Introduction to Hydrology

Planet Earth is endowed with abundant water, but the demand for this vital resource at specific times and places often exceeds available supplies. Efforts to utilize water often result in adverse social impacts, such as disruption of water supplies to downstream users, and the loss of aquatic habitats.

In addition to conflicts over water availability, the quality of water is often compromised by human activity. Use of water and alteration of natural landscapes result in discharges of contaminants that can drastically affect the physical, chemical, and biological properties of water — what we call water quality.

The materials in this book focus on understanding water from both quantity and quality perspectives in the hope that everyone can better utilize this resource — thus preserving and protecting our planet for today’s occupants as well as tomorrow’s.

A brief history

How has water shaped our modern civilization and how has it become so important to human societies?

Many of the earliest writings are of a religious nature. Early religious documents, such as the Bible (Judeo-Christian), Talmud (Judaism), Quran (Islam), Code Smriti (Hindusim), I-Ching (Taosim), and the Analects (Confucianism), place great importance on water to society.

Early human existence was a tug-of-war between feast and famine, and the weather was instrumental in affecting the availability of consumable wildlife, agricultural productivity, and catastrophic inundation. Accounts of floods and droughts have been recorded since the earliest prehistory: the flood of Noah, which may be associated with a breach between the Black and Mediterranean Seas, and the seven plagues of Egypt, which included floods and droughts prompting Moses to flee. Even the great Roman Caesars were vulnerable to assassination during droughts.

While the earliest forms of agriculture may have relied directly on rainfall, the great early societies of Egypt, Mesopotamia, the Indus, and China were linked to irrigation. The ebb and flow of rivers allowed water to flood and fertilize agricultural land during the wet season and supply supplemental water during the dry season. The need to allocate scarce water supplies during droughts provided an impetus for water-resources administration — leading to the establishment of modern civilization.

Knowledge of irrigation spread through the desert regions of North Africa and Southern Europe. The Romans built elaborate aqueducts to transport water over great distances. In the south of France there are remnants of many of these structures, one of the most famous being the Pont du Gard (Figure 1), which is a 50-m structure that is part of the 50-km Nimes Aqueduct.

Figure 1. Pont du Gard on the Nimes Aqueduct.
The Pont du Gard was built by the Romans in the first century and the gradient of the waterway was a steady 1:3000. The precision of the design is phenomenal for the tools and knowledge used by engineers in the Roman era. Roughly 200,000 m³ (200 ML/day) of water were carried along the bridge every day en route to the fountains, baths, and homes of Nimes.

The Saint Clement Aqueduct (Figure 2) is another fantastic hydrologic engineering feat. This 880-m long structure was used to convey water from Saint Clement to the inhabitants of Montpellier in Southern France. While the aqueduct was built much later, around the 17th century, the architectural features are amazing.

Figure 2. Aqueduct St. Clement showing a conveyance structure that is 22-m high and 880-m long.
The elaborate irrigation and drainage systems of the First Americans also developed hand-in-hand with an administration system that could resolve issues of communal work and rewards. The ancient Aztec city of Tenochtitlan was founded on the shallow brackish waters of Lake Texcoco, the current location of metropolis Mexico City, Mexico. Complete with levees, dikes, dams, and aqueducts, the Aztec Nation were master engineers in their ability to make use of the limited fresh water supply.

The Aztecs developed highly productive agricultural systems that involved creating large floating gardens in the lake known as chinampas. Chinampas were made with layers of reeds and mud scraped up from the shallow bed of the lake and were roughly the size of a football field. Each chinampa would be connected through a network of canals and be accessible by canoe.
The fertile mud, hot sun, and water wicking up through the reeds made for a highly productive food system. Chinampas remain relevant today as we seek alternative methods of agriculture that are sustainable and conserve arable land.

Water has also historically been used as a means of transportation and production along rivers as well as the seas and oceans. The accounts of Ulysses in the Odyssey tell the travails associated with primitive travel by ship. Earlier travel in canoes and small sailing craft helped primitive peoples spread across the tropical Pacific, as far as Hawaii and Easter Island in the east Pacific.

In the year 1086, twenty years after William the Conqueror had successfully invaded England, he authorized the inventory of all of his conquest. Included in this so-called Domesday Book, or final accounting, are 6,000 water mills that were used primarily for grinding wheat and other grains to make flour. By the seventeenth century, there were over 60,000 water mills in France producing the flour used to make their daily bread.

Even in early American history, the importance of water mills on local commerce can not be over-emphasized. Many cities in the eastern US were located in proximity to sites where water power could be used for grinding corn and grains, or for powering industries.

Around the world, civilizations in China (Figure 3), India, Mesoamerica, Egypt (Figure 4), and many others, developed advanced water control and irrigation systems. The course of human society was intimately tied to its dependence on water resources.

With the advent of the industrial age, reliance on hydropower as an abundant, cheap, and clean source of energy became widespread. Dams of increasing size were built to harness the energy in water, culminating in the large dams of the twentieth century. Water was still needed to drive the steam turbines used to generate electricity when the primary function of resources shifted as coal, and later nuclear energy, supplemented hydropower.

Water was also used to initially remove human wastes from cities by letting it flow through open sewers to the nearest stream. Discharges of industrial wastewater from mills and factories was as simple as constructing a ditch to the nearest river. Unfortunately, downstream water users were often left to bear the burden of pollution and sickness. While advanced economies have invested in pollution control, many developing countries still lack adequate wastewater treatment.

Greater efforts were placed on maintaining instream water quality as recreation and environmental concerns increased during the late-nineteenth and twentieth-centuries. Restrictions on discharges and an emphasis on wastewater treatment led to major improvements in stream water quality.

These improvements were only for point-sources of discharge, or an identifiable source of pollution. The advancements did not account for stormwater runoff discharged from diffuse nonpoint sources.

American literature reflects the importance of water in American society. The writings of Mark Twain (Samuel Clemens) on the Mississippi River brought home the central role that water played in commerce during nineteenth century America.

The book Silent Spring, written by Rachel Carson in the 1950s, dramatized the plight of American birds due to the widespread application of pesticides, leading to strict controls on environmental toxins.

Carson’s research relied upon the electron capture detector, a technology developed by JE Lovelock, who later proposed the Gaia hypothesis that Planet Earth is a self-regulating system with built-in checks and balances that controls the temperature and atmospheric gas composition.

And finally, presidential candidate Al Gore’s book, Earth in the Balance, outlines the challenges facing modern civilizations when confronted with resource management decisions.

The role of science

The source of water in rivers and streams has been controversial since the dawn of history -- many of the greatest scientists and philosophers have argued over this subject. The early Greeks spent bountiful time trying to understand the origin of rivers and streams.

Thales (640-546 BCE) was an Ionian who popularized the belief that wind blew water into rocks along the coast, forcing water up
Later, Plato (427-347 BCE), an Athenian, argued that water was contained in a single underground cavern, and was pushed up into springs by underground forces. Aristotle (384-322 BCE), also an Athenian, disagreed with Plato, arguing that water vapor from the atmosphere and interior of the earth condensed directly in the soil, making it moist. Seneca (4 BCE - 65 CE), a famous Roman senator, proved to the intellectuals of his day that precipitation that fell to the earth and infiltrated was not sufficient to supply all the water that was observed as streamflow. Even Kepler (1571-1630), a German scientist renowned for his contributions to astronomy, thought that the earth digested salt water and excreted fresh water as waste.

Some ancient cultures believed that land masses floated on top of the water we now know as oceans. They figured that all of the lake and river water was provided from underneath the terrain, where the water met the land. Many cultures believed this along with the thought that rainwater was not enough to provide for the lakes and rivers.

**History of flow measurement.**

“Hydraulic structures existed before recorded history. Archeologists have found irrigation systems in Mesopotamia and hydrologic structures such as “check and diversion” dams on the Arabian Peninsula dating to about 5800 BCE. The first water level records on the Nile River appeared about 3050 BCE. The Romans devised a method of quantifying water distribution in order to charge for water supplied to baths and private residences. This system was rightfully based on pipe area even though they did not fully comprehend hydraulic principles relating to discharge.

“Hero, a Greek of the first century CE, was the first to express the basis for flow measurement as we know it today. This important finding went unnoticed for about 1500 years until Leonardo da Vinci expanded the relationship in the continuity equation, but even da Vinci’s work went unknown until his manuscripts were found in 1690.

“The German engineer, Reinhard Woltman, developed the spoke-vane current meter in 1790, a breakthrough for measuring water velocity in rivers and canals. During the 18th and 19th centuries development and installation of weirs and flumes made flow measurements possible on irrigation canals, and gaging stations were constructed on many rivers to provide records of flows. Today technology enables various water measurement techniques and streamflow data now can be accessed online at over 4,200 gaging stations in the United States.

Regardless of the source of water in streams, many cultures tried to make sense of the rise and fall of rivers. The Cairo Nilometer was a device constructed in the seventh century to measure the water surface, or stage, of the Nile River. It was essentially a well that was connected to the Nile River by a series of tunnels. The water from the Nile would fill the well, and the water level was measured by reading a marble column ruler located in the center of the well.

The minimum annual water level of the Nile River is summarized in Figure 4. The raw data is displayed in aqua blue and a spline smoothing function is displayed in black. The lowest minimum annual water level of 935 mm occurred in 981 CE, and the highest minimum annual water level of 1466 mm occurred in 809 CE. The average minimum annual water level over the entire time period was 1148 mm.

Several temporal trends are highlighted by visual graphics such as plots. There was a shift in the variance of the record that occurred around 720 CE (dotted vertical line), which scholars have hypothesized to be due to an upgrade in the sensor technology, resulting in more precise data collection.

Also, there are clear cyclical trends, made particularly evident by the spline smoothing function imposing a trend line to the data. These trends have been correlated with El Niño - Southern Oscillation (ENSO) events that correspond to warming of the Pacific Ocean off the coast of Peru and Ecuador and have far-reaching impacts on global climate.

It was not until Pierre Perrault (1608-1680), a French scientist, measured 520 mm of rainfall in the Seine River watershed during the period from 1668-1670 and showed that it was six times more than the river flow, which proved to many scientists that the source of water in rivers and streams is atmospheric precipitation falling on the soil. This, in turn, initiated the modern idea of the hydrological cycle, similar to what we currently have, including processes like evaporation, transpiration, and surface runoff.

**How long have people tracked precipitation?**

“In his book Meteorologica, Aristotle (340 BCE) mentioned topics such as clouds, mist, rain, snow, etc, but not the measurement of precipitation. Measuring and recording rainfall did not occur until later in the future.

“The earliest quantitative device for measuring rainfall seems to be credited to Korean kind named King Sejong who lived from 1397 to 1450. In addition to inventing a rain gOne of his goals as king was to make his people literate, not only did he invent a rain gauge, but more importantly, he invented a language and movable type for that language.

“He decided that instead of digging into the soil to check for moisture, it would be better to have a standardized container (30 cm in depth and 14 cm in diameter) that stood on a pillar to measure the rainfall. These containers were to help villagers predict their potential harvest and appropriate taxes across the kingdom! So, these standard containers were distributed to each village. The rain gauge was invented in the fourth month of 1441, according to records.

“The tipping bucket rain gauge was invented in Europe by Christopher Wren circa1661. This device measured rainfall by continuously filling small containers holding a standard weight..."
or volume of fluid. The containers were designed to spill once full and the contraption would record movement over time. The tipping bucket method is still used in many automated electronic gauges today.

"In 1887, Mr. Cleveland Abbe wrote a manual on Meteorological Apparatus and Methods for the US Army Signal Corps (agency responsible for US weather observations at the time). In this booklet, Mr. Abbe described the standards for the weather gauges to be used by the US Army Signal Corps. This standard 8-inch diameter gauge is still in use by many National Weather Service offices and cooperative weather observers across the United States and abroad."

To this day, however, there are still disputes over the source of water in streams. While some believe that streamflow only results from overland flow during rainstorms (which might be true in urban areas where impervious surfaces dominate), this theory is inappropriate in forests and agricultural areas. In these cases, streamflow results from infiltration, recharge, and subsequent exfiltration of water from groundwater.

