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ARCHEOLOGY OF INLAND WATERS

Of all our planet’s activities—geological movements, the reproduction and decay of biota, and even the disruptive propensities of certain species (elephants and humans come to mind)—no force is greater than the hydrologic cycle.

Richard Bangs & Christian Kallen, River Gods

All the rivers run into the sea; yet the sea is not full; unto the place from whence the rivers come, thither they return again.

Ecclesiastes 1:7

I’ve known rivers:
I’ve known rivers ancient as the world and older than the flow of human blood in human veins.
My soul has grown deep like the rivers.
I bathed in the Euphrates when dawns were young.
I built my hut near the Congo and it lulled me to sleep.
I looked upon the Nile and raised the pyramids above it.
I heard the singing of the Mississippi when Abe Lincoln went down to New Orleans, and I’ve seen its muddy bosom turn all golden in the sunset.
I’ve known rivers:
Ancient, dusky rivers.
My soul has grown deep like the rivers.

Langston Hughes (1902–1967), The Negro Speaks of Rivers

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In 1913 the Los Angeles Aqueduct was completed and began delivering water to the City of Los Angeles from the Owens River. With a modest allotment, ranchers and irrigators still enjoyed an adequate supply of water, but after learning that additional water supplies were needed, the City began taking all of the water in the river. Reaching a boiling point for the Owen Valley residents, a group of ranchers blew up segments of the canal, as a protest and perhaps getting water back. As a vivid example of water as contested commodity, we need to appreciate the socioeconomic, cultural, and political dimensions of water are confronted with the acknowledgment that water is political.
In the distant past, nomadic people needed water for drinking, feared floods, and used water environments for fishing and hunting. After becoming sedentary agriculturists dug wells, irrigated land, and built levees for flood protection—to reduce resource insecurities. Infrastructure developments require well-organized societies, which become symbols of progress and identity, like the aqueducts of the Roman Empire, canals in China, and dams in the United States.

Monuments documenting water technology provide a historical perspective in our development of water, where water becomes “as a resource” provides safe drinking supplies, irrigation allotments, transportation routes, managed fisheries, concentrated power generation, elitist aesthetics, and monetized recreation. When water fails to deliver these products, we are confronted by the contradictions of modernity.

The human condition depends on our planet’s inland waters. An effective use of water can impart success, whereas an ineffective use can lead to disaster. If nothing else, like all life forms on Earth, humans require water—water that is both reliably available and free of contaminants and pathogens. Meeting these goals is, perhaps, one of the greatest challenges of human kind. In this chapter, we introduce and analyze case studies to expose the evolving nature of our relationship with water.

After reading this chapter, you should be able to

1. Describe how water use has been central to the development of human societies;
2. Explain how the geography of a place provides specific opportunities and constraints in human-water relations;
3. Describe unintended consequences of water development projects;
4. Summarize examples aimed to improve the sustainable use of water.

**DRINKING WATER AND WASTE**

If there is a universal use of water for humans it starts with drinking water. Yet, securing safe and reliable drinking water supplies continues to be out of reach for over 30% of the world’s population. In fact, it begs the question if there were ever periods of time that humans had access to safe and reliable drinking water supplies.

Part of the question is answered by the extent that people have access to proper waste treatments, which is ~30%! In a rapidly developing planet, increasing concentrations of human settlements means increasing human waste and limited ecosystem capacity to process the waste. Thus as human density increases, the society must improve the infrastructure with plumbing that separates drinking waters from waste waters.

**THE WATER CYCLE**

Water falls to the Earth with relatively low concentrations of salts—although slightly higher when rain clouds form over oceans, due to aerosols of salt produced by the ocean. The precipitation is starting point for freshwaters and falls to the surface as snow or rain in land or on water. On land, water flows from higher elevation to lower elevation basins. The catchment area, the area that facilitates the
movement of surface water to a basin is called a watershed (Fig. 2.1), although many English speaking countries might refer to these as catchment areas. As the water interacts with the landscape, e.g., soils, geologic formations, vegetation, and human activities, the water picks up additional salts and chemicals and carries them to the basin’s outlet.

These processes define the waters available for drinking water. We cannot drink seawater, thus rely on the water cycle to provide relatively dilute concentrations of salts.

Water returns to the atmosphere via evaporation or evapotranspiration (through the leaves of plants). As part of this evaporation process, water fractionates the relative abundance of stable isotopes.

Both Hydrogen and Oxygen have a few stable isotopes—atoms with different numbers of neutrons, thus different weights. The isotopes are stable because they are not in the process of decaying or giving off radiation (radiogenic). Some isotopes are very rare, so we will look at the ones that are commonly measured.

Hydrogen usually has no neutrons, but it can also have one and remain stable. Hydrogen atom with one neutron is referred to as Deuterium and can be symbolized as $^2\text{H}$ or D with different relative abundances: 99.98% H and 0.0156% D. Oxygen has three stable isotopes, which has 8, 9, or 10 neutrons, symbolized as $^{16}\text{O}$, $^{17}\text{O}$, and $^{18}\text{O}$, respectively. They also have differing relative abundances on Earth: 99.76% = $^{16}\text{O}$, 0.04% = $^{17}\text{O}$, and 0.20% = $^{18}\text{O}$. Of course, composed of $\text{H}_2\text{O}$ (two Hydrogen atoms and one Oxygen atom), water can have several combinations of isotopes with differing molecu-
lar weights (MW) and average natural abundances.\footnote{Note the differences between what might be more easily detected and relative fractionation potential. Note that these averages are so sensitive to fractionation that the relative abundances are not found in any given system. Sorted by relative abundance.} Because some of these combinations are so rare, we can effectively ignore them.

Returning to fractionation, it is relevant to note that it is similarly related to mass differences between the nuclei of isotopes, but is associated with incomplete and unidirectional processes, such as evaporation and diffusion. In general, the lighter isotope will react faster and will become concentrated in products.

