Chapter 1

The geography of water

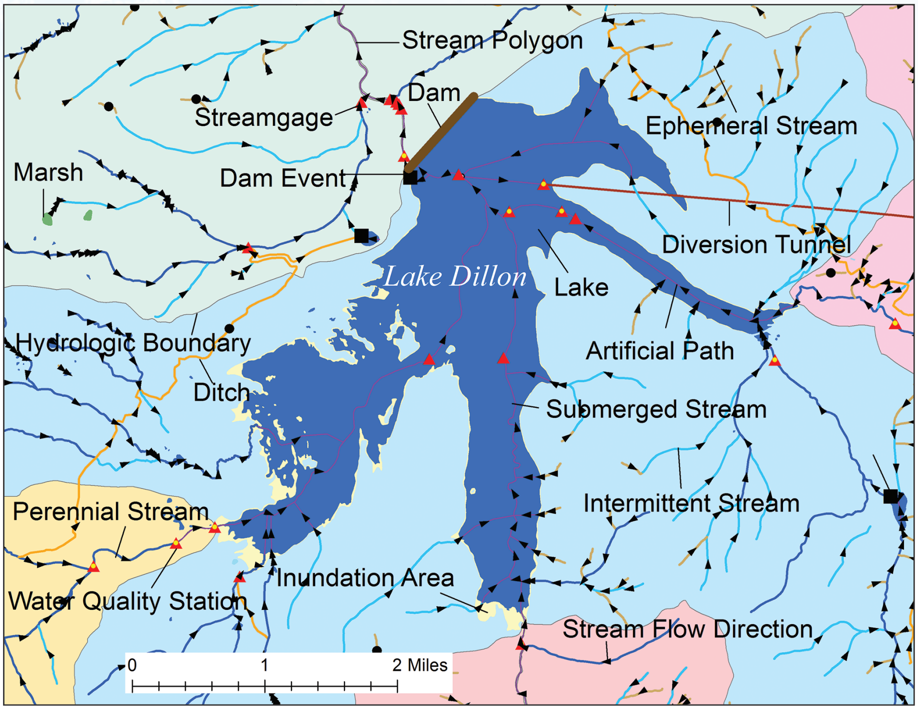

Figure 1.1. An example of the National Hydrography Dataset. Most of the dataset is made up of the vast network of streams and rivers that drain water off the landscape and transport it to the oceans. Data: USGS.

Water is perhaps the most precious resource on Earth. All life on the planet is based on water. The interaction of humans and water must be closely understood to ensure the prolonged survival of both. Water is distributed across the earth's geography and can be characterized with information in many ways. It is ideally suited for study using geographic information systems (GIS) that can harness widely available computing power; convert basic data into powerful information; and transform, organize, and process this information into knowledge of water to give humans insights they have never had before. That knowledge in the hands of capable decision-makers can generate wisdom to ensure the human–water interaction will be forever sustainable. One proven method to capture the knowledge of water in a GIS is to use the National Hydrography Dataset (NHD), which has been developed to map US surface waters. This dataset used in a GIS enables scientists and managers to effectively study the geography of water.

Many things must come together to make this happen. The following chapters provide a cornerstone to give scientists and managers who work on everyone's behalf the ability to build the geographic mechanisms to study water: where the water exists, where it has been, and where it is going. In a sense, this creates a much more elaborate, complex, and powerful water map. Understanding how this map is built, how it works, and how it can be applied is important to the science of water. To solve human–water interaction issues that will impact the world, the number of knowledgeable scientists and managers who are equipped to apply GIS to understand water must vastly increase.

Although this book addresses only surface water, it's a vital component of the water cycle on Earth that most people interact with. This book will show how the United States approached this technology with the NHD in a GIS. It is based on what has been done to date and ends with how those lessons can pave the way for an even stronger future. Although the use of the NHD in a GIS is not a perfect solution, it has turned out to be an excellent strategy, which is highly developed, well tested, and beneficial. The dataset will be of service for many years to come, and spawn even greater approaches to understanding water. The hope is that further study of the NHD in a GIS will encourage readers to solve their own set of problems facing the science and management of water, and inspire them to advance the understanding of GIS for surface water to a higher level.

This chapter will give the reader a better understanding of (1) the basic aspects of water, (2) what the GIS is and does, (3) how that water can be represented in a form within a GIS—namely, the NHD, and (4) how the NHD helps solve water-related problems. Let's now take a closer look at these four basic elements.