Modern perspective

After millennia of confusion, we now have a better (scientific!) concept of water - a molecule of which is composed of two hydrogen atoms attached by covalent bonds to a single atom of oxygen (Figure 5).

![Figure 5. Structure of the water molecule, which is polar due to a positive charge (+) near the hydrogen atoms, and a negative charge (-) near the oxygen atom.](image)

The molecule is not symmetric, however, and this asymmetry is responsible for many of the unusual properties of water that make life possible. The hydrogen atoms do not sit on opposite sides of the oxygen molecule, rather, their bond angle is only 105° (as opposed to 180° if they were symmetrically arranged).

Because the covalent bond results in the hydrogen atoms being positively charged and the oxygen atom negatively charged, the 105°-bond angle results in a molecule with two positive ends and a single negative end. This is termed a polar or dipole molecule.

We have also recognized the components of the hydrologic cycle (Figure 6); where water moves through landscapes in a series of processes, and that there is a balance between inputs of water (precipitation, P) and outputs (evaporation, E, and transpiration, T, to the atmosphere, as well as discharge, Q, and storage, S, of water in soil) within a land area.

Water balance: \[ P = ET + Q + \Delta S \]
Table 1 presents the proportion of water and residence times for Earth’s water reservoirs. Note that glaciers and ice sheets have long residence times, while those in plants and the atmosphere are much shorter. Because of the relatively small amount of fresh surface waters, we have to manage that water delivered to us by the hydrologic cycle - rainfall - or use finite supplies of groundwater. Groundwater accounts for most of the remaining freshwater. Surface freshwater (lakes and rivers) is only 0.001% of the earth's water, and soil water amounts to 0.05% of all freshwater. Even though it is only a tiny fraction of the earth's water, surface and soil water are obviously important to the existence and distribution of terrestrial life.

Table 1 also presents the residence time, which is related to water movement, in that it is the average duration water spends in each reservoir. The residence time, $\tau$ (tau), is calculated by dividing the storage volume, $V$, by the outflow rate, $Q$:

\[
\tau = \frac{V}{Q}
\]

Note that residence time of water in our planet's soils, atmosphere, and plants is brief compared to how long it spends in oceans, glaciers, and groundwater. This also means that losing groundwater and ice masses will have profound effects on global water cycling.

**Landscape and hydrology**

Planet Earth's land surface can be divided into watersheds based on the drainage of water - all land within a specified watershed drains to the same point. Taking the mouth of a river basin as lowest point in the watershed, then all lands upstream of that point lie within that watershed. Thus, when Spaniards claimed the mouth of the Mississippi River -- and all lands that drain into it -- as belonging to their King, they little-realized what a large area that they had in fact acquired.

Some watersheds have large rivers coming out of them, such as the Mississippi and Amazon Rivers. These watersheds lie in wet regions where abundant rainfall exceeds the rate of evapotranspiration, resulting in surplus water that runs to the sea. Other large watersheds may not have large rivers, such as the Colorado River that flows into the Sea of Cortez. Large watersheds with small rivers are generally located in desert areas where the precipitation is small relative to the evapotranspiration rate.

Georgia is situated in a region with small drainage basins (Figure 8). Some of our rivers are shared between states, such as the Savannah and Chattahoochee, where the river demarcates the boundary between states. Others flow into other states, such as the Coosa, Tennessee, Chattahoochee, Flint, Ochlockonee, Withlacoochee, and Suwanee Rivers. Note that no rivers flow into Georgia.

Each watershed has unique qualities that distinguish it from other, nearby watersheds. Understanding why one river or stream behaves differently from another is linked to understanding the unique qualities of each watershed. Humans alter their watersheds by changing landscape properties, such as by increasing impervious surfaces, and by increasing evapotranspiration rates, such as by irrigation agriculture. These changes can and do change the behavior of the rivers that flow through them - increasing peak discharges, decreasing annual discharges.

In the following sections we discuss some of the many features that describe watersheds, and how water moves through the watershed. We distinguish between terrestrial features associated with areas not covered by water from aquatic features, such as rivers and lakes, that are permanently inundated. We also examine wetlands, which transition between these two between features.

**Landscape features**

**Topographic characteristics.** Topographic features are properties of the earth's terrestrial surface that can be used to describe watershed characteristics. The topography determines the slope and aspect of the land surface. Steep slopes dominate mountainous areas, rolling hills have moderate slopes, and flat slopes are found in plains and on plateaus.
Cooler temperatures and wetter soils are normally found on north- and east-facing aspects in northerly latitudes, and on south- and east-facing aspects in southerly latitudes.

**Contour lines** are used to mark points of equal elevation. **Streamlines** are perpendicular to contour lines, and point in the downhill direction. Contour lines are closed (forming a continuous line) around peaks and within depressions. Contour lines are convex if the streamlines are diverging (separating), and concave if they are converging. Contour lines tend to converge near streams, and diverge along ridgelines.

**Geographic Information Systems, GIS,** are commonly used to describe topographic features of our planet's surface. The surface is digitally stored at various resolutions, and then used to represent the elevations and locations of physical features. Other features can also be inventoried, such as vegetation, land use, and soil type.

Besides slope and aspect, vegetation and land-use also affect the runoff of water. Water can be applied from natural sources, such as rainfall, or from snowmelt. Water can also be applied artificially, such as by agricultural and residential irrigation or industrial and municipal discharges.

Water flowing across the terrestrial surface is normally intermittent, otherwise it would lie in a specific channel. These flows are called sheet or overland flow. The flow velocity is usually slow, but can be fast on steeper slopes or where bare soil or rock is exposed.

Georgia has the following **physiographic provinces** and **landscape features**:

**Lower Coastal Plain.** Part of the Coastal Plain Province, consists of flat, rolling hills, includes swamps, marshes, and islands

**Upper Coastal Plain.** Part of the Coastal Plain Province, consists of flat well-drained land and rolling hills

**Piedmont.** Rolling hills and a few mountains, lots of rivers/ravines

**Blue Ridge.** Variation between mountains, ridges and basins in Northeast GA, part of the Piedmont is included in this region

**Ridge and Valley.** Region of parallel ridges and valleys in Northwest GA

**Appalachian Plateau.** Mountainous Region in Northwest GA

**Fall Line.** The bottom border of the Piedmont and the top border of the Upper Coastal Plain. The region north of the fall line has more mountainous and hilly terrain, while the southern region is flat with rolling hills. Likewise, the northern region has clayey soil and smaller streams. The Southern region has sandier soil, and larger floodplains.

**Northern Fall Line.** The western border of the Blue Ridge and the northern border of the Piedmont. The Ridge and Valley lies to the north and west.

Common landscape features include:

**Topographic contours.** Lines of equal elevation

**Slope.** Change in elevation per unit distance

**Aspect.** Direction that the ground surface faces

**Streamlines.** Lines perpendicular to topographic contours

**Concave slopes, hollows.** Zones of diverging streamlines

**Convex slopes, ridges.** Zones of converging streamlines

**Watershed length.** Distance from outlet to most distant point

**Maximum elevation.** Highest point on watershed

**Area-elevation relationship.** Plot of elevation vs amount of land in the elevation class

**Soils.** There are six major soil regions in Georgia, with regional variations in soil type closely tied to the underlying bedrock geology.

In the **Limestone Valley** (also known as the Southern Appalachian Ridge and Valley) region, soils are strongly acid and well drained with clay-enriched subsoils. Soils are shallow on ridgetops but deep in the narrow river valleys and above large limestone formations.

Soils in the **Blue Ridge region** vary widely in depth due to the steep topography, with soil types that are generally loamy or clayey. The entire region is defined by a wet (udic) soil moisture regime, and a moderately warm (mesic) soil temperature regime prevails except for elevations above 4200 ft., where the cool (frigid) soil temperature regime is more characteristic of locations in the northern U.S.

Loamy or clayey soils also dominate in the **Southern Piedmont** region, with a generally udic soil moisture regime and a warm (thermic) soil temperature regime.

In the narrow **Sand Hills** region, deep Cretaceous sands deposited when the region was an ancient shoreline have resulted in deep soils that are sandy or loamy in character, and are well-drained or even excessively drained.

South of the Sand Hills in the generally flat **Southern Coastal Plain**, soils become loamy and very deep. A thermic soil temperature regime prevails, and soils are very moist with a udic or aquic (often saturated) soil moisture regime.

Finally, soils in the **Atlantic Coast Flatwoods** are similar to those of the Southern Coastal Plain in that they are very deep and moist with a thermic soil temperature regime. One difference between these two region is that clayey soils are also present in the Atlantic Coast Flatwoods region, in addition to the loamy soils that predominate in the Southern Coastal Plain.

**Figure 9** shows the land uses of Georgia. Note that most urban areas (shown in red) are located in the northern half of the state, around Atlanta. There are a few other urban areas scattered primarily near the borders of Georgia and South Carolina and/or Alabama, as well as located along a few rivers or other areas with a water source.
Forested areas are located primarily in northern Georgia and central Georgia. Southern Georgia appears to have most of the agricultural areas, though there are some agricultural activities east of the urban areas located on the map.

Georgia’s population over the next century years will most likely increase due to the economic growth in the metro Atlanta area. However, the population in rural areas will remain similar to where it is currently. The population increases in Atlanta and other cities like it around the country will inherently cause an increase in food demand.

Consequently, there is an increased pressure put on rural agricultural areas like Georgia’s piedmont. With increased agriculture comes a need for more water. The increased population of the urban areas then compounds this need for water. The next millennium brings a whole new set of unknowns.

If food supplies are affected by a changing climate, it is possible that Georgia’s agriculture will increase. If that occurs, water will be diverted to increase yields. The world’s population will have skyrocketed by then and the need for immense amounts of food could be overwhelming.

**Subsurface characteristics.** In addition to surface features, subsurface features are also important from a landscape, or watersheds, perspective. Ground, or subsurface, water is important for many reasons - it sustains our rivers and streams during times of dry weather, wells provide us with additional supplies of drinking water, and water for our factories and fields. Areas without groundwater are more reliant on the randomness and uncertainties associated with precipitation, and are more prone to droughts.

The water table is the elevation of the water surface found in wells. The region below the water table is called the saturated zone where all pores are filled with water. The region above the water table, but still below the surface, is called the vadose or unsaturated zone. Both the unsaturated and saturated zones are key to understanding why and where water moves in the subsurface.

Groundwater is held mainly in the pore spaces of the saturated unconsolidated sediments. The porosity is the volume of water per unit volume of media. Solid rock, such as granite, may have very small porosities, while sands and clays may have much larger porosities. The total porosity is the sum of the interconnected porosity, plus the isolated, or dead end porosity.

While some rocks, such as basalt, may have a large total porosity, water may not easily move through these rocks because the pores are not interconnected. Also, sand and clay may have similar porosities, but water does not flow as readily through clay because the pores are much finer.

Generally, sandy layers are aquifers and clay rich layers are classified as aquitards or aquicludes. Water flow in the subsurface is not uniform - an aquifer is a geologic unit that transmits water rapidly to wells, while aquitards (confining layers) are geologic units that retard the movement of water.

Aquifers and confining units are mappable bodies of rock or sediment that transmit sufficient amounts of water or have hydraulic conductivities significantly lower than that of the adjacent aquifer, respectively. These units are informal subdivisions characterized by properties significantly different from the rest of the unit.

Many geologic formations can be identified in the subsurface as distinct layers with a measurable thickness, usually in the vertical direction. Hydraulic conductivity, color, chemistry, or lithology may be the establishing feature of a zone.

An aquifer system may contain one or more aquifers that transmit groundwater on a regional basis. Confining units that have local but not regional effects may exist within an aquifer system. A confining system is comprised of one or more confining units that impede regional groundwater flow.

**Hydrologic features**

**Oceans, seas, and estuaries.** The marine environment consists of those interconnected aquatic features which are dominated by the presence of salt water. We previously grouped inland seas with lakes because they are not directly connected to the marine environment. The marine environment dominates Planet Earth, covering most of its surface - perhaps our planet should be named Oceanus instead!