For water, the higher the mass number, the lower the vapor pressure. Thus \(^{16}\text{O}\) and H preferentially enter the vapor phase, whereas \(^{18}\text{O}\) and D preferentially concentrate in the liquid phase. Consequently, in evaporation, water vapor is enriched in \(^{16}\text{O}\) and H, whereas the remaining liquid water is enriched in \(^{18}\text{O}\) and \(^{2}\text{H}\). More specifically, \(^{18}\text{H}_2\text{O}\) is enriched in liquid water by 1\% relative to its concentration in water vapor at the same temperature.

The fate of water can be “followed” using isotopic abundances as it completes the water cycle (Fig. 2.2). Various pools have signatures that reflect the fractionation processes (Table 2.1): evap-

![Figure 2.2](image-url)

**Figure 2.2**
Water fractionation modified from Sodemann (2006).

| Isotope   | MW | Relative Abundance (%) |
|-----------|----|------------------------|
| \(^{18}\text{H}_2\text{O}\) | 18 | 99.72                  |
| \(^{18}\text{H}_2\text{O}\) | 20 | 0.20                   |
| \(^{18}\text{H}_2\text{O}\) | 19 | 0.040                  |
| HD\(^{16}\text{O}\) | 19 | 0.016                  |
| HD\(^{18}\text{O}\) | 21 | 3.1 \(\times 10^{-5}\) |
| HD\(^{17}\text{O}\) | 20 | 6.3 \(\times 10^{-6}\) |
| D\(^{16}\text{O}\)    | 20 | 2.4 \(\times 10^{-6}\) |
| D\(^{18}\text{O}\)    | 22 | 4.9 \(\times 10^{-9}\) |
| D\(^{17}\text{O}\)    | 21 | 9.7 \(\times 10^{-10}\) |
Table 2.1 Stable isotopes of water.

| Natural Reservoir               | δ¹⁸O‰ | δD‰  |
|--------------------------------|-------|-------|
| Ocean Water                    | -6 – +3| -28 - +10 |
| Arctic Sea Ice                 | -3 – +3| 0 – +25 |
| Marine moisture                | -15 – -11| -100 – +75 |
| Lake Chat                      | +8 – +16| +15 – +50 |
| Alpine Glaciers                | -19 – -3| -130 – -90 |
| (Sub)Tropical precipitation    | -8 – -2| -50 – -100 |
| Mid-latitude precipitation     | -10 – -3| -80 – -20 |
| Mid-latitude snow              | -20 – -10| -160 – -80 |

oration, precipitation, freezing, melting, sublimation, etc. These fractionation processes allow us to evaluate the residence time for water in each pool—oceans, atmosphere, glacial ice, alpine lakes, etc.

Before completing the water cycle, water interacts with the lithosphere or biosphere in a myriad number of ways. Water in glaciers or groundwater might be stored for hundreds of thousands or millions of years. Water might flow through creeks and streams and into major rivers and estuaries before ending up in the ocean, where the average time a water molecule remains is about 3000 years. In contrast, the average time in the atmosphere is about 9 days.

RELIABLE WATER SUPPLIES

Singapore receives approximately 2.3 meters of rain per year. This is over twice as much rainfall as Seattle and Dallas, Texas, both of which receive about 852 mm of rain per year. Whereas we might think of Seattle as a wet city, the rainfall in Dallas is surprising when we think of the region as arid. More surprising yet is that Singapore’s government acknowledges that their water supply is tenuous, because storing the water is extremely difficult in small country (Fig. 2.3). Stored water for human use relies on lakes and reservoirs and groundwater. If the geology of a region does not have water bearing formations, i.e., aquifers, to develop, then topography might be used to store water behind dams. If these characteristics are not adequate or the funding is absent to build big dams, communities might rely on surface waters, which can be notoriously finicky. For example, Cape Town, South Africa nearly reached a complete shut down of its municipal water supply in 2018, demonstrating its vulnerability even with reservoirs.

Of course, the water supply in many regions relies on groundwater. One of the most obvious, but poorly captured by policy makers, is the fundamental relationship between surface and ground waters. In part, due to pumping and climate change, groundwater elevations are changing. The GRACE satellite mission has done well to document these changes by analyzing changes in the Earth’s gravity. Throughout the book, we will reference the relevance of the relationships between surface and groundwater as an ecologically important and economic value, especially as aquifers are overpumped (Fig. 2.4).
FIGURE 2.3
Upper Peirce Reservoir in Singapore.

SOCIAL COSTS OF LEAD PLUMBING

Plumbing to improve water supplies has been a marker of development and advances to democratize indoor plumbing has been a key aspect of economic development. Lead (Pb) was convenient to use for plumbing—for many centuries, lead was the favored material for water pipes, because its malleability made it practical to work it into the desired shape. In fact, its use was so common that the word “plumbing” is derived from the Latin word for lead—plumbum (Fig. 2.5).

Use of lead for water pipes may have been the most damaging feature of the advanced water technology of ancient times. Even before the health hazards of ingesting lead was understood, the lead-related health problems, such as stillbirths and high rates of infant mortality, was linked to lead piping. Nevertheless, lead water pipes were still widely used in the early 20th century, and remain in many households.

Despite the Romans’ common use of lead pipes, their aqueducts rarely poisoned people. Unlike other parts of the world, where lead pipes cause poisoning, high calcium concentrations created a layer of plaque that prevented the water contacting the lead itself in Roman plumbing.

And yet the use of Pb in water pipes is a reoccurring public health threat. Even in highly developed countries, the historic use of Pb pipes remains problematic. Old lead pipes used in the water system of Flint, Michigan has been linked to a public health crisis. The root cause of the Flint lead crisis was corrosion. For 50 years, Flint had purchased its water from Detroit, 90 miles away. However, in 2014, it switched water sources to save money without appreciating how the slightly more acidic water of the Flint River would impact the city’s pipes.