The basics of water

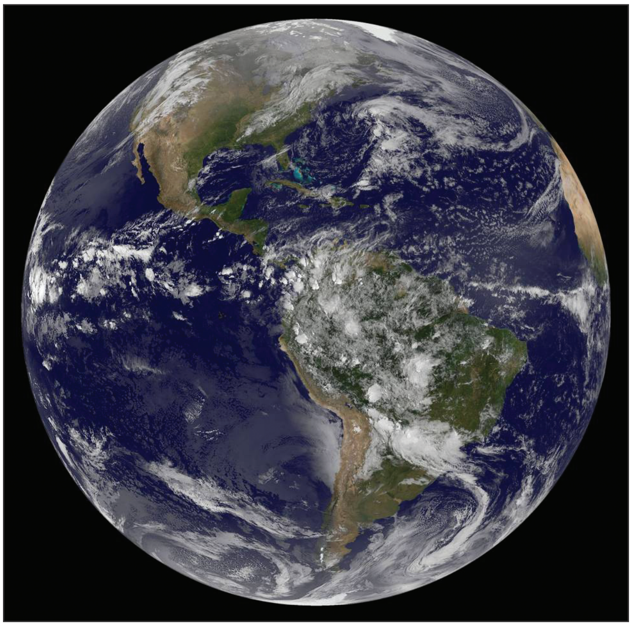

Figure 1.2. NOAA's GOES-East satellite captured this view of Earth on Earth Day, April 22, 2014. The water in the oceans, in the clouds, and the green biota of life dominates the scene. Courtesy NASA/NOAA/GOES Project.

The first thing you see when looking at the earth from space is water. Water is everywhere: in the oceans, clouds, ice caps, lakes, rivers, and the green biota of life. The abundance of liquid water is the defining element of the planet, and it's what makes the earth different. Water is the planet's lifeblood and is found in every living organism.

Water is also the great sculptor of the planet, shaping our landscape. Most of the landforms we see on the planet were molded by water and ice. Geologic uplift often starts the landform process, and as this is happening the water transforms the terrain into an evolving form. The great chasm of the Grand Canyon is an example of this process. As the Colorado Plateau Province rose 5,000–13,000 feet above sea level, the Colorado River continuously dug into the rock and transported trillions of cubic yards of the resulting sediment downstream out of the canyon. On a smaller scale, the millions of gullies that transect the land all around us are formed by the erosional effects of water over time.

Water has given rise to civilization as the peoples of the world have congregated around sources of freshwater for drinking, cleansing, and growing food. Many cities have been built on the banks of rivers such as the Tigris, Euphrates, Ganges, and the Nile, or on estuaries that flow into the ocean. Water has been the conduit for exploration, travel, and migration as people used rivers to cross the land. The Lewis and Clark exploration saw western America from the viewpoint of a river. The same waterways that provided exploration often later became a mode of transportation for people and resources. The Mississippi River is the foundation of a vast network of river traffic to this day. Water also provides recreation such as sailing or white-water rafting. Water is also a source of kinetic energy that powers waterwheels and turbines, having made possible the milling of wheat and later the production of electricity. Water exists even in less observable forms such as the aquifers under the land, the moisture in the soil and in plants, and the water in our sky.

Figure 1.3 The relative amount of water (blue ball) on Earth (basketball) by volume.

Considering the importance of water on Earth, there isn't much of it. Although water covers about 70 percent of the planet, it is just a thin film lying on top, akin to wrapping a globe in a layer of ordinary kitchen plastic wrap. Whereas the earth is about 260 billion cubic miles in volume,[1] there is an estimated 332 million cubic miles of water on Earth.[2] That's a ratio of 1 part water to 782 parts Earth by volume, or about 0.13 percent of Earth's volume is water. If the earth was a basketball, the comparable volume of water would be about the size of a marble, less than an inch in diameter. In terms of mass, the water on Earth exists at about 1 ton of water to 4,266 tons of earth, or about 0.023 percent of Earth's mass.[3] Comparatively, Earth's atmosphere, the other distinguishing characteristic of the planet, is 0.000085 percent of Earth's mass.

Where did the water come from? It came from within the very rocks that formed together to create Earth some 4.6 billion years ago.[4] Although some theories suggest that the water came to Earth later in comets, it turns out that the isotopes of hydrogen in water found in comets do not match the hydrogen isotopes of water on Earth. Rather, the carbonaceous chondrites found in meteorites that formed Earth are known to contain a great deal of water and are the likely source of the bulk of Earth's water. This period of water accumulation occurred about 14 million years after the origin of Earth. Earth went through its initial formation to a point of stabilization approximately 3.8 billion years ago when a combination of cooling and sufficient volcanic and caldera activity allowed the initial creation of ocean basins.