The major oceans (Table 2) include the Pacific, Atlantic, Indian, and Arctic, with countless smaller marine water bodies, such as the Caribbean, Mediterranean, Baltic, and Bering Seas. While these oceans and seas are interconnected, their circulation and water chemistry may differ in essential ways from each other.
Table 2. Major marine water bodies.

<table>
<thead>
<tr>
<th>Water Body</th>
<th>Area</th>
<th>(% of Globe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pacific Ocean</td>
<td>165.65</td>
<td>32.5</td>
</tr>
<tr>
<td>Atlantic Ocean</td>
<td>81.62</td>
<td>16.0</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td>73.41</td>
<td>14.4</td>
</tr>
<tr>
<td>Arctic Ocean</td>
<td>14.34</td>
<td>2.8</td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>2.96</td>
<td>0.6</td>
</tr>
<tr>
<td>Bering Sea</td>
<td>2.27</td>
<td>0.4</td>
</tr>
<tr>
<td>Caribbean Sea</td>
<td>1.94</td>
<td>0.4</td>
</tr>
<tr>
<td>Gulf of Mexico</td>
<td>1.81</td>
<td>0.4</td>
</tr>
<tr>
<td>Sea of Okhotsk</td>
<td>1.52</td>
<td>0.3</td>
</tr>
<tr>
<td>East China Sea</td>
<td>1.25</td>
<td>0.2</td>
</tr>
<tr>
<td>Hudson Bay</td>
<td>1.23</td>
<td>0.2</td>
</tr>
<tr>
<td>Sea of Japan</td>
<td>1.05</td>
<td>0.2</td>
</tr>
<tr>
<td>Total Marine</td>
<td>359</td>
<td>70.4</td>
</tr>
</tbody>
</table>

Rivers and streams. Our planet is blessed with waterways large and small. From the great rivers of Asia (Yangtze, Yellow, Mekong, Ganges), Africa (Nile, Congo, Niger), Europe (Danube, Rhine), North America (Mississippi, Mackenzie, Columbia), and South America (Amazon, Paraná) to the small rivulets scattered everywhere, we live within a landscape influenced by water. Table 3 presents some of these great rivers, upon which our billions of people depend everyday, everywhere. The depth is found by dividing the discharge by the area:

**Runoff depth:** \[ D = \frac{Q}{A} \]

Note that the greatest runoff depths are found in the Amazon, Mekong, and Yangtze Rivers due to the increased rainfall in these basins. Also note that the lowest depths are found in the Nile and Yellow Rivers, which flow through arid terrains.

Table 3. Great rivers of the world.

<table>
<thead>
<tr>
<th>River</th>
<th>Length (km)</th>
<th>Area (10^3 \text{ m}^2)</th>
<th>Discharge (10^6 \text{ L/s})</th>
<th>Depth (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nile</td>
<td>6,850</td>
<td>3.25</td>
<td>2.80</td>
<td>27</td>
</tr>
<tr>
<td>Amazon</td>
<td>6,990</td>
<td>7.05</td>
<td>209</td>
<td>935</td>
</tr>
<tr>
<td>Yangtze</td>
<td>6,300</td>
<td>1.80</td>
<td>31.9</td>
<td>559</td>
</tr>
<tr>
<td>Mississippi</td>
<td>6,280</td>
<td>2.98</td>
<td>16.2</td>
<td>171</td>
</tr>
<tr>
<td>Yenisei</td>
<td>5,540</td>
<td>2.58</td>
<td>19.6</td>
<td>240</td>
</tr>
<tr>
<td>Yellow</td>
<td>5,464</td>
<td>0.75</td>
<td>2.11</td>
<td>89</td>
</tr>
<tr>
<td>Ob</td>
<td>5,410</td>
<td>2.99</td>
<td>12.8</td>
<td>135</td>
</tr>
<tr>
<td>Paraná</td>
<td>4,880</td>
<td>2.56</td>
<td>18.0</td>
<td>222</td>
</tr>
<tr>
<td>Congo</td>
<td>4,700</td>
<td>3.68</td>
<td>41.8</td>
<td>358</td>
</tr>
<tr>
<td>Amur</td>
<td>4,444</td>
<td>1.86</td>
<td>11.4</td>
<td>193</td>
</tr>
</tbody>
</table>

So, one of the first things a land manager might do in evaluating an area is to assess the hydrologic conditions of the area: get information on rainfall, ET amounts for given vegetation types, and sizes and flows of major streams. These are all important determinants of hydrologic behavior.

The unit of land area typically used for such an assessment is called the **watershed**: this is a land area within the boundaries of which all water drains to a single outlet point, as illustrated in Figure 10. Here a single perennial stream (which flows more-or-less continually) branches into smaller intermittent streams (dashed lines) which only flow during storm events, when surface runoff may occur and soils are nearly saturated.

Figure 10. Watershed definition sketch. (Source: Hewlett and Nutter)

Springs may occur where a water table (saturated zone in the subsoil) outcrops to the surface, feeding the main channel flow. Note that water that percolates into the soil and below may continue to flow (leak) through the bedrock to some deeper water table below, or may follow a flow path different from the surface watershed divides.

Note the sub-basin in Figure 9, which defines a smaller basin within the whole; watersheds obviously are nested, and can range in size from the simple stream in Figure 9 (20-30 acres) up to the Mississippi River itself (millions of acres).

Mapping stream properties is useful for describing how these systems behave. A low-order stream has a small discharge and responds quickly to precipitation, while a high-order stream has a larger mean discharge, and responds more slowly.

**Stream order** defines the size of the stream based on how many other streams intersect it, counting only perennial streams (Figure 11). A first-order stream therefore has no perennial tributaries, while a second order is made up of intersecting first order, etc. The largest rivers are seventh or eighth order; moderate ones like the Oconee are fourth or fifth order.
Figure 11. Stream orders, from small first-order streams to larger fourth-order streams.

One way to understand stream order is to relate stream discharge to watershed area. For example, if discharge increases with watershed area and net precipitation, $R$ (precipitation less evapotranspiration), then mean annual discharge is simply:

$$Q = RA$$

In Georgia, $R$ is approximately 400 mm/yr (16"/yr), so that one hectare of land ($10,000 \text{ m}^2$) generates 4000 $\text{ m}^3$/yr = 0.13 Lps (liters per second).

Thus, a 250-ha (1 mi$^2$) watershed will generate approximately 32 Lps (1 cfs), which corresponds to the flow from a first-order stream. Because a second-order stream normally has a ten-fold increase in flows, the average watershed size is approximately 25 km$^2$ (10 mi$^2$). The Oconee River Watershed (at Penfield) is 2500 km$^2$ (940 mi$^2$) is therefore a fourth-order stream!

For the Mississippi River, or any other watershed, one would need to know the net precipitation to find the relationship between stream order as a function of watershed area. Greater net precipitation means that rivers increase in size more rapidly than those in drier areas.

The stream length is the distance from its source to a confluence with another stream or water body. The length of a meandering stream is much longer than a straight stream, and is harder to determine because it is hard to measure every curve in the stream.

Streams are never straight, they tend to meander across the river valley. The tortuosity (or sinusity) of a stream, $\tau = L / L_m$, is the ratio of the measured straight line distance, $L_m$, to the true length of the stream, $L$. A stream with a tortuosity of two means that the river is actually twice as long as the distance from it's headwaters to its mouth. Fractals are self-similar geometric scaling objects that allow modelers to develop realistic landscape illustrations.

Watershed features that are scale-dependent include:

**Shorelines.** Length of land-ocean boundary increases as ruler length decreases

**Stream density.** Number and length of waterways increases as map scale becomes finer

**Soils.** Scaling of particles shifts soil-moisture characteristic curves to common shape

**Geophysics.** Bulk resistivity is not just product of resistivity and porosity

**Fractured media.** Fracture density changes as the scale of measurement changes

The stream profile is a plot of the elevation of a stream as a function of the distance of the stream from its source. The slope of the stream profile plot is equivalent to the slope of the stream. The stream profile is useful for describing stream power, which is the product of the discharge and the slope.

Common stream features include:

**Stream order.** Smallest streams are given order (1). Larger streams are given order (2), etc.

**Stream length.** Distance of stream from its confluence to its source.

**Stream profile.** Slope of stream along length of stream

**Drainage density.** Sum of all stream lengths divided by total area

**Stream order density.** Sum of stream lengths in each stream order divided by sum of all lengths

**Spring magnitude.** Largest springs are given magnitude (1). Smaller streams are given order (2), etc.

**Longitudinal features.** Pools, riffles, steps, glides

**Latitudinal features.** Point bars, cut banks

**Thalweg.** Main channel

**Floodplain.** Overbank flows

**Terrace.** Abandoned floodplain

Stream networks in the landscape tend to form distinctive patterns based on how streams intersect and the stream density (length of stream per area). The dendritic pattern (Figure 12) is the most common, where streams intersect at acute angles, and form a more-or-less random, branch-like network, which is common in the Piedmont.

Figure 12. Stream drainage patterns; dendritic (left), rectangular (center), and trellis (right).

The rectangular pattern is often determined by geology - ridges often direct major streams through valleys, with smaller
streams running up hillslopes (this is common in the Valley and Ridge province). The trellis pattern sometimes develops in loose, erodible soils where major streams quickly cut down into the landscape and feeder streams branch out laterally. Some parts of the Coastal Plain have trellis drainage patterns.

The major rivers in Georgia are shown on the state map in Figure 13. You can imagine the watersheds, or drainage basins, for each river by outlining the areas around the rivers which would tend to drain toward the river, rather than toward the adjacent one. Notice in north Georgia the rivers follow the direction of the mountains, flowing northeast to southwest; in extreme northeast Georgia, flow is actually to the north, into the Tennessee Valley (this is where the continental divide is located). Near Atlanta the Chattahoochee follows a geologic fault zone before heading south to the Gulf of Mexico.

**Figure 13.** Major rivers of Georgia and their relationship to physiographic provinces.

Most of the eastern part of the state drains to the Atlantic Ocean through the Savannah, Ogeechee, and Altamaha Rivers, while the western part drains to the Gulf via the Flint and Chattahoochee. The divide between these two major basins lies between Athens and Atlanta, where the headwaters of the Oconee and Chattahoochee come close to each other.

The location of the river along the Fall Line, in the Sand Hills, is also interesting: the fall of the rivers off the Piedmont down to the Coastal Plain provided water power for early settlers in towns like Macon, Augusta, and Columbus.

**Lakes and inland seas.** These are large water bodies that support diverse ecological communities, provide recreation, navigation, and water storage. Table 4 summarizes the largest of these features. Unfortunately, reductions of flows have reduced the volumes and areas, disrupting many communities and ecosystems. Figure 14 presents water level trends for several large systems. Note that water levels fluctuate over long periods, but are stable in the long term.

### Table 4. Major lakes and inland seas. Values are uncertain because many lakes and seas (Aral Sea, Lake Eire, Lake Chad) are shrinking due to irrigation withdrawals and climate change, especially in arid regions.

<table>
<thead>
<tr>
<th>Lake or Inland Sea</th>
<th>Area ($10^3$ km$^2$)</th>
<th>Volume ($10^3$ km$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caspian Sea</td>
<td>424.1</td>
<td>78.2</td>
</tr>
<tr>
<td>Lake Superior</td>
<td>82.33</td>
<td>12.1</td>
</tr>
<tr>
<td>Lake Victoria</td>
<td>69.38</td>
<td>2.75</td>
</tr>
<tr>
<td>Aral Sea</td>
<td>63.69</td>
<td>0.19</td>
</tr>
<tr>
<td>Lake Huron</td>
<td>59.54</td>
<td>3.54</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>58.00</td>
<td>4.92</td>
</tr>
<tr>
<td>Lake Tanganyika</td>
<td>32.88</td>
<td>18.9</td>
</tr>
<tr>
<td>Lake Baikal</td>
<td>31.58</td>
<td>23.6</td>
</tr>
<tr>
<td>Great Bear Lake</td>
<td>31.07</td>
<td>2.24</td>
</tr>
<tr>
<td>Great Slave Lake</td>
<td>29.00</td>
<td>1.58</td>
</tr>
<tr>
<td>Lake Nyasa</td>
<td>28.48</td>
<td>7.78</td>
</tr>
<tr>
<td>Lake Eire</td>
<td>25.63</td>
<td>0.48</td>
</tr>
<tr>
<td>Lake Chad</td>
<td>20.71</td>
<td>0.07</td>
</tr>
</tbody>
</table>
Lakes and inland seas generally have negligible water velocities and a lack of shade on the water surface. The primary cause of water movement is wind energy, which causes mixing in the surface layer, as well as lake-wide water circulation and seiches.