Furthermore, officials did not use common corrosion control methods that Detroit and many other cities use in their water systems, e.g., adding phosphates to the water to help keep lead from dissolving into the water flowing through the pipes. The corrosive water pumping underneath Flint quickly ate away at the protective layer inside the city’s old lead pipes, exposing bare lead to the water flowing through them. When the city switched water supplies, a protective layer of rust began to be stripped away from the interior of the pipes, strongly discoloring the water and leaching the lead from that rust into the water (Fig. 2.6).
FIGURE 2.4
Map of the United States (excluding Alaska) showing cumulative groundwater depletion, 1900 through 2008, in 40 assess aquifer systems or subareas (Source: USGS).

FIGURE 2.5
Lead water pipe, Roman, 1–300 CE. The inscription cast into the side of the pipe indicates that the work was undertaken by a team under an “Imperial Freeman Procurator Aquarum” — an official in charge of maintaining the water supply. In some cases, piped water supplies in the Roman empire were quite complex and sophisticated.
The most vulnerable population, children, suffer both short- and long-term affects, including the loss of memory, eye-hand coordination, and appropriate weight gain. Some of the people responsible were criminally charged for an assortment of crimes. As environmental scientists, we must be vigilant to protect vulnerable populations by working hard to understand the history and science of the lessons to manage infrastructure appropriately.

WASTES AND WATERBORNE DISEASES

Of course, for many it is not merely access to water that is important, but water free from water-borne diseases. From a public health perspective, the threats posed by water-borne diseases are always a concern—but these risks are unevenly distributed across the globe.

It is not likely that we would have much concern about the fate of human waste if it was not associated with disease, but understanding this relationship has been unevenly appreciated across various cultures, and our capacity to reduce the risks associated with human waste has also been a process in human development.

Waterborne diseases are caused by pathogenic microorganisms that most commonly are transmitted in contaminated freshwater. Infection commonly results during bathing, washing, drinking, in the preparation of food, or the consumption of food that is infected, caused by a range of organisms (Table 2.2). Various forms of waterborne diarrheal disease probably are the most prominent examples, and affect mainly children in developing countries; according to the World Health Organization, such diseases account for an estimated 3.6% of the total DALY global burden of disease, and cause about 1.5 million human deaths annually. The World Health Organization estimates that 58% of that burden, or 842,000 deaths per year, is attributable to unsafe water supply, sanitation, hygiene, and cleanliness.

HYDROLOGY: APPLIED SCIENCE FOR PROGRESS

Hydrology is the study of water flow. Using Newtonian physics, hydrologists related water velocity (m/s), water flow (m$^3$/s), velocity head ($v^2/2g$), and hydraulic head ($\psi + z$), where m is meters, s is second, $v$ is velocity (m/s), $\psi$ is difference in elevations, and $z$ is the bottom of water table.
Table 2.2 Major water-borne illnesses.

| Disease         | Agent                  | Source                                                                 | Symptoms                                                                                      |
|-----------------|------------------------|-------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| Amoebiasis      | Entamoeba histolytica  | Nontreated drinking water, flies in water supply                        | Abdominal discomfort, fatigue, weight loss, diarrhea, bloating, fever                         |
| Cryptosporidiosis| Cryptosporidium parvum | Water filters and membranes that cannot be disinfected, animal manure, seasonal runoff of water. | Flu-like symptoms, watery diarrhea, loss of appetite, substantial loss of weight, bloating, increased gas, nausea |
| Cyclosporiasis  | Cyclospora cayetanensis| Nontreated drinking water                                                | Cramps, nausea, vomiting, muscle aches, fever, and fatigue                                    |
| Giardiasis      | Giardia lamblia        | Untreated water, poor disinfection, groundwater contamination, campgrounds where humans and wildlife use same source of water. Beavers and muskrats create ponds that act as reservoirs for Giardia. | Diarrhea, abdominal discomfort, bloating, and flatulence                                       |
| SARS (Severe Acute Respiratory Syndrome) | Coronavirus | Manifests itself in improperly treated water | Symptoms include fever, myalgia, lethargy, gastrointestinal symptoms, cough, and sore throat |
| Hepatitis A     | Hepatitis A virus      | Can manifest in water and food                                           | Symptoms are only acute and include fatigue, fever, abdominal pain, nausea, diarrhea, weight loss, itching, jaundice and depression. |
| Poliomyelitis (Polio) | Poliovirus     | Enters water through the feces of infected individuals                  | Symptoms vary, from delirium, headache, fever, and occasional seizures; to spastic paralysis, non-paralytic aseptic meningitis; or even paralysis or death |

Henry Darcy, a French hydraulic engineer interested in purifying water supplies using sand filters, conducted experiments to determine the flow rate of water through the filters. As a member of the Corps, Henry built an impressive pressurized water distribution system in Dijon following the failure of attempts to supply adequate freshwater by drilling wells. The system carried water from Rosoir Spring 12.7 km away through a covered aqueduct (watercourse) to reservoirs near the city, which then fed into a network of 28,000 meters of pressurized pipes delivering water too much of the city. The system was fully closed and driven by gravity, and thus required no pumps with just sand acting as a filter. Later, he conducted column experiments that established what has become known as Darcy’s law; initially developed to describe flow through sands, it has since been generalized to a variety of situations, and is in widespread use today.

Darcy’s law that discharge rate \( Q \) is a simple proportional relationship between the instantaneous discharge rate through a porous medium, the viscosity of the fluid, and the pressure drop over a given
FIGURE 2.7
Darcy used sand filters to develop equations for the pressure changes that have been used to design water treatment facilities and groundwater models (drawn by Luyi Huang).

\[ Q = -\frac{\kappa A (p_b - p_a)}{\mu L}. \]  

The total discharge, \( Q \) (units of volume per time, e.g., \( \text{m}^3/\text{s} \)) is equal to the product of the intrinsic permeability of the medium, \( \kappa \) (\( \text{m}^2 \)), the cross-sectional area to flow, \( A \) (units of area, e.g., \( \text{m}^2 \)), and the total pressure drop \( \rho_b - \rho_a \) (pascals), all divided by the viscosity, \( \mu \) (\( \text{Pa} \cdot \text{s} \)) and the length, over which the pressure drop is taking place \( L \) (m). The negative sign is needed because fluid flows from high pressure to low pressure. Note that the elevation head must be taken into account if the inlet and outlet are at different elevations. If the change in pressure is negative (where \( \rho_b > \rho_a \)), then the flow will be in the positive \( x \)-direction. There have been several proposals for a constitutive equation for absolute permeability, and the most famous one is probably the Kozeny equation (also called Kozeny–Carman equation) (Fig. 2.7).