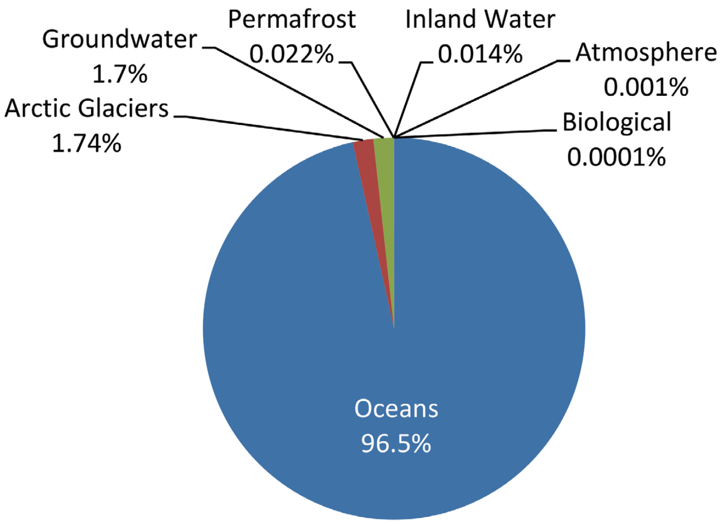

Figure 1.4. Basic breakdown of Earth's water. Gleick, P. H. 2011. "1996: Water Resources." In *Encyclopedia of Climate and Weather*, vol. 2, edited by S. H. Schneider, 817–23. New York: Oxford University Press.

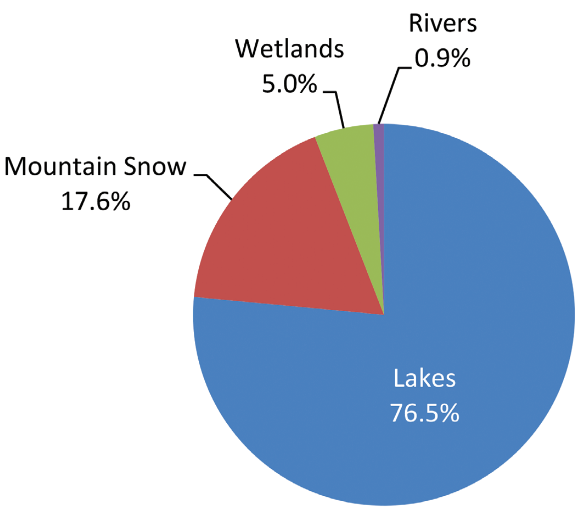

Figure 1.5. Basic breakdown of Earth's inland water. Gleick, P. H. 2011. "1996: Water Resources." In *Encyclopedia of Climate and Weather*, vol. 2, edited by S. H. Schneider, 817–23. New York: Oxford University Press.

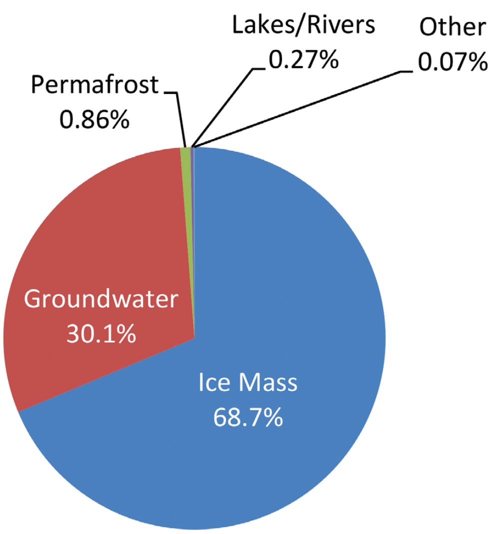

Figure 1.6. Basic breakdown of Earth's freshwater. Gleick, P. H. 2011. "1996: Water Resources." In *Encyclopedia of Climate and Weather*, vol. 2, edited by S. H. Schneider, 817–23. New York: Oxford University Press.

The water volume for lakes, both fresh and saline, adds up to 42,320 cubic miles. For rivers, the total is 509 cubic miles. The United States has about 8 percent of the world's freshwater, but this is skewed by the enormous amount of the world's freshwater stored in the Great Lakes. The Great Lakes are the world's largest freshwater system, holding a fifth of the world's freshwater.[5]

Understanding what a GIS is and does

Because water is so integral to life, it's important that we understand it as a resource. Water is distributed across the landscape horizontally and vertically. It is spatial in nature and a major component of the geography of our planet. It is not surprising then that water is the overriding feature found on maps. As maps have evolved into GIS, our understanding of water has also evolved. GIS has now reached a point where water is much more than a blue line on a map. Water can be represented in the digital form of a computer and be examined in ways never before possible. Scientists can use a GIS to model and analyze water in new ways to gain a vast understanding of this precious resource. Just as water is becoming more critical to the planet's growing population, GIS now has the means to have a fuller insight into this lifeblood of the planet.