Lakes and ponds are water bodies composed of fresh water, while inland seas (and salt lakes) have substantial salinity. Lakes and inland seas form by natural geologic processes, such as by glaciation, landslides, and tectonic or geologic subsidence, while reservoirs and ponds are normally constructed by humans, or by other dam-building animals such as beaver.

Because of slow water velocities and the lack of shading of the water surface, solar radiation tends to heat the near-surface water in the photic zone. As the water warms, it becomes more buoyant than the underlying, cooler water, resulting in stratification.

Stratification of a water column is normally greatest in summer, and breaks up in fall as the water surface cools. If the water is covered with ice, then an additional period of winter stratification may occur, resulting to two periods within the year that the water-body is stratified (dimictic).

Discharge from lakes and inland seas is normally from the epilimnion, which is usually warmer in the summer and colder in the winter. Discharges from ponds and reservoirs depends upon the outlet structure. If the discharge is from an overflow structure on the water surface, then the outflows will mimic natural discharges.

On the other hand, discharge structures located deeper in the water column will be cooler than natural discharges during the summer. groundwater seepage through the dam or bottom of the lake is another mechanism for these water bodies to affect regional water budgets.

Discharge from inland seas is usually absent, so that there is no outlet. Any water entering these water bodies is lost to evaporation, concentrating any salts contained in the inflows.

Inland seas are often located in desert areas where precipitation is much less than evapotranspiration. These water bodies are extremely vulnerable because human diversion of inflow waters for agricultural irrigation often has dramatic adverse effects. Some water bodies are permanently stratified. The Dead Sea, located between Jordan and Palestine, was stratified for thousands of years due to the accumulation of heavier, salt-rich waters in the deeper sections of the water-body. As upstream inflows of freshwater were diverted by Israel, the upper layer disappeared, resulting in mixing and a large release of CO$_2$ and H$_2$S that had been trapped in the deeper layer.

A similar disaster occurred in Cameroon in 1983 when a deadly cloud of CO$_2$ was released from a lake that de-stratified (turned over) when large volumes of colder water flowed into the lake during a rainy period. Common lake features include:

- **Photic zone.** Zone near the surface of the lake with sufficient sunlight for photosynthesis.
- **Thermocline.** Point of inflection on temperature curve, separating the well-mixed water near the surface from the poorly mixed water at depth.
- **Stratification.** The separation of a water column into distinct layers.
- **Epilimnion.** Zone of well-mixed water near lake surface above the thermocline.
- **Hypolimnion.** Zone of poorly mixed water below the thermocline.
- **Metalimnion.** Zone of moderately mixed water near the thermocline.
- **Seiche.** A random oscillation of the water surface due to wind, changes in barometric pressure, or earthquakes.
- **Littoral zone.** Shallow water zone along shoreline. Zone where rooted macrophytic vegetation most likely.
- **Open water zone.** Deeper water away from shoreline. Free-floating plants most likely.

**Wetlands.** Wetlands have many unique hydrologic attributes. One particularly important attribute is their position as the transition zone between aquatic and terrestrial ecosystems. Wetlands have aspects of both aquatic and terrestrial environments because of this position.

On one hand, most freshwater and marine aquatic environments, such as lakes, rivers, estuaries, and the oceans, are characterized as having permanent water. On the other hand, terrestrial environments are generally characterized as having drier conditions, with an unsaturated (vadose) zones present for most of the annual cycle. Wetland thus occupy a zone that is the transition between dominantly wet and dry environments.

**EPA estimates** that the Continental United States (CONUS) contains around 110.1 million acres of wetlands, with Alaska containing another 174 million acres. The West Siberian Plains in Russia is vastly larger at 1.2 million square miles.

Wetlands are usually shallow - the upper extent of the zone of saturation within wetlands extends from quasi-flooded (i.e., water covering the surface) to quasi-dry (i.e., the water table
within the root zone). This shallow hydrologic environment creates unique biogeochemical conditions that distinguishes it from freshwater, marine, and terrestrial environments. In freshwater and marine habitats, the water surface lies above the land surface, while in terrestrial environments it lies some distance below the root zone as a water table or zone of saturation.

Wetlands tend to form where surface water and groundwater accumulate within topographic depressions (such as in flood plains, potholes, and behind dunes, levees, and glacial moraines, lime sinks, pocosins, and Carolina Bays), where groundwater discharges on slopes (such as along the shores of streams, lakes, and oceans), and above low-permeability substrates where infiltration is restricted (Novitzki, 1989).

Wetlands are a fundamental hydrologic landscape unit (Winter, 2001) that generally form on flat areas, or on shallow slopes, where perennial water lies at or near the land surface, either above or below. Wetlands may form initially in depressions, but may modify their environment as they mature. Peatlands may develop to substantially modify the original landscape (Daniel, 1981).

Wetlands are normally found in low energy environments, in part, because the land surface is relatively flat in these areas (Orme, 1990). Because wetlands lie in relatively flat landscapes, their surface area expands and contracts as the water stage changes. This large change in area results in the ability to store large volumes of water. Wetlands therefore serve as a moderator of hydrologic variability - storing flood flows during wet weather in particular. In addition, shallow depths and low slopes, consistent with low energy environments, are important for trapping nutrients and sediments.

Wetlands contain features found in both aquatic and terrestrial environments as well as exhibiting some unique features on their own. Wetlands begin to form when surface runoff and groundwater accumulate in topographic depressions within the landscape, where groundwater discharges on slopes, and above low permeability substrates where infiltration is restricted. Wetlands tend to form in regions where the land is flat or on very shallow slopes and are often found where perennial water lies at or near the land surface, either above or below. Peatlands may develop to further modify the original landscape.

The Okefenokee Swamp is the largest wetland in Georgia with an area of 628 square miles. Figure 15 presents water levels over time, as well as a histogram these levels. Figure 16 shows the various ecological zones within the wetland.

Sources of streamflow

Today we know that some of the water in streams comes from overland flow across impervious surfaces. This is especially the case in landscapes altered by humans, such as in cities and agricultural areas. There are fewer impervious surfaces in forests and other areas less affected by humans. Streamflow in these areas is dominated by groundwater discharge as exfiltration from subsurface sources. Water infiltrates into the soil, recharging aquifers that then supply flow to streams.

One way of explaining runoff is the concept of the contributing area. The contributing area, or variable source area, model assumes that only certain areas within a watershed contribute to streamflow. These include saturated areas, such as lakes...
and ponds, stream channels, wetlands, and other areas of standing water, as well as areas where the soil is saturated at the surface.

The variable source area approach assumes that all rainfall infiltrates in some areas, while rainfall does not infiltrate in other areas because the soil is already saturated in these areas and runs off the surface. The observed runoff only comes from these contributing areas.

**Figure 17** presents a conceptual model of flow components on a hillslope. Note that flow to a stream is a combination of surface, shallow subsurface, and groundwater components.

The streamflow is thus a mixture of sources from across the landscape, including the following components:

**Precipitation on channels:** Some rainfall lands directly on the surfaces of streams, rivers, wetlands, and lakes, and obviously becomes stormflow immediately. This is usually a small percentage of the stormflow, however, because surface waters usually cover a small part of the landscape. This is not true in swamps, however, such as the Okefenokee, where large areas are covered with water.

**Precipitation on saturated areas:** Some parts of the landscape tend to stay wetter than others because water continually drains toward these areas between storms or because saturated soils lie near the surface. Hillslope hollows, low areas around streams and rivers, wetlands, and the margins of wetlands are examples of these areas.

During rainfall, soils in these areas may become completely saturated, and their infiltration rates may fall to zero. When this occurs, overland flow occurs on these saturated areas. This runoff generation process is also called the variable source area concept, because these saturated areas expand during rainstorms or during wet seasons because larger areas becomes saturated.

If the rate of rainfall exceeds the soil infiltration rate (the rate at which soil absorbs water), then water ponds on the soil surface. If the soil surface is sloped, the ponded water flows downhill toward the channel system. This is referred to as overland flow, sheet flow, or surface runoff. It is also called Hortonian flow after R.E. Horton, the hydrologist who first described this process in his seminal paper, “The role of infiltration in the hydrologic cycle” in 1933.

The most obvious example of Hortonian flow is on streets and parking lots. In Georgia, Hortonian flow is also common on plowed fields and bare soils, but it rarely occurs in forests unless it rains hard, such as during a hurricane.

Even then, however, forest runoff is more likely to occur due to saturation of the underlying soils, rather than due to low infiltration rates across the soil surface. The difference between the rainfall rate and the infiltration rate is the amount of rain that runs off the landscape.

Potential infiltration rates tend to decrease over time. When rainfall begins, the relatively dry soils near the soil surface absorb water faster than it can be carried by gravity alone. This uptake (also called imbibition) of water is the result of capillary forces (like how a paper towel absorbs water) in the soils.

As soil moisture contents become uniform with depth near the surface, the infiltration rate becomes equal to the soil hydraulic conductivity (the permeability of the soil) for that moisture content. As infiltration occurs, there is typically a sharp moisture difference between the newly wetted soils and the drier soils below them. This sharp break in the moisture contents is called the wetting front, and it moves downward during the storm.

Because of the change in potential infiltration rates during rainfall, the occurrence of surface runoff depends not only on...
the intensity of the rainfall, but also on the timing of the intensity. For example, a rainfall rate of ten cm/hr is much more likely to cause surface runoff if it occurs after two days of light rain than if it occurs at the beginning of a storm.

Water flowing across terrestrial surfaces can be called overland flow. This flow is intermittent because it depends on several variables. If the flow was not intermittent, it would be a specific channel. The runoff process is a variable source area, because rainstorms or wet seasons cause larger areas to become saturated.

Hortonian overland flow occurs when the rate of rainfall exceeds the soil infiltration rate, and groundwater ponds on the surface. The difference between the rainfall rate and the infiltration rate is the amount runoff water generated. The slope of the land and the roughness of the terrain will cause the runoff to move faster or slower.

Hortonian flow occurs when the rainfall rate exceeds the soil infiltration rate. This results in water ponding on the surface and ultimately produces runoff if the surface is sloped. Hortonian flow is much more likely to be observed in a parking lot, assuming that the lot is constructed with typical impervious materials such as asphalt or concrete, because the low infiltration rate associated with the impervious cover is easily exceeded by even the most modest of rainfall events.

Hortonian flow is less common in a natural forested environment because large precipitation events are required to produce surface runoff. The higher rainfall rates required to produce Hortonian flow in forests can generally be attributed to the higher infiltration rates common to more natural land covers. Additionally, throughfall is commonly lower in forests, as the canopy intercepts a percentage of the rainfall, which means higher rainfall rates are required for large quantities of water to reach the surface.

Infiltration rates have a tendency of decreasing over time, so longer storms will begin producing a greater runoff rate, if the rainfall rate maintains its intensity. More intense rainfalls are more likely to cause overland flow. High groundwater tables will contribute to overland flow because the soil will become saturated quicker.

The hydraulic conductivity of soil types is also a factor for overland flow, for example, a sandy location will have a higher infiltration rate than a clayey location. More specifically, urban areas with a lot of pavements are more likely to see the occurrence of overland flow because of the large area of impermeable surfaces.

**Interflow**: Interflow is shallow, lateral, subsurface flow that occurs on hillslopes with shallow permeable soil layers overlying low permeability layers. Interflow can occur as either saturated (soil pores are filled with water) or unsaturated (soil pores are only partially filled with water) flow. Interflow begins in a soil layer as soon as the wetting front crosses that layer and reaches the surface of the layer below.