Dividing both sides of the equation by the area and using more general notation leads to

\[ q = -\frac{\kappa}{\mu} \nabla p, \]  

where \( q \) is the flux (discharge per unit area, with units of length per time, m/s) and \( \nabla p \) is the pressure gradient vector (Pa/m). This value of flux, often referred to as the Darcy flux or Darcy velocity, is not the velocity which the fluid traveling through the pores is experiencing.
It might be hard to see how these equations might revolutionize the science of water—but these are the foundation of water treatment facilities that have been used to reduce the risk of water-borne diseases and allow urban centers to become increasingly dense.

**FISHERIES AND FOOD**

Obtaining fish as food dates back over 100,000 years for hominids. Prehistoric artifacts—fishing hooks, fishing nets, and discarded fish bones—are ubiquitous ancient human populations. In East Timor, a 42,000 year old fish hook documents pelagic fishery. There is no doubt that humans have been exploiting inland fishes and mollusks well before this documented example.

Currently, 94% of the developing world rely on fish diets. And 6% of the world’s protein comes from fish, whereas in some cases, some countries are composed of over 20% fish diets. The most common species include salmon, talapia, carp, catfish, and trout.

In one example, almost all fisheries in the Zambezi River system have experienced severe declines in catch rates, loss of larger, most valuable fish species, and increased use of environmentally damaging active fishing gears. The fisheries of the Barotse, Caprivi, and Kafue floodplains, and lakes Kariba (Zambian sector), Malawi and Malombe are all fished down. The concept of balanced harvesting with moderate effort has no relevance to these African inland fisheries, where rapid human population growth and lack of alternative livelihoods for small-scale fishers means they have no choice but to continue fishing despite dwindling returns. In some areas, e.g., Liuwa Plain National Park in Zambia and conservancies in Namibia, comanagement with local communities has potential for success, but other fisheries, e.g., Lake Malombe in Malawi, are so severely fished down that there is no prospect of recovery without radical restructuring of exploitation patterns coupled with habitat restoration.

**CROP DOMESTICATION AND IRRIGATION**

Neolithic periods saw the importance of three cereals—emmer, einkorn and barley, however, other crops were soon domesticated as well: flax, peas, chickpeas, bitter vetch, and lentils. In the corridor around the Fertile Crescent and later in Europe, domestication may have occurred over a relatively short period of between 20 and 200 years.

Early irrigation schemes, which promoted crop surpluses was the likely start of hydromodification (Fig. 2.8).

**ARID CLIMATES: PRE-COLOMBIAN COMMUNITIES**

Like many cultures in arid climates, Native Americans developed sophisticated irrigation systems to improve the reliability of water supplies and maintain domesticated crops. In the south-west, Hohokam people canals to bring river water to fields dated back to 2000 BCE. Rainwater-capture systems, which were well developed by the Pueblo peoples, is another example of social organization and the development of water infrastructure (Fig. 2.9).
FIGURE 2.8
Mesopotamia irrigation system (Source: Persian Qanat Iran Heritage).

FIGURE 2.9
Rainwater was captured by early Puebloans, which was directed to small plots to grow various crops (Source: National Park Service).

IRRIGATION AND LEGAL SYSTEMS
The first reservoirs were built for irrigation. But to be effective, in whatever environment, these reservoirs required agreements between users to maintain the reservoirs and ensure an adequate distribution. Ancient irrigation codes impress modern irrigation specialists because of their longevity. The Spanish agricultural cooperatives were probably built on a foundation of social networks built around common lands and irrigation communities. With high levels of human capital and the existence of a wide layer of middle size farms, cooperative irrigation systems developed.
MIGRATIONS, COLONIZATION, AND TRANSFORMATIONS

The expansion and migration of human populations has been a constant process, each group bringing with them certain cultural practices. For example, hunters who have reached new regions, e.g., North America, may have reduced the size of megafauna and introduced new species. Not only have species introductions been one of many ecological transformations, the landscape was altered as people brought certain cultural ideas and ideologies with them. For example, the native peoples and the landscape of Baja California were transformed by colonization by Spanish colonialists. As a mix of practical and religious meaning, the Jesuit priest missionaries appreciated surface waters, called oases, which were used to support introduced crops and development of predictable water supplies. As a result, these oases became sacred places and now support heritage crops, biodiversity, and traditional foods (Fig. 2.10).

In California Alta (nominally the state of California), missions were built with the same colonizing goals that displaced native peoples, while also developing irrigation systems to support the mission crop production. For example, the Los Angeles Mission was one of the first projects to alter the Los Angeles River that would culminate with the replacing the channel with concrete levies.

IRRIGATION SCHEMES: DISTRIBUTION AND RESERVES

The Dujiangyan irrigation scheme has served China for 18 centuries. Like the Roman aqueducts, this system provides cultural symbols of organizational capacity and planning that have become emblematic of cultural organization. Originally constructed around 256 BC by the State of Qin as an irrigation and flood control project, the system’s infrastructure is on the Min River (Minjiang), the longest tributary of the Yangtze. Originally, the Min rushed down from the Min Mountains, but slowed abruptly after reaching the Chengdu Plain, filling the watercourse with silt, which made the nearby areas extremely prone to floods. Li Bing, then governor of Shu for the state of Qin, and his son headed the construction of the Dujiangyan, which harnessed the river using a new method of channeling and dividing the water rather than simply following the old way of dam building (Fig. 2.11). The Dujiangyan irrigates over 5300 square km of land in the region.
EXORHEIC AND ENDORHEIC BASINS

Historically, there have been highly variable Pleistocene Lakes in Great Basin and many of them have gone dry with the melting of the ice-sheets. In the anthropocentric, the rate of drying has been increasing dramatically. For example, the Aral Sea has been declining rapidly due to agricultural diversions, and the North American’s endorheic lakes face the same plight, e.g., Walker Lake and Pyramid Lake (Fig. 2.22).