A GIS performs several functions to help us study water. First is the basic computing power, storage holding, and map displays of the hardware. The NHD contains more than 30 million features, each containing dozens of attributes, and possibly linked to dozens of databases with even more attributes. Storing, processing, and displaying all this information requires substantial hardware. The current size of the NHD at about 20 gigabytes is a good match for most hardware systems, and hardware size is rarely a limiting factor in working with the NHD. However, hardware speed can limit some operations. Second, GIS software performs operations on the data such as determining which stream segment is the next downstream segment, making the stream appear red instead of blue when it is a specific navigation path, or sorting through all the data to display streams with more than a certain amount of water flowing through them. There are many different types of software, some of which is non-NHD and can process any type of data and software that is specific to the NHD. The software is customizable so the user can create or change it as needed.

The third function of GIS includes the algorithms processed by the software and hardware. Algorithms are the logic that makes the software do what is needed. Some algorithms simply sort through a list of values and select only the specified values. Other algorithms must be specifically designed to take advantage of the NHD, such as navigating downstream in the NHD without traversing secondary divergences. The fourth component is the web, which establishes communication between computers. The web can link and transfer data to and from applications running on computers. These links can occur at several levels, from simply transferring data, such as pulling streamflow from a streamgage, to actually doing all the computing and supplying the results, such as giving the user a map of the best places to kayak this weekend. The fifth component is the network of databases that store data, such as the NHD. The GIS can organize basic data in ways to make it more easily understood and most suitable to the algorithms used by the software and hardware. For example, the NHD is organized into lines (streams) and polygons (rivers) because the algorithms/software/hardware work best when these two water forms are separated into these two geometric forms. But it doesn't have to be that way.

Some databases might prefer not to segregate them. These first five components—hardware, software, algorithms, the web, and databases—can limit the functionality of the NHD. For this reason, the NHD is often generalized to make operations go faster, particularly when working at a national scale.

The sixth and final component is the group of people that create the GIS, make it work, create results, and interpret the results to make decisions. To be effective, these GIS users and developers must be competent with computers and understand the type of geography being studied, whether it is electric utilities, tax mapping, landslides, epidemiology, the census, or the flow of rivers.

Functions of a GIS

The GIS performs several operations that make a database such as the NHD come to life.

- **Assembling tools and information:** putting everything we need at our fingertips.
- **Providing a database:** creating a storage container to organize data and information.
- **Displaying the data:** transforming the data geometry and interactively displaying it.
- **Providing layer control:** organizing, creating, and cataloging different types of data.
- **Supplying geoprocessing tools:** processing the geometry of features.
- **Building queries:** searching, sorting, calculating, and selecting database attributes.
- **Editing:** altering the geometry or attributes of features.
- **Linear referencing:** linking external information to the linear geometry.
- **Networking:** organizing the geometry into a network and navigating it.
- **Modeling:** building new and unique algorithms integrated with the GIS to generate new attributes.
- **Using the web:** performing and sharing GIS capabilities and maps over the web.
- **Creating cartography:** designing symbology to make simple or sophisticated maps.

The fundamental function of a GIS in studying surface water is to analyze the movement of water through the water network, whether it is pollution carried downstream or an invasive species migrating upstream. This movement leads to cause-and-effect relationships such as how a chemical spill might flow downstream and affect a drinking water supply or how an invasive species from the Great Lakes might swim upstream to affect inland lakes. These analyses require that the geometry making up the network of water contains flow direction and segment-to-segment connections to permit the tracing of the downstream flow of water or upstream navigation. You can create such a network by using geometric vectors, which are naturally created by using lines for streams, and continuing these vectors through waterbodies. A dataset is then needed to code all the flow connections throughout the national network to drain all water flow to the oceans or internal sinks such as the Great Salt Lake.

The NHD

It is not practical to study surface water at a scale of 1:1 so you must make an abstraction using some type of map that will put all the water at your fingertips. The first European map of North America that showed inland water was Martin Waldseemüller's 1507 *Map of the World*, and from this, the mapping of water has evolved into the NHD of today. The NHD provides a singular nationwide digital map coverage of US surface water that is consistent and seamless. The data is free and easily accessible from the web for use in a GIS where you can use the NHD to perform various forms of analysis or simply make maps. The dataset was designed and produced by a consortium of users around the country led by the US Geological Survey (USGS) with the objective to address issues facing scientists and managers in a broad range of surface water disciplines. The development of this dataset has involved a partnership of over 100 government agencies working together to achieve common goals. The data is available at a level of detail found on 1:24,000-scale topographic maps made by the USGS and at smaller and larger scales. The database allows the scientific analysis of the US surface water system to be performed uniformly anywhere in the country so that the science is unbiased by political boundaries or organizational policy. The referencing of scientific data to a universal surface water model makes it possible to easily share data, which reduces costs, eliminates the duplication of efforts, and increases scientists' efficiency.