Obviously, interflow does not reach stream channels as quickly as surface flow, but interflow is fast enough to generate part of the stormflow response. In some forested areas, interflow dominates stormflow response. Interflow continues between storms, transporting soil water from higher portions of the landscape to lower portions of the landscape. Interflow is of the processes that create variable source areas (saturated areas near streams).

Interflow does not occur in all landscapes. Interflow is more important when soil layers are thin and when slopes are relatively large. The Bt horizon can cause interflow because of its low permeability.

**Baseflow**: Streamflow between storms comes from groundwater discharge (water stored in underground aquifers), interflow (hillslope drainage), and the draining of water stored in lakes and wetlands. Baseflow is not constant. It steadily but slowly decreases between rainfall events as water drains from the watershed (like how a bathtub drains more slowly as it empties). Baseflow is a critical determinant of habitat conditions in streams and rivers.

When flows are lower, there is less dilution of pollutant inputs resulting in higher concentrations of contaminants during low flow periods. Also, there is less buffering (attenuation) against solar and atmospheric heating of the water. Thus, stream temperatures can be a problem for fish during summer low flow periods. The groundwater characteristics of a basin largely control the quantity, quality, and temperature of baseflow.

Regardless of the source of water in streams, surface water, soil water, and groundwater are important resources, and their amounts and quality are highly vulnerable to human-induced and climatic changes. **Soil storage** is a major factor determining water availability to plants, productivity of land, timing and volume of streamflow, and water chemistry.

Every type of landscape has a unique hydrologic regime and water balance, depending on the climate (how much rain, the temperature and wind, which affect ET) as well as the topography, vegetation, soil properties and structure of the underlying rock which influence how water moves in the landscape.

**Current issues**

**Sustainability.** Trying to incorporate principles of sustainability in regional development is (or should be) a major effort of water resources management. As noted by Judge Magnuson in his court decision (July 17, 2009) related to the Florida v. Georgia lawsuit over water allocations, "Too often, state, local, and even national government actors do not consider the long-term consequences of their decisions."

While protecting ecosystems for their intrinsic worth is a noble endeavor, important ancillary benefits are the services they render. From plentiful and clean water, to recreational and aesthetic values, these services become more valuable as human systems increase in complexity and sophistication.
How to achieve sustainability is our grand challenge. Decreasing our ecological footprint while reducing our sensitivity to climatic extremes is an engineering question that remains unsolved. In answering these management questions, the first step is to identify those best able to frame and describe the problem.

The scientific and professional communities have a duty to provide a path for transitioning from Growth 1.0 to Growth 2.0. Yet there is firm resistance within the resource management community, due in large part to the need to assure stakeholders, as well as residual uncertainties in how ecologic systems function and respond to disturbance. As demonstrated many times, only a complete failure is sufficient motivation for change.

**Ecosystem services.** Ecosystems provide many benefits to mankind, especially an abundant supply of clean water. Wis usually manage these ecosystems to protect both water quantity and quality. Too much water - too little water, are both issues of water quality. Flood control and drought protection are opposite ends of the water quality spectrum. Dams, bridges, canals, revetments, harbors, etc., are all structures used to protect people and property from natural variations in weather.

Water quantity management has historically been the domain of the engineering profession, with some opportunities for economists. Design of so-called structural remedies, and the ability to pay for these structures, have preoccupied federal, state and local agencies since the beginning of the nation. In recent years, however, increasing attention is being placed on managing facilities, and providing initiatives for individuals to avoid building in flood-prone land, thus replacing structural with non-structural remedies to water resource problems.

Little legislation exists to regulate water quantity on the national scale. Regional compacts are usually negotiated at the state or local level to find an acceptable allocation of water between jurisdictions, primarily for periods of drought. Little national legislation exists related to the regulation of flooding, other than requirements related to building in the floodplain.

Unlike water quality, the maintenance of water quality has a rigorous legal foundation, focusing on the protection of the quality of water supplies. We can divide modern water quality management into three categories; water supply, wastewater treatment, and the protection of aquatic habitats. Issues and career opportunities are often uniquely defined within each category due to its legislative history.

**Water supply**

This topic relates to the need of society for abundant sources of inexpensive water of acceptable quality. Surface water quality issues related to drinking water fall under the **Source Water Assessment and Protection** (SWAP) program, which is a part of **Safe Drinking Water Act**. A similar program for groundwater quality is the **Wellhead Protection Program** (WHPP), which also falls under the Safe Drinking Water Act. These programs are intended to preserve and protect drinking water supplies so that chronic and acute exposures to hazardous contaminants are minimized.

In addition to water quality protection, new water supplies are routinely needed in growing communities for both municipal and industrial purposes. Reservoirs are one option for capturing excess streamflow during the winter months, and storing it for delivery during the drier summer months. Groundwater is another resource that many communities are tapping whenever possible. Wastewater reuse is a potential source of new water for meeting the demands of growing communities.

Efforts are also underway to recharge excess surface water in groundwater aquifers. The intent is to avoid the need to construct surface-water reservoirs, and to use the subsurface as an underground reservoir to store excess streamflow until it is needed.

Important legislation related to water supply includes:

- **Organic Act of 1897.** Signed into law on June 4,1897, by President William McKinley for the purpose of timber production, watershed protection, and forest protection. The goal was to use federal lands to preserve wood and water supplies for the long-term benefit of the public. Of specific interest was "securing favorable conditions of water flows".

- **Weeks Act of 1911.** Passed by the US Congress on March 1, 1911. It authorized the Secretary of Agriculture to "Examine, locate and recommend for purchase … such lands within the watersheds of navigable streams as … may be necessary to the regulation of flow of navigable streams..."

This act resulted in the creation of many National Forests in the eastern United States.

- **Flood Control Act of 1937.** Signed into law by President Franklin D Roosevelt on August 28, 1937, in response to major flooding throughout the United States in the 1930s, culminating with the **Super Flood** of January 1937, the greatest flood recorded on the lower Ohio River. The act provided funds for the initial construction of projects selected by the Chief of Engineers, including construction of floodwalls, levees, and revetments along Wolf River and Nonconnah Creek for protection of Memphis, TN, and modified the Yazoo River project.

- **Wilderness Act of 1964.** Signed into law by President Lyndon B. Johnson on September 3, 1964. It created the legal definition of wilderness in the United States, and protected some nine million acres of federal land. The goal was to protect watersheds and clean-water supplies vital to downstream municipalities and agriculture, as well as habitats supporting diverse wildlife, including endangered species, while logging and oil and gas drilling are prohibited.

- **2010 Georgia Water Stewardship Act.** Passed by the Georgia General Assembly, restricted the use of water in local communities between the hours of 10am and 4pm, called for plumbing codes to be updated, and legislated the completion of annual water loss audits.
Wastewater treatment

This topic includes the mitigation of point discharges as well as stormwater runoff from nonpoint sources, such as farms, homes, forests, etc. These programs fall under the Clean Water Act. Also included in this category is the cleanup of sites where hazardous and toxic wastes were discharged, primarily in the subsurface, during the years when such dumping was allowed. These programs fall under either CERCLA or RCRA.

The cleanup of current and historical contaminants is a challenge in this, and many other industrial and developing countries. Many poor countries are faced with the options of either destitute populations, or the discharge environmentally destructive compounds.

Nonpoint source issues related to stormwater runoff are manifested by erosion and sedimentation, as well as pathogens, heavy metals, herbicides, pesticides, and excessive nutrients. A new tool for establishing linkages between both point and nonpoint pollution abatement programs is watershed assessments, which inventories the watershed from the perspective both sources of pollution, as well as the importance of water supply protection.

Another strategy for using urban stormwater includes green (vegetated) roofs, which are roof structures that are covered with vegetation, a soil layer, and a membrane that prevents moisture from going into the structure. Green roofs prevent runoff from roofs and alleviate heat island effects.

While providing clean, abundant, and inexpensive water supplies is clearly linked to the cleanup of wastewater and the prevention of contamination, inadequate linkages between the myriad federal water quality legislation makes integrating these programs difficult. Example types of legislation include:

- **Soil Conservation and Domestic Allotment Act.** Passed on April 27, 1935, that allowed the government to pay farmers to reduce production so as to conserve soil and prevent erosion. The act was intended to conserve soil in the High Plains by planting trees and native grass - soil that created the huge dust bowls during the 1930s. Soil conservation in the Deep South was also targeted. Soil erosion dropped 65 percent within three years after the act was passed.

- **Clean Water Act.** Passed in 1972 and regulates discharges to navigable waters. The act introduced a permit system for regulating point sources of pollution, and created a new requirement for technology-based standards for these discharges.

- **Safe Drinking Water Act.** Passed in 1974. Prior to the 1970s the protection of basic air and water supplies was a matter mainly left to each state. During the 1970s, responsibility for clean air and water was shifted to the federal government. Discovery of organic contamination in public drinking water and the lack of enforceable, national standards persuaded congress to take action. The act applies to public water systems, but does not cover private wells or bottled water.

- **Resource Conservation and Recovery Act.** Enacted in 1976. It is the principal law governing the disposal of solid waste and hazardous wastes. Congress enacted the law to address the increasing problems from these wastes, setting national goals for protecting human health and the environment.

- **Comprehensive Environmental Response, Compensation, and Liability Act.** (CERCLA or Superfund) was passed in 1980 to clean up abandoned hazardous waste sites. The act provides authority to clean up releases or threatened releases of hazardous substances that may endanger public health or the environment. The law authorized the Environmental Protection Agency (EPA) to identify parties responsible for contamination of sites and compel the parties to clean up the sites. Where responsible parties cannot be found, the Agency is authorized to clean up sites itself, using a special trust fund.

Environmental protection

This topic includes the protection of habitat of threatened and endangered species. Federal endangered species legislation is a controversial area of law related to protecting aquatic and terrestrial habitats.

The Georgia River Corridor Protection Act provides for limitations on riparian zone development along the larger rivers and streams in the state for the purpose of protecting habitat for aquatic and riparian habitats.

Additional acts include:

- **National Environmental Policies Act.** Enacted in 1970 to establish a national policy promoting the enhancement of the environment and also established the President's Council on Environmental Quality (CEQ). NEPA's most significant effect was to set up procedural requirements for all federal government agencies to prepare Environmental Assessments (EAs) and Environmental Impact Statements (EISs). EAs and EISs contain statements of the environmental effects of proposed federal agency actions.

- **Endangered Species Act.** Passed in 1973 to protect critically imperiled species from extinction as a "consequence of economic growth and development untempered by adequate concern and conservation". The act is the most wide-ranging of the dozens of United States environmental laws passed in the 1970s. The stated purpose of the Endangered Species Act is to protect species and also "the ecosystems upon which they depend".

- **Swampbuster Provisions.** Passed in 1985 as a provision of the Food Security Act to discourage the conversion of wetlands to cropland use. Producers converting a wetland area to cropland lose eligibility for several federal farm program benefits.

- **Wild and Scenic Rivers Act.** Signed into law on October 2, 1968, by President Lyndon B. Johnson. Rivers are designated by the US Congress or the Secretary of the Interior and are preserved in their free-flowing condition and are not dammed or otherwise impeded. A total of 156 rivers had wild and scenic status in 2004. Selected rivers are preserved for possessing outstandingly, remarkable scenic, recreational, geologic, fish
and wildlife, historic, cultural, or other similar values. The intent of this law was for the federal government to preserve the status of the rivers as untouched so that generations of Americans could enjoy the recreational and natural values of the rivers.

**Careers**

**Federal agencies**

**US Geological Survey.** Agency with offices in each state that monitor streamflow, groundwater levels, and water quality.

**US Environmental Protection Agency.** Agency with nine regions in the nation, plus research facilities around the US, devoted to the regulatory oversight of water quality programs. The US EPA works to protect water resources by supporting legislation, monitoring water quality, and funding water research pertaining to quality, quantity, sustainability, distribution systems, and security.

**US Army Corps of Engineers.** Agency divided into watershed-based districts that focuses on managing water resources infrastructure.

