Boundary Dataset (U.S. Geological Survey and U.S. Department of Agriculture, 2013). Original 2-digit hydrologic units did not include region 22 for Guam and American Samoa (Seaber, Kapinos, and Knapp, 1994).



Hydrologic unit name	Historical name	Average size (square miles)	Approximate number of hydrologic units
2 digit	Region	177,560	21 (actual)
4 digit	Subregion	16,800	222
6 digit	Basin	10,596	370
8 digit	Subbasin	700	2,270
10 digit	Watershed	227 (40,000–250,000 acres)	20,000
12 digit	Subwatershed	40 (10,000–40,000 acres)	100,000
14 digit	(None)	Open	Open
16 digit	(None)	Open	Open

4.2 Hydrologic Feature Representation

HY_Features is a hydrologic feature reference system from the Global Runoff Data Centre (GRDC) (Dornblut and Atkinson, 2013) that has been adopted by the OGC. The GRDC is a program under the World Meteorological Organization (WMO) and focusses on maintaining a river discharge database and making it available to stakeholders for research and policy studies. The model is a system for referencing unique hydrographic features regardless of scale and linking them to associated hydrologic features or other data (Blodgett and Dornblut, 2018):

“The OGC Surface Hydrology Features (HY Features) standard defines a common conceptual information model for identification of specific hydrologic features independent of their geometric representation and scale. The model describes types of surface hydrologic features by defining fundamental relationships among various components of the hydrosphere. This includes relationships such as hierarchies of catchments, segmentation of rivers and lakes, and the hydrologically determined topological connectivity of features such as catchments and waterbodies… The HY Features model is based on an abstract catchment feature type that can have multiple alternate hydrology-specific realizations and geometric representations. It supports referencing information about a hydrologic feature across disparate information systems or products to help improve data integration within and among organizations. The model can be applied to cataloging of observations, model results, or other study information involving hydrologic features. The ability to represent the same catchment, river, or other hydrologic feature in several ways is critical for aggregation of cross-referenced or related features into integrated data sets and data products on global, regional, or basin scales.”

The aim of the HY Features model—to link data through scale and across formats—speaks to the complexity of aggregating disparate data for analysis of wide-ranging hydrologic phenomena. The increasing volume of remote sensing data, hydrologic field studies, and unconventional data such as cell phone images and social media feeds have the potential to reveal multi-temporal and multi-scale hydrologic processes not previously visible. GIS data will be integral to cataloging, processing, analyzing, and visualizing the data and the hydrologic insights to come.

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