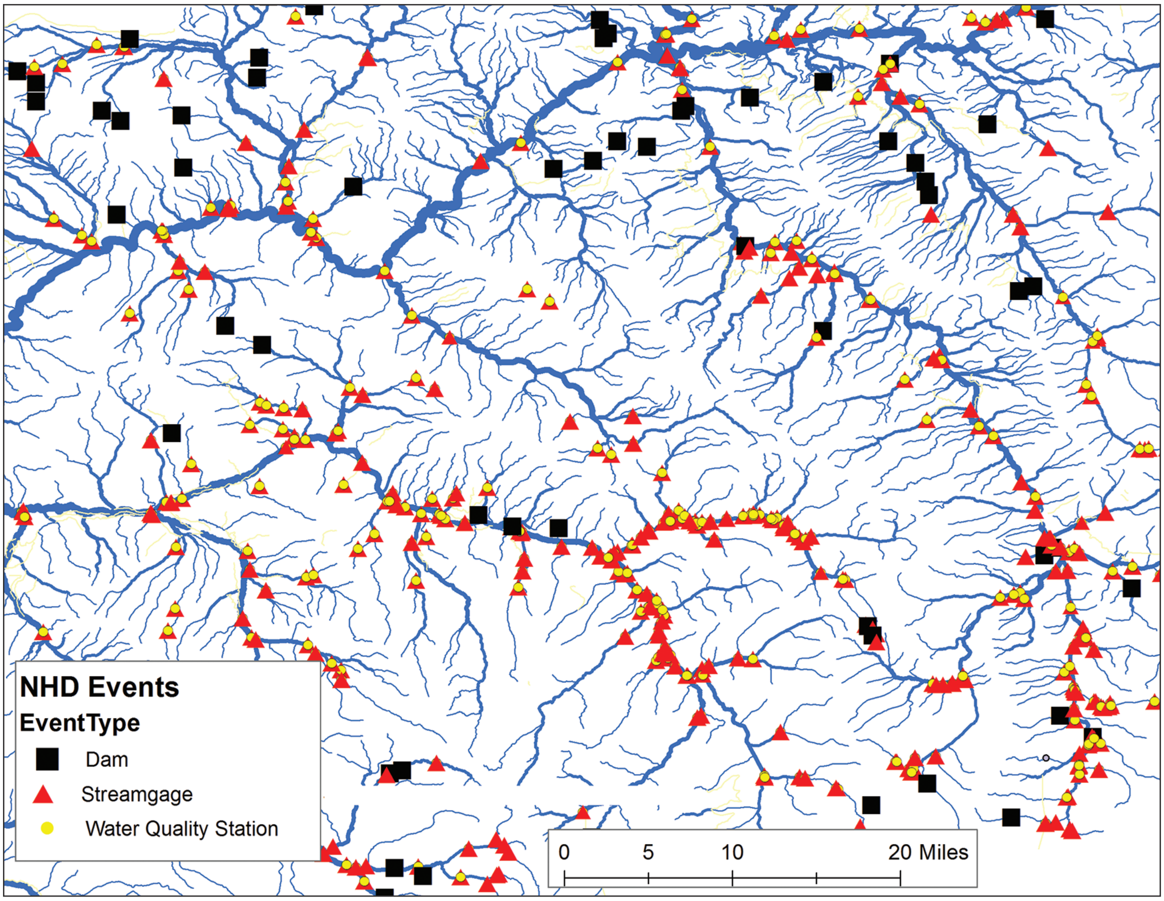

Figure 1.7. Example of the NHD in central Colorado with event information linked to it. The red triangles are streamgages, yellow dots are water-quality sampling locations coincident with a streamgage, and black squares are dams. Data: USGS.

The dataset is defined by a set of standards, but it is intended to be a work in progress, allowing users to incorporate their needs into the dataset, such as the level of detail desired and the linking of information. A process of continuous improvement refines the initial framework of data until the user community is satisfied with the results. The business model practiced by the partnership allows all users to participate. Although the NHD will largely be guided by the USGS, the stewardship of the dataset will ultimately be turned over to the community of users. The users will evolve the dataset to best meet their needs while embracing the need for national standards.

The NHD incorporates a few fundamental objectives. First is the creation of a national flow network navigable by a GIS, and the second is the ability to place information within that network. This information comes in the form of attributes and special events relating to cause-and-effect relationships, such as the location of a drinking water intake or a pollution discharge. The relationship of the two events can be established by network connections. Identifying the fact that the pollution discharge is positioned upstream of the drinking water intake on the flow network provides the capability to discover notable relationships.