The outlet of many watersheds drain into the ocean; these watersheds are called exorheic. However, many waters cannot drain to the ocean because they are surrounded by mountains. These basins are called endorheic. In fact, much of the continental United States contain basins that do not drain into the ocean. Mono Lake (California), the Great Salt Lake (Utah), Pyramid Lake (Nevada), Devils Lake (North Dakota), and even Death Valley (California) are examples endorheic basins in the United States. Well known examples of endorheic basins in other countries include the Aral Sea (Kazakhstan / Uzbekistan) and Lake Chad (Chad).

Because endorheic basins have no outlet, water exits the basin by evaporation. Thus the salts or other chemicals dissolved in the water remain in the water, where their concentrations will increase for thousands of years or more. The balance between inflow and outflow in these basins depends on the regional climate, and as you might guess, are very vulnerable to climate changes or water diversions by humans.

In both surface and groundwater sources, the balance between inputs and outputs is a key indicator of the sustainability of their use. If lakes are declining or groundwater withdrawals exceed recharge, then the use of the basins are out of balance, indicating unsustainable water use. Water withdrawals from the Aral Sea watershed is one of the most dramatic examples of unsustainable water use, where salt concentrations exceeded the physiological limits of the fish, leading to the collapse of the fishery (Fig. 2.12).

WATER AND TRANSPORTATION

THE GRAND CANAL

The Grand Canal or the Beijing–Hangzhou Grand Canal is the longest canal in the world (1776 km). Starting at Beijing, it passes through Tianjin and the provinces of Hebei, Shandong, Jiangsu, and Zhejiang to the city of Hangzhou, linking the Yellow River and Yangtze River. The oldest parts of the canal
date back to the 5th century BC, although various dynasties expanded, rebuilt, and altered the canal over time. The canal was designed to transport goods between the provinces, but could also be used to flood attacking armies in low lying areas.

**COLONIZATION: SUEZ, PANAMA, AND NICARAGUA CANALS**

The idea of constructing a canal connecting the Mediterranean and the Red Sea was first proposed by French engineers during Napoleon Bonaparte’s occupation of Egypt, but construction did not commence until 1859 and was completed 10 years later. For the next 87 years, it remained largely under British and French control, and Europe depended on it as an inexpensive shipping route for oil from the Middle East. Since its construction, the canal reenforced colonial power, a symbol for the aspiration for sovereignty and proximate causes of armed conflicts for regional and geopolitical aims—the Suez Canal is more than just a ditch filled with water in the desert.

In addition, the canal has had ecological impacts. For example, the Bitter Lakes, which were hypersaline natural lakes, were linked by the canal. At first, because of the high salinity, they prevented Red Sea species from invading the Mediterranean. However, the lakes gradually equalized with canal water from Red Sea, and plants and animals from the Red Sea colonized the eastern Mediterranean.

Invasive species that originated from the Red Sea and introduced into the Mediterranean by the canal have become a major component of the Mediterranean ecosystem and have serious impacts on the ecology, endangering many local and endemic species. About 300 species from the Red Sea have been identified in the Mediterranean, and there are probably others yet unidentified.
Not to be outdone by the Europeans, the United States supported Colombian rebels and an independent Panama to construct the Panama Canal. The treaty imposed on the newly independent Panama ensured that the profits went to US businessmen and investors with little return to Panama. The embittered Panamanians finally won control of the Panama Canal in 1977, and the United States formally withdrew from the Canal Zone, which had been a US territory.

The project planners then had to find a way to fill this area above the sea with water. They found such a good opportunity in the Chagres River, which they used to build a dam. The dam flooded a massive area close to the river, and thus helped create the Gatun Lake, which now forms the main part of the canal (Fig. 2.13). Since the canal is above the sea level, it needs an effective transit mechanism that would lift and lower the vessels as they pass along the waterway. This mechanism comes in a system of locks which work at several stages of the canal’s length, and do just that—lift and lower the ships. To operate properly, the canal has to use vast amounts of water, which is collected during the rainy season. The Gatun Lake is also very important as a water source for the canal’s operation during the dry season. The isolation, completed by 1914, of Barro Colorado Island from mainland Panama by the waters of Gatun Lake, accelerated extinction on this island, because populations threatened by local extinction were now much less likely to be reinforced or reestablished by colonists from elsewhere. In addition, introduced species have reshaped the food web of the lake (see Chapter 3).

In June 2013, Nicaragua’s National Assembly approved a bill to grant a 50-year concession to finance and manage the project to the private company headed by a Chinese billionaire. The concession can be extended for another 50 years once the waterway is operational. Media reports suggest the project would have been delayed or even possibly canceled, but such projects seem to have the capacity to be resurrected depending on the political and economic context.

Scientists are concerned about the project’s environmental impact, as Lake Nicaragua is Central America’s key freshwater ecosystem, where endemic freshwater sharks live (Fig. 2.14). Construction of a canal using the San Juan River as an access route to Lake Nicaragua was first proposed in the early colonial era. The United States abandoned plans to construct a waterway in Nicaragua in the early 20th century after it purchased the French interests in the Panama Canal. By May 2017, no concrete action had been reportedly taken to construct the canal and doubts were expressed about its financing.

**WATER AND POWER**

**INDUSTRIALIZATION AND WATER**

Industrialization requires power. Although coal could be used to create steam and drive mechanical force, the use of wind and water dates back even further. A waterwheel is a machine for converting the energy of flowing or falling water into useful forms of power, often in a watermill (Fig. 2.15). A waterwheel consists of a wheel (usually constructed from wood or metal), with a number of blades or buckets arranged on the outside rim, forming the driving surface. Most commonly, the wheel is mounted vertically on a horizontal axle, but can also be mounted horizontally on a vertical shaft, for example, the tub or Norse. Vertical wheels can transmit power either through the axle or via a ring gear, and typically drive belts or gears; horizontal wheels usually directly drive their load.