**US Bureau of Reclamation.** Agency that focuses on managing water resources in the western US

**US Fish and Wildlife Service.** Agency that inventories and manages aquatic habitats.

**US Forest Service.** Agency that manages forest land for water, timber production, recreation, grazing, and habitat.

**US Bureau of Land Management.** Manages grazing lands for water, timber production, recreation, grazing, and habitat.

**US Bureau of Indian Affairs.** Agency that administers and manages 55.7 million acres of land held in trust by the United States for Native Americans in the United States, Native American Tribes, and Alaska Natives.

**US National Oceanographic and Atmospheric Administration.** A scientific agency within the US Department of Commerce that focuses on the conditions of the oceans and the atmosphere. NOAA warns of dangerous weather, charts seas and skies, guides the use and protection of ocean and coastal resources, and conducts research to improve understanding and stewardship of the environment.

**USDA Natural Resources Conservation Service.** Agency within the US Department of Agriculture that provides technical assistance to farmers and other private landowners and managers. Its mission is to improve, protect, and conserve natural resources on private lands through a cooperative partnership with local and state agencies. While its primary focus has been agricultural lands, it has made many technical contributions to soil surveying, classification and water quality improvement.

**USDA Agricultural Research Service.** The principal research agency of the US Department of Agriculture (USDA). ARS is one of four USDA agencies in Research, Education, and Economics (REE) mission area. ARS is charged with extending the Nation's scientific knowledge with programs in agriculture, human nutrition, food safety, natural resources, the environment, library and information services, and other topics affecting the American people on a daily basis.

**Georgia agencies**

**GA Department of Natural Resources.** Primary agency responsible for managing and regulating natural resources, composed of:

- Environmental Protection Division
- Pollution Prevention Assistance Division
- Coastal Resources Division
- Wildlife Resources Division
- Georgia Geologic Survey

**GA Soil and Water Conservation Commission.** Responsible for assisting landowners with water and soil conservation.

**GA Forestry Commission.** Responsible for assisting landowners with forest management and protection.

**GA Regional Water Management Districts.** The Georgia Comprehensive Statewide Water Management Plan was adopted by the General Assembly in 2008, providing for:

The Georgia Environmental Protection Division to conduct water resource assessments to determine how much water there is in Georgia and how much pollution the waterways can handle before water quality is unacceptably degraded;

The creation of regional water planning councils (Figure 17) to prepare recommended water development and conservation plans to characterize the water needs for each region as those needs relate to the needs of adjacent regions and the preferred management practices to use in each region to close any “gap” between water capacities and water needs;

Regional water planning guidance, including the development by major water use stakeholders of a Water Conservation Implementation Plan; and,

Water quality and water supply permitting decisions to be made by EPD in accordance with the state water plan.
Non-governmental organizations

Upper Oconee Watershed Network. The Upper Oconee Watershed Network is a non-profit organization that helps to monitor and protect water quality in the upper Oconee River watershed. This watershed includes the Middle and North Oconee rivers that flow through the Athens area, the upper reaches of the main stem of the Oconee River, and numerous smaller rivers and streams which feed these rivers. The Network is involved in a variety of projects including quarterly water quality monitoring, stream cleanup events, community educational outreach, and recreational events that showcase area streams.

Georgia River Network. Founded in 1998, Georgia River Network serves as the voice of Georgia's rivers and works to empower everyone to enjoy, connect with, and advocate for economically vital and clean flowing rivers. They connect citizens to Georgia's rivers by providing fun, meaningful and educational water adventures. This is often where responsible river stewardship begins. They are also the only organization in Georgia that provides specialized water trail development assistance.

American Rivers. They combine national advocacy with field work in key river basins to deliver the greatest impact. They are practical problem-solvers with positions informed by science to build partnerships and work closely with local river advocates, business and agriculture interests, recreation groups and others to forge win-win solutions.

The Nature Conservancy. TNC focuses on five areas, lands, waters, oceans, cities, and climate. From supporting natural solutions to climate change to creating sustainable fisheries to investing in nature in urban areas, TNC is breaking the traditional mold of “setting land aside” and working across aisles to ensure true conservation success.

Trout Unlimited. TU is an American non-profit organization dedicated to the conservation of freshwater streams, rivers, and associated upland habitats for trout, salmon, other aquatic species, and people. The organization began in 1959 in Michigan and has since spread throughout the United States.

Land Trusts. A private, nonprofit organization that, as all or part of its mission, actively works to conserve land by undertaking or assisting in land or conservation easement acquisition, or by its stewardship of such land or easements.

University of Georgia resources

UGA water resources faculty. The UGA Water Resources Faculty is an informal group of faculty who meet several times each year to discuss water resource issues and opportunities. The faculty has grown over time from an initial group of three in 1993 to over 100 faculty from ten different academic units. The primary means of communication amongst the group is a water resources listserv that also includes staff, students, and water resources professionals with an interest in water resources.

The listserv is supplemented by a website, that summarizes UGA activities related to water resources. While never formalized, the Water Resources Faculty have found that meeting and sharing information using the listserv and website helps to coordinate research, teaching, and outreach.

The UGA Water Faculty, at the behest of then-Provost Karen Holbrook in 2001, prepared a white paper, A Proposal to Form a Water Resources Faculty at the University of Georgia, which is referred to as the Keeler Report after the primary author, Professor Andrew “Andy” Keeler, who was then a professor within the Department of Agricultural and Environmental Economics, College of Agricultural and Environmental Sciences.

The Keeler Report, the result of discussions amongst twelve UGA faculty, established the rationale for a formal Water Faculty, including better internal and external teaching, research, and outreach coordination. The faculty would also provide greater visibility to the university and individual faculty. The report summarized the ongoing strengths in water resources at UGA, including 1) Measuring, Assessing, and Modifying Water Resources; 2) Aquatic Ecosystems; and 3) Human Systems, Technology and Policy.

The Keeler Report finished by recommending a number of "Next Steps", including providing resources for: 1) A full-time faculty director to devise and implement programs to achieve the goals of the faculty; 2) A Faculty Advisory Board to represent faculty interests and provide guidance; and 3) Staff to enhance internal and external communications, survey and catalog faculty activities and expertise, design and maintain a web site, and identify and help capitalize on funding opportunities. While the report represented the consensus of the water faculty, resources were not available at the time to implement the recommendations.
Institutes, Centers, and Laboratories. Within UGA, colleges, schools, and departments are devoted directly or indirectly to various aspects of water resources investigations, management, policy, and development. Additionally, many institutes, centers, and laboratories are also directly or indirectly engaged in water science, including, but not limited to:

- River Basin Center
- Carl Vinson Institute of Government
- Center for Applied Isotope Studies
- Marine Education Center and Aquarium
- Center for Remote Sensing and Mapping Science
- Center for Archeological Sciences
- Marine Institute on Sapelo Island
- Savannah River Ecology Laboratory
- Watershed Assessment Laboratory
- Environmental Process Control Laboratory
- Chemical Analysis Laboratory
- National Environmentally Sound Production Agriculture Laboratory (NESPAL)
- Natural Resources Spatial Analysis Laboratory
- Environmental Analysis Laboratory
- Geomorphology Laboratory
- LTER - Georgia Coastal Ecosystems
- LTER - Coweeta Hydrologic Laboratory
- CSREES Regional Program
- Sea-Grant Program
- Southern Regional Forestry Program

Undergraduate Certificate in Water Resources. The Undergraduate Certificate in Water Resources was approved in 2002, and graduated its first students the following year. The undergraduate certificate is administered by the UGA Water Resources Faculty, and the program is directed by Todd Rasmussen and Jenny Yearwood.

The Water Resources Certificate Program prepares students for related careers in water science and management. Protecting the long-term ecological health of our aquatic systems is an important national goal. Yet our society has ever-increasing demands for inexpensive supplies of high-quality water. The Program provides a common curriculum to meet the educational needs of the next generation of water resource scientists and managers.

Many of the courses provide hands-on experiences to learn about water resources in both laboratory and outdoor settings. The purpose of the program is to train students to manage our scarce water resources for the maximum benefit of the world’s population, while at the same time preserving the ecological integrity of our aquatic resources.

Graduate Certificate in Water Resources. The UGA Water Resources Faculty have also created a Graduate Certificate in Water Resources. The purpose of the graduate certificate is to establish a program of study that fulfills the needs of water resource professionals. The program provides incentives and structure for graduate students in water-related fields to broaden and strengthen their education in the area of water resources.

While earning a graduate degree in a specific discipline related to water resources, students in the certificate program will be introduced to other disciplines that are equally essential to creating and maintaining healthy water systems. Students who earn a Graduate Water Resources Certificate will acquire an improved understanding of the biophysical, social, and institutional aspects of terrestrial and aquatic systems.

This greater knowledge and enhanced skills strengthen graduates’ credentials for professional employment and enable greater multidisciplinary communication among future water resource professionals.

UGA Civil Engineering. The Civil Engineering curriculum has many courses related to water resources. There are many hydraulic engineering courses available, including, Hydraulics of Closed Conduit Flow, Open Channel Hydraulics, Mechanics of Jets and Plumes. All these courses and others teach valuable engineering methods for managing our water resources.

UGA Water and Soil Resources. This major is in the College of Agricultural and Environmental Sciences, Department of Crop Sciences.

UGA Geology.

UGA Geography.

UGA Atmospheric Sciences.

UGA Marine Sciences.

UGA Landscape Architecture.

UGA Odum School of Ecology.

UGA Natural Resources Management and Sustainability.

Georgia Water Resources Conference. The Georgia Water Resources Conference has been held biennially since 1989, as a collaborative gathering of people interested in Georgia’s water resources. This collaborative conference has led to the advancement of water science and management in the state by providing a neutral and open forum for diverse perspectives to be presented and discussed. Since its inception, the goal of the Georgia Water Resources Conference has been to provide an open forum for the discussion of current water policies, research, projects, and management in Georgia. Papers on topics related to water policies, legislation, research, on-going studies, technical innovations, issues and concerns, current situation and trends, new approaches, management programs, data and information, education, public participation, institutional and financial arrangements, history, culture, future needs and solutions, and other topics related to water management have been encouraged and actively solicited.

Georgia Cooperative Extension Program. As a land grant university, UGA maintains faculty in every county through the Cooperative Extension Service. While these agents have traditionally worked with agriculture, many of the current demands, especially in urban areas, are related to natural
resources and the environment. Agents routinely receive water resource related training from UGA faculty and then distribute this knowledge to the local community through county meetings and programs, local newspaper and radio shows, and through Master Gardeners, 4-H students, and other volunteers. Agents have proven to be particularly helpful in assisting local communities with stormwater and water conservation education programs. Many states (e.g., Wisconsin, Oregon, North Carolina) have implemented the concept of using Watershed Agents to implement water resource programs at the local level. While UGA has discussed this (and temporarily had one watershed agent in the Upper Oconee Watershed), lack of resources has prevented implementation of this program.

**UGA Archway Partnership.** The Archway Partnership is a vehicle to bring community stakeholders together in one room to identify and solve community problems; the mechanism that brings higher education resources to bear on those problems; and the platform embraced by the entire campus to bring to bear the full weight of UGA on local issues. A key function of the Archway Partnership is the linkage and process established to bring community stakeholders together in a routine and systematic basis to work for the betterment of their community. Local stakeholders include city and county governments, boards’ of education, chambers of commerce, development authorities, technical colleges, local colleges and universities, hospital authorities, and similar entities. The partnership provides a mechanism for grassroots needs assessment, strategic planning, and the connecting of higher education resources that can be beneficial in helping the community achieve its goals and objectives. Archway communities have established a strong reputation for collaborative effort that is unprecedented.

**Suggested reading**

These are some books of direct relevance to understanding the subject of water resources. They are generally written for the non-technical audience, and should be an easy read. Abstracts are supplied by the author, publisher, or reviewer.