The amount of information that can be connected to surface water has hundreds of attributes. Two attributes in particular greatly multiply the NHD's value: water flow volume and its velocity. Flow volume is a critical value characteristic of the stream that can be used in many ways, while velocity allows time of travel calculations. Actual flow volume and velocity are known only at the relatively small number of streamgage locations where they are measured using streamgages, but flow volume and velocity can be modeled to include every stream reach in the dataset. This modeling is done by integrating surface elevation models to generate upstream drainage areas for each reach, additional climate data, information from the NHD network, and finally using the data from actual streamgages to ensure the accuracy of the modeling. This type of analysis has been the work of the NHDPlus, a vital enhancement to the NHD.

Another major enhancement to the NHD is the further development of the surface water content. The NHD has been largely compiled from topographic maps, and although these maps do an excellent job of portraying the nation's surface water, they may not meet more advanced needs. Problems may exist related to the currency of maps or GIS databases, map-to-map inconsistencies, map-to-digital transformations, and the level of feature detail. The advent of new high-resolution surface elevation models made possible through advanced sensing technologies gives promise to the independent creation of entirely new surface water data.

The best way to move forward is to put the data into the hands of the users and give them the power to become the stewards of the NHD. A program of stewardship sponsored by the USGS has been under way to give users the authority, training, tools, and processes to upgrade the data to meet their needs and applications and share the results in an evolving dataset. There is some danger that this will create inconsistencies in the data as users tailor it to meet their local needs, but methods can be developed to "normalize" the data to yield a nationwide uniformity. The far greater danger is that if the NHD does not accommodate users' needs, these users will inevitably create their own spin-off versions and quickly fragment the national dataset into uncoordinated individual databases.

Solving water-related problems

All this effort to build the technology to study water in a GIS is designed to perform two basic functions: First is to increase our knowledge of surface water so we fully understand where the water is located, how much water there is, the characteristics of the water, and where it comes from and where it is going. For example, with the NHD in a GIS it is possible to catalog every single stream and lake that contributes water to the Mississippi River, know the flow volume at any point on any of these streams, and for much of that water, understand its chemistry. From this information, we are given a solid foundation to define the surface water so we know what we are dealing with. Second is to model the behavior of the water to understand how the water became what it is, and what will happen to it next. For example, if a major thunderstorm sweeps across Nebraska, the flow-volume algorithms can be rerun and generate a new set of flow-volume estimates for all the streams in Nebraska as well as follow the resulting surge of water down the Missouri and Mississippi Rivers in a time series. Similarly, if a pollutant is introduced into the stream network through a spill, the concentration of that pollutant can be calculated at any point through time and give emergency managers the ability to close a drinking water intake to prevent ingestion of the pollutant. It is therefore possible to predict the future of the water as well as use a reverse process to explain what has happened to it. Again, it is a matter of cause and effect. Something may happen to create a cause and we seek the effect that it will have, and the opposite is also true. For example, heavy concentrations of nitrogen and phosphorus can be found in the Mississippi River. This begs the question: What is the source of these substances? We know the effect—what is the cause? Figuring out these relationships is a significant function of the NHD in a GIS.

The analysis of water using GIS predates the NHD and was the driving force behind its creation. Once built, the NHD then enabled many additional users to begin a more sophisticated approach to study surface water. These users found ways to use the NHD for many purposes: (1) hydrology, (2) emergency management, (3) pollution control, (4) water resource management, (5) aquatic biota, and (6) cartography. The use of the NHD in hydrology started with simple inventories of water and the creation of the flow network enabling users to understand the routing of water and the accumulation of these routes in the network. A significant boost to hydrology came when the NHD was integrated with digital terrain models to calculate drainage areas, and then this information was processed through models to produce flow volume and velocity estimates in the NHDPlus. This analysis reequipped hydrologists with a vastly expanded knowledge of water everywhere on the drainage network, not just at specific sample points. Emergency managers have likewise taken advantage of the NHDPlus to model the flow of toxins that enter the drainage network as described previously. This type of analysis is also made possible by the integration of events, or "points of interest" such as release points, streamgages, and drinking water intakes. Emergency managers can also take advantage of the contributions of the NHDPlus to hydrology to better understand flooding, particularly with the further integration of digital terrain models into analysis. Just as emergency managers can model toxins in the drainage network, so can a host of pollution control scientists and managers who want to study a large array of chemical and biologic contaminants in the water. Many of these discharges are not just one-time events, but the result of years of contributing various levels of contaminants. The substances are not always bad and may even be at concentrations that are acceptable. That's one of the reasons why the NHD is so important, because it can better provide scientists with improved modeling using flow volume to understand levels of concentration and know when a substance may be too large of a load for the environment.