Waterwheels were still in commercial use well into the 20th century, but they are no longer in common use. Uses included milling flour in gristmills, grinding wood into pulp for papermaking,
FIGURE 2.13
Barro Colorado Island is located in the man-made Gatun Lake in the middle of the Panama Canal. The island was formed when the waters of the Chagres River were dammed to form the lake in 1913. When the waters rose, they covered a significant part of the existing tropical forest, but certain hilltops remained as islands in the middle of the lake.

hammering wrought iron, machining, ore crushing, and pounding fiber for use in the manufacture of cloth.

Some waterwheels are fed by water from a mill pond, which is formed when a flowing stream is dammed. A channel for the water flowing to or from a waterwheel is called a millrace. The race bringing water from the mill pond to the waterwheel is a headrace; the one carrying water after it has left the wheel is commonly referred to as a tailrace.

In the mid to late 18th century John Smeaton’s scientific investigation of the waterwheel led to significant increases in efficiency, supplying much needed power for the Industrial Revolution.
FIGURE 2.14
Image of a bull shark. Lake Nicaragua, despite being a freshwater lake, has sawfish, tarpon, and sharks. Initially, scientists thought the sharks in the lake belonged to an endemic species, but has been identified as the bull shark, *Carcharhinus Leucas*, a shark that regularly enters freshwaters (Source: Ben Team).

FIGURE 2.15
*De re metallica* was a book that described the state of the art of mining, refining, and smelting metals by Georg Bauer, whose pen name was the latinized Georgius Agricola.
FIGURE 2.16
Single and two-phase AC synchronous motors were inefficient and cumbersome. This application of single phase AC meant that motors had to be synchronized with the generator during startup. You can imagine how difficult this was with miles between the two machines, let alone the use multiple motors in various different locations (drawn by Luyi Huang).

GENERATING MECHANICAL POWER
Hydropower or waterpower is power derived from the energy of falling water or fast running water, which may be harnessed for useful purposes. Since ancient times, hydropower from many kinds of watermills has been used as a renewable energy source for irrigation and the operation of various mechanical devices, such as gristmills, sawmills, and textile mills.

GENERATING ELECTRICAL POWER
In the late 19th century, hydropower became a source for generating electricity. Cragside in Northern England was the first house powered by hydroelectricity in 1878; one of the first commercial hydroelectric power plant was built at Niagara Falls in 1879, and powered street lamps installed in the city of Niagara Falls by 1881. The development of the electrical generators and motors allowed for the spatial separation between electrical generation and the use of electricity to do work. In 1890 Cyrus Baldwin (the first president of Pomona College, Claremont, CA) initiated the development of power generator using San Antonio Creek. However, direct current (DC) could not be transmitted over the 14 mile distance to Pomona. Nonetheless, Tesela’s experiments with alternating current and transformers in Germany was used to design a transmit power a record 28 miles to San Bernardino, CA.

The designer, Almarian Decker, however, wanted to design the power station to run three-phase alternating current (Fig. 2.16). However, Westinghouse refused to build a three-phase AC generator calling it “inpractible” for the San Antonio power station, Redlands’ Mill Creek. Mill Creek No 1, the first commercially viable three-phase power plant in the world, began its power generation September 7th, 1893, powering irrigation pumps for citrus groves in the California Desert.
Since the early 20th century, the term hydropower has been used almost exclusively in conjunction with the modern development of hydroelectric power. International institutions, such as the World Bank, view hydropower as a means for economic development.

The Three Gorges Dam is a hydroelectric gravity dam that spans the Yangtze River in the Hubei Province, China. The Three Gorges Dam is the world’s largest power station in terms of installed capacity (22,500 MW). In 2014 the dam generated 98.8 terawatt-hours (TWh) and had the world record, but was surpassed by Itaipú Dam (Paraná River, Uruguay) that set the new world record in 2016 producing 103.1 TWh (Fig. 2.17).

As well as producing electricity, the dam is intended to increase the Yangtze River’s shipping capacity and reduce the potential for floods downstream by providing flood storage space. However, due to flooding of archaeological and cultural sites, leading to the displacement of some 1.3 million people, and causing significant ecological changes, including an increased risk of landslides, the dam has been controversial both domestically and abroad.

**THE HYDROGRAPH: DISCHARGE RECORDS TO REDUCE RISKS AND PROMOTE DEVELOPMENT**

The sources of stream flow include rain, snow, glacier melt waters, and springs or seeps along hill-slope gradients or geological discontinuities. The flow might be seasonal, perennial, or periodic. Steam reaches flow through steep canyons or across broad flood plains. Over the course of their lifetime, a stream might pass through a range of habitat types: meadows, forests, chaparral, savannas, grasslands, and tidal marshes. At their terminus, they might drain into the ocean (exorheic) or into landlocked basins (endorheic).

Because stream flows depend on a number of sources, their flow rates can vary dramatically, but often depend on precipitation as an important driver of variation. Of course, even the idea of a normal rainfall year is a widely accepted misnomer—no yearly patterns reflects “the average.” In spite of some dominant seasonal trends, rain events patterns vary dramatically from year to year. The variation in
stream behavior then influences the variations in the ecology of streams. Understanding the flood-return intervals, for example, allow planners to reduce the risk of catastrophic flooding—of course, the record here is uneven and we will follow this up more in Chapter 9.

The comparison between the Eel, Sacramento, and Mojave rivers is a good example of how stream flows vary. The Eel River drains temperate rain forests and discharge peaks during the winter rainy season; the Sacramento drains from mountain headwaters, whose discharge is dominated by snow melt and then modulated by the construction and operation of Shasta dam starting in the 1940s, and the Mojave River’s intermittent flow depends on desert rainfall events in streambed that is often dry (Fig. 2.18).