**A Civil Action** by Jonathan Harr. "This riveting work of legal reportage is at once the story of an emotionally explosive lawsuit and a searing expose of the American legal system. When young lawyer Jan Schlichtmann initiates a civil suit against two of the nation's largest corporations who stand accused of the deaths of children in a Massachusetts suburb, he finds himself locked in an epic struggle that costs him his home, his reputation, and very nearly his sanity."

**Cadillac Desert** by Marc Reisner. "The story of the American West is the story of a relentless quest for a precious resource: Water. It is a tale of rivers diverted and dammed, of political corruption and intrigue, of billion-dollar battles over water rights, of ecologic and economic disaster. In Cadillac Desert, Marc Reisner writes of its earliest settlers, lured by the promise of paradise, and of the ruthless tactics employed by Los Angeles politicians and business interests to ensure the city's growth. He documents the bitter rivalry between two government giants, the Bureau of Reclamation and the US Army Corps of Engineers, in the competition to transform the West."

**Future Eaters: An Ecological History of the Australasian Lands and People** by Tim Flannery. "In this illustrated ecological history, acclaimed scientist and historian Flannery follows the environment of the islands through the age of dinosaurs to the age of mammals and the arrival of humans, to the European colonizers and industrial society. Penetrating, gripping, and provocative, this book combines natural history, anthropology, and ecology on an epic scale."

**Rising Tide: The Great Mississippi Flood of 1927 and How It Changed America** by John M. Barry. "This gripping account of the mammoth flooding of 1927 that devastated Mississippi and Louisiana and sent political shock waves to Washington is a brilliant match of scholarship and investigative journalism."

**Water Wars: Drought, Flood, Folly, and the Politics of Thirst** by Diane Raines Ward. "This is a wonderful book, a wake-up call of startling clarity and insight, with a flood of facts and anecdotes that place the abstract into riveting human perspective. I will never turn on the tap again without thinking about where water comes from and where it goes."

**Water Follies: Groundwater Pumping and the Fate of America’s Fresh Waters** by Robert Glennon. "This book is a timely and much needed wake-up call concerning the all-too-frequent pollution and misuse of the groundwater tables that America relies upon for fresh drinking water. Consisting of a selection of anecdotes about how the Santa Cruz River in Tucson went dry, the rampant greed in Tampa Bay, watershed initiatives concerning Massachusetts' Ipswich River Basin, and a great deal more, Water Follies is a clarion warning and very strongly recommended contribution for Environmental Studies reference collections."

**Unquenchable: America’s Water Crisis and What To Do About It** by Robert Glennon. "Robert Glennon captures the irony - and tragedy - of America’s water crisis in a book that is both frightening and wickedly comical. From manufactured snow for tourists in Atlanta to trillions of gallons of water flushed down the toilet each year. Unquenchable reveals the heady extravagances and everyday inefficiencies that are sucking the nation dry."

**Confluence of a River, The Environment, Politics, and the Fate of All Humanity** by Nathaniel Tripp. "Tripp, author of
Father, Soldier, Son (1997), has long been fascinated by the flow of water: I could find more in the swamp down below the high school than I ever could in the classrooms. And he has spent some of his happiest days on the Connecticut River, paddling its waterways with his sons, investigating Atlantic salmon restoration, and visiting its broad, glittering reservoirs. Each chapter in this slender volume discusses a specific watershed of the Connecticut, which divides Vermont and New Hampshire, with the exception of a side trip to northern Quebec. Tripp is a knowledgeable guide, whether discussing the dwarf wedge mussel or hydroelectric politics. The state of our rivers is grim, to be sure, but one person, argues Tripp, can make a difference. Much like the beginnings of a river itself: The river begins as all rivers do, with a drop of rain, a wisp of fog." [Review by Rebecca Maksel]

Dam Break in Georgia: Sadness and Joy at Toccoa Falls by Kenneth Neill Foster. "A true story about the flooding disaster of Toccoa Falls College on November 6, 1977. A moving story telling of the horror and subsequent victory, and of the people involved. Kelly Barnes Dam, located above the Toccoa Falls Bible College near Toccoa, Georgia, failed in the early morning hours of November 6, 1977. The campus was inundated within minutes. One dormitory had 8 ft of water on the ground floor. A trailer park associated with the college was destroyed as 10 ft of water rushed through it. Thirty-nine deaths and $2.8 million in damages occurred during this flash flood." [Review by Gregory McNamee]

Encounters with the Archdruid by John McPhee. "Born in 1915, the mountaineer and outdoorsman David Brower has arguably been the single most influential American environmentalist in the last half of the 20th century; even his erstwhile foes at the Department of the Interior grudgingly credit him with having nearly single-handedly halted the construction of a dam in the heart of the Grand Canyon, and he has converted thousands, even millions, of his compatriots to the preservationist cause through his work with the Sierra Club, Friends of the Earth, and other organizations." [Review by John McNamee]

The Founding Fish by John McPhee. "In his newest (after Annals), McPhee leads readers out to the river-pole and lures in hand-to-angle for American shad. McPhee knows where the fish are running, so to speak, and he opens with a tall tale about his long vigil with a giant roe shad on the line. Night falls, a crowd gathers on a nearby bridge to watch and still the fish refuses to roll over; however embellished, it's a comic story. He then probes the natural history of the shad, known as Alosa sapidissima and traces the fish's storied place in American history and economics. The shad manages to turn up, at least in legend, at George Washington's camp at Valley Forge; it waylaid Confederate General Pickett in the defense of Richmond and hastened the end of the Civil War; it even played a minor role in John Wilkes Booth's murder of Lincoln. McPhee consults specialists like a fish behaviorist, an anatomist of fishes and a zoo-archeologist who studies 18th-century trash pits to see whether Washington indeed ate shad at Mount Vernon. The author studies under a master shad dart maker and in an appendix gives recipes, too. McPhee reaffirms his stature as a bold American original. His prose is rugged, straightforward and unassuming, and can be just as witty. This book sings like anglers' lines cast on the water. It runs with the wisdom of ocean-going shad." [Review by Publishers Weekly]

The Control of Nature by John McPhee. "Master how-it-works writer John McPhee has instructed his readers in the arcana of how oranges are commercially graded, how mountains form, how canoes are built and oceans crossed. In The Control of Nature he turns his attention once more to geology and the human struggle against nature. In one sketch, he explores the US Army Corps of Engineers' unrealized plan to divert the flow of the Mississippi River into a tributary, the Atchafalaya, for flood control; in another, he looks at the ingenious ways in which an Icelandic engineer saved a southern harbor on that island from being destroyed by a lava flow; in a third, he examines a complex scheme to protect Los Angeles from boulders ejected from mountains by compression and tectonic movement. As always, McPhee combines a deep knowledge of his subject with a narrative approach that is wholly accessible; you may not have thought you were interested in earthquakes and flood control, but he gently leads you to take a passionate concern in such matters."

When the Rivers Run Dry by Fred Pearce. "Veteran science writer Pearce (Turning Up the Heat) makes a strong - and scary - case that a worldwide water shortage is the most fearful looming environmental crisis. With a drumbeat of facts both horrific (thousands of wells in India and Bangladesh are poisoned by fluoride and arsenic) and fascinating (it takes 20 tons of water to make one pound of coffee), the former New Scientist news editor documents a "kind of cataclysm" already affecting many of the world's great rivers. The Rio Grande is drying up before it reaches the Gulf of Mexico; the Nile has been dammed to a trickle; reservoirs behind ill-conceived dams sacrifice millions of gallons of water to evaporation, while wetlands and floodplains downriver dry up as water flow dwindles. In India, villagers lacking access to clean water for irrigation and drinking are sinking tube wells hundreds of feet down, plundering underground supplies far faster than rainfall can replace them. The same fate facing the Ogallala aquifer of the American Midwest. The news, recounted with a scientist's relentless accumulation of observable fact, is grim." [Review by Publishers Weekly]

Guns, Germs, and Steel: The Fates of Human Societies by Jared Diamond. "Explaining what William McNeill called The Rise of the West has become the central problem in the study of global history. In Guns, Germs, and Steel Jared Diamond presents the biologist's answer: geography, demography, and ecological happenstance. Diamond evenhandedly reviews human history on every continent since the Ice Age at a rate that emphasizes only the broadest movements of peoples and ideas. Yet his survey is binocular: one eye has the rather distant vision of the evolutionary biologist, while the other eye - and his heart - belongs to the people of New Guinea, where he has done fieldwork for more than 30 years." [Review on Amazon.com]
Collapse: How Societies Choose to Fail or Succeed by Jared Diamond. "This book is the glass-half-empty follow-up to his Pulitzer Prize-winning Guns, Germs, and Steel. While Guns, Germs, and Steel explained the geographic and environmental reasons why some human populations have flourished, Collapse uses the same factors to examine why ancient societies, including the Anasazi of the American Southwest and the Viking colonies of Greenland, as well as modern ones such as Rwanda, have fallen apart. Not every collapse has an environmental origin, but an eco-meltdown is often the main catalyst, he argues, particularly when combined with society's response to (or disregard for) the coming disaster. Still, right from the outset of Collapse, the author makes clear that this is not a mere environmentalist's diatribe. He begins by setting the book's main question in the small communities of present-day Montana as they face a decline in living standards and a depletion of natural resources. Once-vital mines now leak toxins into the soil, while prion diseases infect some deer and elk and older hydroelectric dams have become decrepit. On all these issues, and particularly with the hot-button topic of logging and wildfires, Diamond writes with equanimity." [Review by Jennifer Buckendorff]

A.D. New Orleans after the Deluge by Josh Neufeld. "A graphic history of hurricane Katrina in New Orleans and the aftermath. The author traces the experiences of five different groups of people as they decide to stay or evacuate, the storm, and trying to start life over after the storm."

The Two-mile Time Machine: Ice Cores, Abrupt Climate Change, and Our Future by Richard B. Alley. "Richard Alley, one of the world's leading climate researchers, tells the fascinating history of global climate changes as revealed by reading the annual rings of ice from cores drilled in Greenland. In the 1990s he and his colleagues made headlines with the discovery that the last ice age came to an abrupt end over a period of only three years. Here Alley offers the first popular account of the wildly fluctuating climate that characterized most of prehistory--long deep freezes alternating briefly with mild conditions--and explains that we humans have experienced an unusually temperate climate. But, he warns, our comfortable environment could come to an end in a matter of years."

The Long Summer: How Climate Changed Civilization by Brian M. Fagan. "Humanity evolved in an Ice Age in which glaciers covered much of the world. But starting about 15,000 years ago, temperatures began to climb. Civilization and all of recorded history occurred in this warm period, the era known as the Holocene—the long summer of the human species. In The Long Summer, Brian Fagan brings us the first detailed record of climate change during these 15,000 years of warming, and shows how this climate change gave rise to civilization. A thousand-year chill led people in the Near East to take up the cultivation of plant foods; a catastrophic flood drove settlers to inhabit Europe; the drying of the Sahara forced its inhabitants to live along the banks of the Nile; and increased rainfall in East Africa provoked the bubonic plague. The Long Summer illuminates for the first time the centuries-long pattern of human adaptation to the demands and challenges of an ever-changing climate—challenges that are still with us today."

Pompeii by Robert Harris. "All along the Mediterranean coast, the Roman empire's richest citizens are relaxing in their luxurious villas, enjoying the last days of summer. The world's largest navy lies peacefully at anchor in Misenum. The tourists are spending their money in the seaside resorts of Baiae, Herculaneum, and Pompeii. But the carefree lifestyle and gorgeous weather belie an impending cataclysm, and only one man is worried. The young engineer Marcus Attilius Primus has just taken charge of the Aqua Augusta, the enormous aqueduct that brings fresh water to a quarter of a million people in nine towns around the Bay of Naples. His predecessor has disappeared. Springs are failing for the first time in generations. And now there is a crisis on the Augusta's sixty-mile main line—somewhere to the north of Pompeii, on the slopes of Mount Vesuvius."

Salmon Country: A History of the Pacific Salmon by Robert H. Busch. "The annual migration of salmon is one of North America's greatest wildlife wonders, a sight that ranks as a must-see for the growing number of people starved for the sight of natural marvels in an increasingly high-tech world. Each year thousands of tourists crowd into British Columbia's Adams River valley to watch as the sockeye return to their spawning ground."