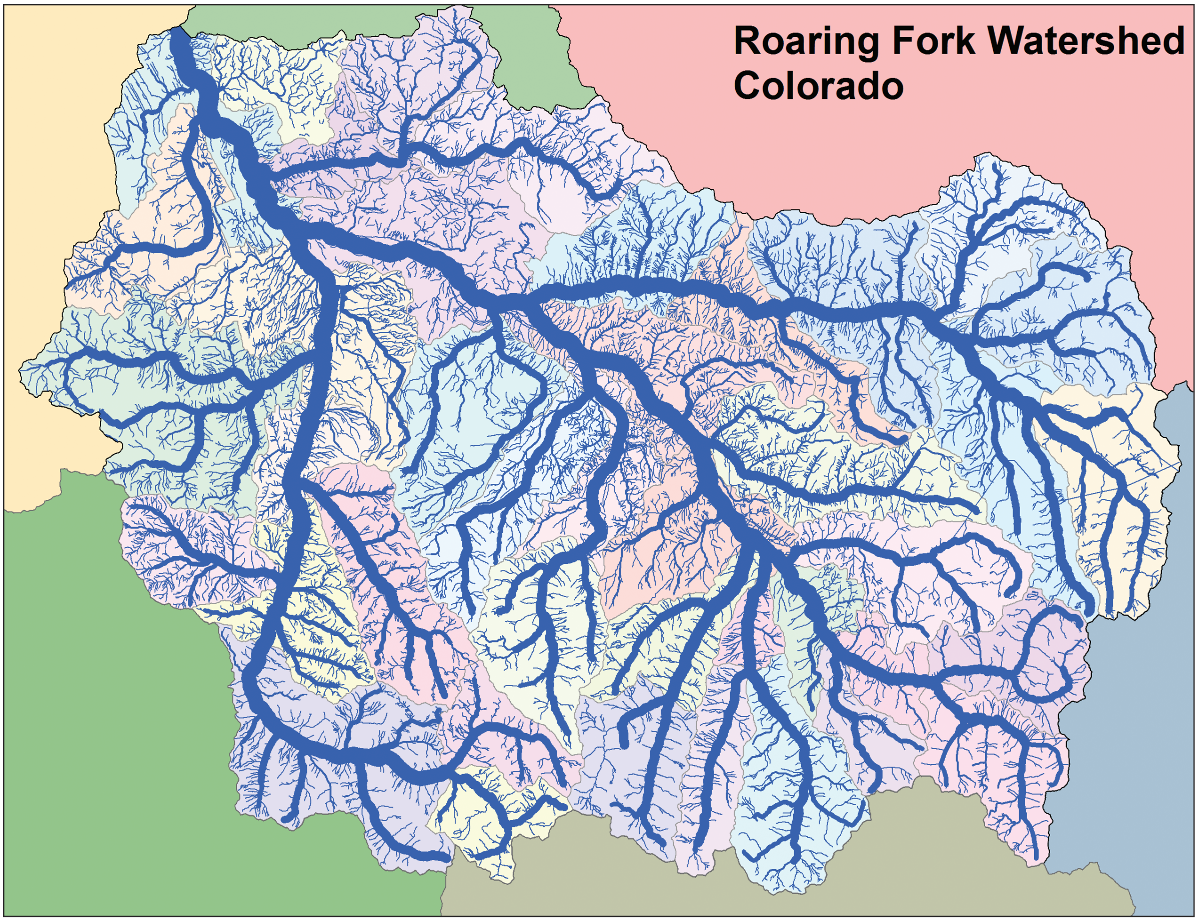

Figure 1.8. NHDPlus map showing the flow volume of water in the Roaring Fork drainage of Colorado. Streams' line width is governed by a hydrologic model. Data: EPA and USGS.

The fourth discipline in which the NHD has found substantial use is in water resource management. Often this field of study has to do with water inventories, such as the number of miles of streams in a particular national park. It also deals with permitting, such as the need for a permit when disturbing the ground in close proximity to a perennial stream. In many cases, it deals with water rights, water ownership, and in-stream flow rights. In much of the western United States, specific entities are guaranteed a certain flow of water and have "rights" to that water, even if it is on someone else's property. These rights are based on a seniority process in which senior holders of a water right are guaranteed their supply of water before junior holders are allowed their quota. Certain streams may also have a guaranteed flow to sustain fish. Recording all this information is a role for the NHD.