As a keystone to understand river dynamics, hydrographs have been used to design hydroelectric dams, estimate reservoir storage and release criteria, and irrigation water availability. In effect, the hydrograph is scientific equivalent of religious icons: representing a set of values and specialized knowledge with veiled view of the future (assuming that river flow will follow patterns in the past).

**GREEN REVOLUTION: POWER AND IRRIGATION**

An important link in the Green Revolution is the linkage between energy and food production. The TVA (Tennessee Valley Authority) is the ultimate symbol to link these two human production projects. The Tennessee Valley Authority was enacted by congress to create a network of dams across state jurisdictions and used to generate electricity. During WWII, the energy was harnessed to produce munitions (nitrate for explosives). Once the war was over, TVA continued to make nitrate, but now used as fertilizers to increase agricultural production. Some will argue that WWII actually created the supply for fertilizers that was then looking for a market, and increasing acres of farmland began receiving this product. Unfortunately, the United States now suffers from a nearly universal problem of over fertilized farmlands, and the loss of excess nitrate promotes algal blooms that have negative impacts on surface- and groundwaters.

The Green Revolution project was a development model designed to be exported as a package to developing countries that included high-yielding varieties, fertilizer inputs, chemical pest controls, and irrigation. When the Ashwan Dam was built in the Nile River, it was the symbol of modernity for Egypt and participation in the Green Revolution project. But just as the environmental movement was developing, the ecology and public health costs cast a long shadow on the project. Built to irrigate and generate electricity, the dam construction forced the removal of important ancient archeological sites; impounded water increased the rate of schistosomiasis, irrigated waters increased the rate of soil salinization in crop plantings, and reduced water flow into the eastern Mediterranean Sea reduced fishery production.

**ENERGY FOR MONOPOLISTIC TRANSNATIONALS**

Malaysia, having diversified sources of energy—crude oil, coal, natural gas, and hydroelectric—has argued that the construction of 12 hydropower dams will decrease Malaysia’s dependence on crude oil. Recently, the “Four-Fuel Diversification” strategy has given way to the “Five-Fuel Diversification” strategy to include renewable energy sources. Certainly, these are positive steps, but the construction of hydroelectric capacity was designed on the assumption that energy demand and GDP were closely linked. Unfortunately, the optimistic expectation that GDP would continue to grow at 8%, and then
FIGURE 2.18
Discharge is a common way to evaluate waterflow and these “hydrographs” are standard tools for hydrologists (Source: USGS).

require 166 Mega tons of oil equivalents (Mtoe) by 2020 is far from the reality. Instead, Malaysia’s energy demand is only 51.6 Mtoe in 2013. To boost the demand, the government has worked tirelessly to attract (with cut-rate energy prices) various energy-intensive, heavy industries, most notably bauxite processing for aluminum.
Energy scarcity and energy poverty describe how populations have inadequate access to energy, usually in terms of electricity. Currently, most estimate that about 5–10% of the population is located in inaccessible locations for the power grid—thus, the Bakun and Baram are inappropriate projects for these communities. In other words, the projects like the Bakun and Baram were not designed for those who might be described as energy poor; if addressing energy poverty was the goal, the government would develop very different projects, i.e., small scale and widely distributed energy, e.g., minihydro.

RECREATION
Recreation adjacent to and on waters has a long cultural history, but in the 20th century, recreation was monetized. For inland waters, these activities include fishing, motorized boats, jet skis, and whitewater rapid adventures. According to the United States Bureau of Reclamation, recreation and tourism is the largest industry within the western states and second largest U.S. employer. Outdoor recreation in the United States is a $350 billion industry, with approximately $140 billion attributable to public lands and $40 billion to public waterways. Recreation and travel combined is one of the world’s largest businesses.

UTILITARIANISM
ALTERNATIVE MARSHLAND MANAGEMENT PRACTICES
For modern Europeans, a marshland has rarely been considered to have much economic value, but more of a place to be drained and then grazed or ploughed and farmed. But for the peoples of ancient South America, the rivers of the Euphraties, and much of Southeast Asia, marshland was clearly “home”, rice productions, or desirable because of the wide range of wildlife attracted to these watery environments.

For example, in the Pananal and Beni region of Bolivia, whereas Europeans created canals to drain landscapes, ancient South Americans created canals to flood the landscape and lived on artificial islands and lagoons (Fig. 2.19). These canals were highly engineered, where some followed contours of the land, and others followed the natural topography.

EXTRACTION AND MINING OF WATER
Viewing the planet as a resource has become the bedrock of resource economics, where the use of resources can be viewed from an anthropogenic lens. In other words, the planet’s resources have value inasmuch as they have value to human beings. On the surface this sounds reasonable way to think about sustainability if we include maintaining the resource for future generations, and consider that humans also value noneconomic uses of the planet.

In the case of groundwater use, the application of these concepts can become a bit hazy. For example, how should we evaluate groundwater mining, which is the removal or withdrawal of water in the natural ground over a period of time that exceeds the recharge rate of the supply aquifer. It is also called “overdraft” or “mining the aquifer.”
Groundwater is contained in specific rock units called aquifers. Water, ultimately from rain or snow, percolates downward directly from rain, or from a riverbed or lakebed, through soil, sediment, and rock, following the route of least pressure, to reach a level where it is saturated. It is then groundwater, occupying the microscopic spaces between the rock particles in the aquifer. In natural circumstances an aquifer is close to equilibrium in its water content, with recharge balancing outflow.

The water level in a natural aquifer is called the water table. Although it may rise and fall from season to season and year to year, the water table usually varies round some average depth. If the water table reaches the ground surface, water will tend to ooze out, as a natural seep or spring. In the end, every drop of groundwater eventually leaves the aquifer by outflow as a natural spring, or as seepage into a lake, river, or the sea, or pumped out of a well, but by that time it has been replaced by other water. Waterflow above or below ground follows physical laws that are well understood. In general, groundwater flows very slowly compared with the unconfined flows that are familiar in rivers and streams: rates are more of the order of feet per day rather than feet per second.