Angle of Repose by Wallace Stegner. "Wallace Stegner's Pulitzer Prize-winning novel is a story of discovery—personal, historical, and geographical. Confined to a wheelchair, retired historian Lyman Ward sets out to write his grandparents' remarkable story, chronicling their days spent carving civilization into the surface of America's western frontier. But his research reveals even more about his own life than he's willing to admit. What emerges is an enthralling portrait of four generations in the life of an American family."

The River Why by David James Duncan. "Since its publication in 1983, THE RIVER WHY has become a classic. David James Duncan's sweeping novel is a coming-of-age comedy about love, nature, and the quest for self-discovery, written in a voice as distinct and powerful as any in American letters. Gus Orviston is a young fly fisherman who leaves behind his comically schizoid family to find his own path. Taking refuge in a remote cabin, he sets out in pursuit of the Pacific Northwest's elusive steelhead. But what begins as a physical quarry becomes a spiritual one as his quest for self-knowledge batters him with unforeseeable experiences."

Monkey Wrench Gang by Edward Abbey. "Ex-Green Beret George Hayduke has returned from war to find his beloved southwestern desert threatened by industrial development. Joining with Bronx exile and feminist saboteur Bonnie Abzug, wilderness guide and outcast Mormon Seldom Seen Smith, and libertarian billboard torcher Doc Sarvis, M.D., Hayduke is ready to fight the power—taking on the strip miners, clear-cutters, and the highway, dam, and bridge builders who are threatening the natural habitat. The Monkey Wrench Gang is on the move—and peaceful coexistence be damned!"
The Swamp: The Everglades, Florida, and the Politics of Paradise by Michael Grunwald. "The Everglades was once reviled as a liquid wasteland, and Americans dreamed of draining it. Now it is revered as a national treasure, and Americans have launched the largest environmental project in history to try to save it. The Swamp is the stunning story of the destruction and possible resurrection of the Everglades, the saga of man's abuse of nature in southern Florida and his unprecedented efforts to make amends. Michael Grunwald, a prize-winning national reporter for The Washington Post, takes readers on a riveting journey from the Ice Ages to the present, illuminating the natural, social and political history of one of America's most beguiling but least understood patches of land."

Wetland Drainage, Restoration, and Repair by Thomas R. Biebighauser. "Wetlands are a vital part of the landscape and ecology of the United States, providing food and shelter for species ranging from the beautiful wood duck to the tiny fairy shrimp. These areas provide critical habitat for fish and wildlife, protect communities from flooding, and recharge groundwater supplies—yet they continue to be destroyed at an alarming rate. A detailed analysis of wetlands management, Wetland Drainage, Restoration, and Repair is a comprehensive guide to the past, present, and future of wetland recovery in the United States."

The Great Lakes Water Wars by Peter Annin. "The Great Lakes are the largest collection of fresh surface water on earth, and more than 40 million Americans and Canadians live in their basin. Will we divert water from the Great Lakes, causing them to end up like Central Asia's Aral Sea, which has lost 90 percent of its surface area and 75 percent of its volume since 1960? Or will we come to see that unregulated water withdrawals are ultimately catastrophic? Peter Annin writes a fast-paced account of the people and stories behind these upcoming battles. Destined to be the definitive story for the general public as well as policymakers, The Great Lakes Water Wars is a balanced, comprehensive look behind the scenes at the conflicts and compromises that are the past-and future-of this unique resource."

Cool It: The Skeptical Environmentalist’s Guide to Global Warming by Bjorn Lomborg. "A groundbreaking book that transforms the debate about global warming by offering a fresh perspective based on human needs as well as environmental concerns. Bjorn Lomborg argues that many of the elaborate and expensive actions now being considered to stop global warming will cost hundreds of billions of dollars, are often based on emotional rather than strictly scientific assumptions, and may very well have little impact on the world's temperature for hundreds of years. Rather than starting with the most radical procedures, Lomborg argues that we should first focus our resources on more immediate concerns, such as fighting malaria and HIV/AIDS and assuring and maintaining a safe, fresh water supply—which can be addressed at a fraction of the cost and save millions of lives within our lifetime. He asks why the debate over climate change has stifled rational dialogue and killed meaningful dissent."

Swimming in Circles: Aquaculture and the End of Wild Oceans by Paul Molyneaux. "Expanding on the author's year-long study of the shrimp and salmon aquaculture industries as an Alicia Patterson Foundation Fellow, the book lays out the rationale behind aquaculture development: increasing the world food supply and creating jobs in areas hard hit by declining landings in wild fisheries. However, reality is something else entirely: ravaged ecosystems and bankrupted local economies. The author expands on his existing case studies, near his homes in eastern Maine, and Sonora, Mexico, and links them to events in other parts of the world. The author's 30 years experience in fisheries and aquaculture qualifies him to weigh the rhetoric and sift out the truth of this story. In six years as a freelance journalist, writing for the New York Times, Yankee, National Fisherman, and other publications, he has managed to describe complex material in an interesting and palatable style."

Mirage: Florida and the Vanishing Water of the Eastern US by Cynthia Barnett. "Mirage is the finest general study to date of the freshwater-supply crisis in Florida. Well-meaning villains abound in Cynthia Barnett's story, but so too do heroes, such as Arthur R. Marshall Jr., Nathaniel Reed, and Marjorie Harris Carr. The author's research is as thorough as her prose is graceful. Drinking water is the new oil. Get used to it." [Michael Gannon, Distinguished Professor of history, University of Florida]

Blue Revolution: Unmaking America's Water Crisis by Cynthia Barnett. "Americans see water as abundant and cheap: we turn on the faucet and out it gushes, for less than a penny a gallon. We use more water than any other culture in the world, much to quench what's now our largest crop—the lawn. Yet most Americans cannot name the river or aquifer that flows to our taps, irrigates our food, and produces our electricity. And most don't realize these freshwater sources are in deep trouble. Blue Revolution exposes the truth about the water crisis—driven not as much by lawn sprinklers as by a tradition that has encouraged everyone, from homeowners to farmers to utilities, to tap more and more. But the book also offers much reason for hope. Award-winning journalist Cynthia Barnett argues that the best solution is also the simplest and least expensive: a water ethic for America. Just as the green movement helped build awareness about energy and sustainability, so a blue movement will reconnect Americans to their water, helping us value and conserve our most life-giving resource. Avoiding past mistakes, living within our water means, and turning to “local water” as we do local foods are all part of this new, blue revolution."

Rain: A Natural and Cultural History by Cynthia Barnett. "Cynthia Barnett's Rain begins four billion years ago with the torrents that filled the oceans, and builds to the storms of climate change. It weaves together science—the true shape of a raindrop, the mysteries of frog and fish rains—with the human story of our ambition to control rain, from ancient rain dances to the 2,203 miles of levees that attempt to straitjacket the Mississippi River. It offers a glimpse of our "founding forecaster," Thomas Jefferson, who measured every drizzle long before modern meteorology. Two centuries later, rainy
skies would help inspire Morrissey’s mopes and Kurt Cobain’s grunge. Rain is also a travelogue, taking readers to Scotland to tell the surprising story of the mackintosh raincoat, and to India, where villagers extract the scent of rain from the monsoon-drenched earth and turn it into perfume.”

**Homework**

**A. History**

1. Describe how an ancient culture (e.g., Chinese, Egyptian, Persian, Babylonian, Mayan) described water resources.
2. Create a diagram depicting the water cycle as it was understood by one of the ancient civilizations.
3. Religious literature often provides the earliest accounts of the role of water in human society. Search for references to water in religious literature using either published or internet sources. Note the importance or role of water in the reference.

**B. The role of science**

1. Download maximum annual water levels from the so-called Nilometer. Summarize the source of the data and the types of behavior it displays.
2. There are many water resources engineering marvels from the ancient past. Pick one and describe its purpose and relevance to the society of its time.
3. Select a scientist from the past who had some influence on changing how we think about water resources. Describe how they contributed to our modern understanding.
4. Provide an example of an ancient water engineering feat and describe how its principles are still applicable today.
5. Research and discuss a modern, sustainable method or device used with respect to water resources.

**C. Landscape features**

1. Describe each of the five physiographic regions of Georgia. How do the Northern and Southern Fall Lines relate to these features?
2. Identify the major types of aquifers in Georgia, and where they are located.
3. How do soils vary across the state?
4. Find a map of land uses of Georgia. Where are most of the urban areas located? Forested? Agricultural?
5. How do you think Georgia land use and population will change over the next century? Millennium?
6. How does the supply and demand for water change throughout different regions of the US? What factors (landforms, aquifers, population, etc.) play roles in the differing geographical water requirements?
7. Using [this web tool](#), pick one of the physiographic regions of GA and describe a typical soil profile of the region.

**D. Hydrologic features**

1. Delineate a major watershed in Georgia using a map of the rivers and streams.

2. Find the mean annual flow for this watershed using U.S. Geological Survey stream gauging data.
3. Find the water yield for this watershed by dividing the mean annual flow by the watershed area.
4. Find the runoff efficiency by dividing the mean annual flow by the mean annual precipitation.
5. Confirm the data in Tables 1-4.
6. Find the area of the largest wetland in Georgia. How does this compare to other wetlands in the United States? In the world?
7. Name the major stream network types and where in Georgia you would find a representative of each.
8. Assuming Dupuit conditions, how does water flow in an unconfined aquifer, confined aquifer, aquitard, and aquiclude.
9. Describe the difference between porosity, intrinsic permeability, and hydraulic conductivity in relation flow within a wetland and fractured shale bedrock.

**E. Streamflow sources**

1. What is Hortonian flow? Would you be more likely to witness this phenomenon in a parking lot or a forest? Defend your answer.
2. Discuss what must happen for Horton overland flow to occur and describe a few factors that may contribute to the occurrence of overland flow. What type of locations is this likely to happen?
3. Describe the processes involved in forming a wetland.
4. Select a USGS groundwater monitoring well and a nearby precipitation gage. How do the head levels in the well respond to precipitation events? How much lag is there between the precipitation event and aquifer response?

**F. Current issues**

1. Select a recent or current regional water conflict. Describe the issues that have led to the conflict and any steps that have been taken to address them.
2. Think about your hometown, how is water viewed in your community? What are the major water resource issues within your community, and how can they be resolved?
3. What are some recent hydrological innovations that have been in the news, magazines, articles, etc.? Find a recent news story that involved water resources. Quickly summarize it. Do you agree with the perspective that was taken? Why?
4. Select a movie to watch on some aspect of water resources. Describe the setting, characters, and plot. Indicate how important the movie was in terms of changing the way we think of water.
5. Select a book to read on some aspect of water resources. Describe the setting, characters, and plot. Indicate how important the book was in terms of changing the way we think of water.
G. Legislation and policy

1. Describe a river that benefited from the Wild and Scenic Rivers Act.
2. Compare two pieces of legislation and their effects on water resource management.
3. Create your own water resource legislation based on a water quality problem that troubles you.
4. Select an important piece of water resources legislation. Discuss the intent of the legislation with respect to water resources.
5. If a rapid change in the global climate is observed in the next few years, can you suggest legislation to deal with it?
6. Provide a basic and broad view explanation of how the US Federal Government's perspective and management of water resources has changed over the past fifty years.

H. Careers

1. Describe an academic program related to water resources at the University of Georgia. Identify and describe a faculty member in that program that is involved in water resources. Indicate what kind of teaching, research, or extension activities they are involved with.
2. Describe the UGA Water Resources Certificates. What are some advantages to gaining a UGA Undergraduate or Graduate Water Resource certificate? Identify the classes that would be of interest to you that would allow you to get a certificate.
3. What are some future needs from engineers and scientists in the areas of water resources? Name several activities that could be implemented to help improve situations in areas that have severe water problems.
4. Select a state or federal agency and discuss their mission and role with respect to water resources.
5. Name and describe the mission of an NGO that works on water resources in a watershed where you have lived.
6. Describe a professional engineering or geotechnical firm that hires hydrologists. What kinds of career opportunities do they offer?