Surface water is also the home for a tremendous diversity of living organisms referred to as the *aquatic biota*. Many organizations such as the US Forest Service record the species occupying the surface water represented by the NHD, such as the extent and populations of cutthroat trout. Organizations such as the Bureau of Land Management study and record the health and condition of the riparian zone adjacent to the stream. The NHD is an enormous resource for scientific study in a GIS, and it is also an enormous resource for making maps in a GIS. The maps may be made specifically of the water, or the water may be a piece of ancillary information used in the map's background. The characteristics of the NHD, its direct attributes, as well as externally linked attributes, make mapping surface water simple. These maps may be printed or interactive maps. Streams may be symbolized on the basis of the periodicity of water, arrows may be used to show the direction of flow, names can be linked, the content can be generalized on the basis of flow volume, and symbology can be used on many linked attributes such as fish species, ownership, health of the water, and many other things. With the NHD, cartographers have many options at their disposal for portraying surface water on maps.

Surface water disciplines addressed by the NHD

- Hydrology
- Emergency management
- Pollution control
- Water resources
- Aquatic biota
- Cartography

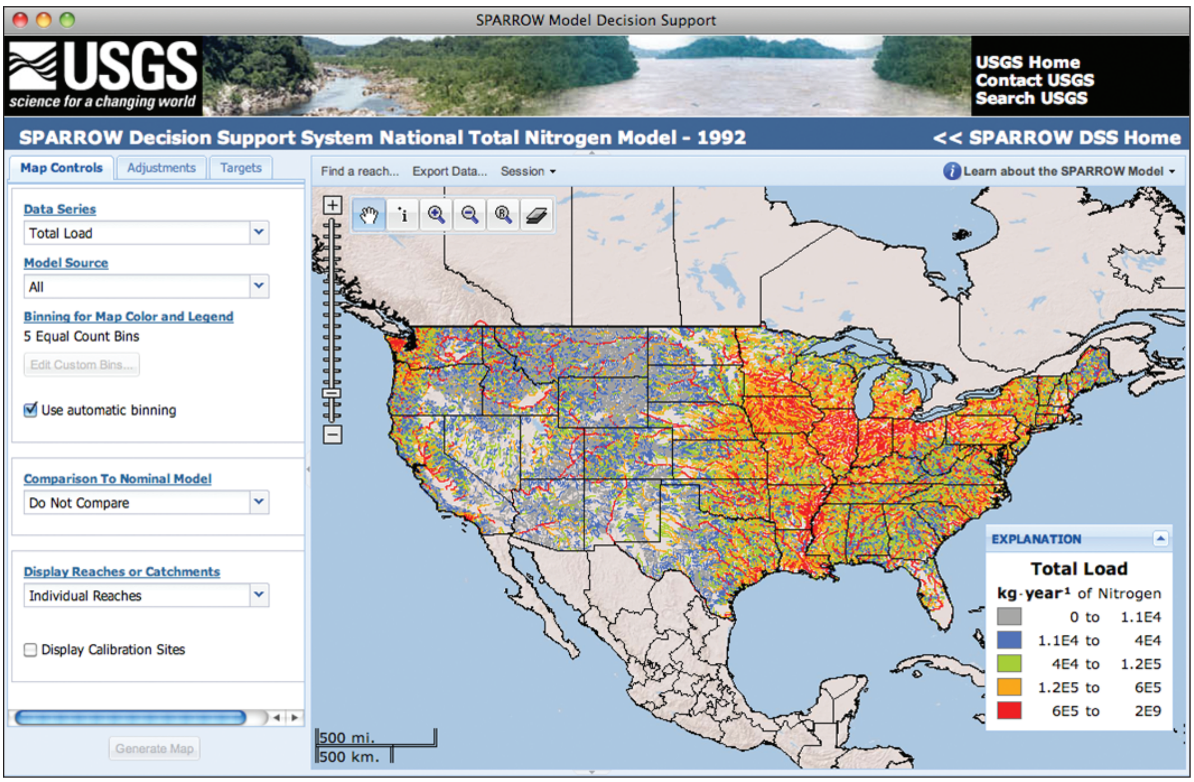

Figure 1.9. Nitrogen loads in US rivers. Courtesy USGS.

Looking ahead

The combination of water, GIS, the NHD, and problem solving has created a tremendous opportunity to create a more sustainable nation. Water is our lifeblood, and it has to be there for us to survive. In the past several decades, we have entered an era when our water resources have become stressed through pollution and depletion. We have fixed many of these problems with the Clean Water Act, the building of reclamation projects, and conservation. But as the population continues to grow, the stresses require new strategies. And now we are equipped with ever-advancing tools that allow us to develop these strategies such as the GIS for surface water using the NHD.

Notes

1. NASA. n.d. "Earth Fact Sheet." Accessed January 13, 2016. http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html.
2. Gleick, P. H. 2011. "1996: Water Resources." In *Encyclopedia of Climate and Weather*, vol. 2, edited by S. H. Schneider, 817–23. New York: Oxford University Press.
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