Hydrogeology is the study of aquifers and the water contained in them. It is crucial in assessing the impact of human activities on groundwater and in planning for the wise use of water in the future, thus falls within a clearly utilitarian approach.

**WATER AND ECOSYSTEM SERVICES**

As environmental sciences have developed, so has our understanding of the social, ecological, and economic value of inland waters. These might fall into a category of “ecosystem service”, where we integrate the human interests with ecosystems processes. The service is to human beings, thus reinforces an anthropocentric value-system. We might contrast this to an ecocentric value-system, where the nonhuman world has inherent value, irrespective of what we think we might value. There is much
debate about these concepts, their importance, and epistemological roots. Nevertheless, it is important to appreciate the limitations of the anthropocentric view, where ecosystem services might not be a robust way to value our inland waters.

Evaluating water is a multidimensional endeavor.

| Structural metrics                                      | Functional metrics                                      |
|---------------------------------------------------------|--------------------------------------------------------|
| • Biological diversity                                 | • Productivity/reproduction, migration, trophic status |
| • Native riparian vegetation width                      | • pollutant removal rates                               |
| • Floodplain presence/width                            | • hydraulic retention                                  |
| • Canopy cover                                          | • photosynthetic active radiation                       |
| • Oxygen level                                          | • Biochemical Oxygen Demand and whole stream metabolism|
| • N and P concentrations                                | • Nutrient cycling/flux rates                           |
| • Pollutant concentration                               | • Pollutant removal or sequestration                    |
| • Organic matter                                        | • decomposition rates                                   |
| • Temperature                                           | • thermal regime (magnitude, duration, and timing)     |
| • Mean annual flow and depth                            | • flow regime (magnitude, duration and timing)         |
| • Turbidity                                             | • Sediment flux                                        |
| • Channel morphology                                    | • Channel migration, erosion rate                       |
| • Stream bed substrate                                  | • Stream bed mobility                                  |

AESTHETICS & EXISTENCE VALUE

WILD AND SCENIC

In 1972, California passed the Wild and Scenic River System Act, which was strengthened by the National Wild and Scenic River Act in 1982 as amended from the 1968 act. The act attempted to strike a balance between dam and designating permanent protection important for free-flowing rivers. To accomplish this, the act prohibits federal support for construction of dams or other instream activities that would disrupt the river’s free-flowing condition, water quality, or resource values. However, designation does not affect existing water rights, or the existing jurisdiction of states and the federal government over waters as determined by established principles of law.

On signing the Wild & Scenic Rivers Act, President Lyndon Johnson said:

_In the past 50 years, we have learned—all too slowly, I think—to prize and protect God’s precious gifts. Because we have, our own children and grandchildren will come to know and come to love the great forests and the wild rivers that we have protected and left to them… An unspoiled river is a very rare thing in this Nation today. Their flow and vitality have been harnessed by dams and too often they have been turned into open sewers by communities and by industries. It makes us all very fearful that all rivers will go this way unless somebody acts now to try to balance our river development._

The act has three designations,
Wild River Areas  rivers or sections of rivers that are free of impoundments and generally inaccessible, except by trail, with watersheds or shorelines essentially primitive and waters unpolluted. These represent vestiges of pre-columbian America.

Scenic River Areas  rivers or sections of rivers that are free of impoundments, with shorelines or watersheds still largely primitive and shorelines largely undeveloped, but accessible in places by roads.

Recreational River Areas  rivers or sections of rivers that are readily accessible by road or railroad, that may have some development along their shorelines, and that may have undergone some impoundment or diversion in the past.

As of August 2018, the National System protects 13,416 miles of 226 rivers in 41 states and the Commonwealth of Puerto Rico; this is less than 0.25% of the nation’s rivers. By comparison, more than 75,000 large dams across the country have modified at least 600,000 miles, or ~17%, of US river system.

LAND USE AND WATER: CARMEL RIVER — A RUINED RIVER?

Along the coast of California is the Carmel River. This relatively small river used to support a healthy population of steelhead fish and a diverse riparian vegetation. However, efforts to reduce flooding and promote development in the floodplain initiated the construction of levees. Agriculture, housing developments, and golf courses began competing for water supplies. The riparian vegetation has become significantly degraded due to the lowered watertable and streamflow fails to support a robust steelhead run. The cumulative impacts of water diversions, dam building, and developments in the floodplain are reaping dramatic ecological changes (Fig. 2.20). But just as in the case of the Aral Sea, to address the human impacts on these ecological systems, we will need thoughtful approaches to create sustainable ecosystems.
NAMING SPECIES BEFORE THEY ARE LOST: LINNAEUS AND EO WILSON

Wilson, whose expertise is ants, has been a strong advocate to protect biodiversity. Along with Robert MacArthur, he described how islands could maintain a greater number of diverse species. That idea was the foundation for nature reserve design, which he describes as islands in a sea of land, what is termed as island biogeography.

Approximately 2 billion species have been given scientific names, a process started by Carl Linnaeus, a Swedish biologist in 1735. Based on what we know today, we estimate 10 billion species exists. Unfortunately, based on the tradition of protecting species, unless the species is named, it does not exist—at least for conservation purposes.

With an estimated rate of anthropogenically caused extinction, between 100 and 1000 times above background, 1/2 of the species on Earth may become extinct by the end of the 2100 century. As Wilson and others argue, the only effective way to protect these species is to evaluate the role of expanding reserves to protect biodiversity. For Wilson, this is a call to improve the science, and a call to develop the political will to create socially just political structures designed to avoid a catastrophic loss of biodiversity.

ECOLOGY OF SCARCITY: INFRASTRUCTURE AND HUMAN DEVELOPMENT

ROMAN AND MAYAN INFRASTRUCTURE

Urban hydraulic systems started to develop in the Bronze Age, and particularly in the mid-third millennium BCE, in an area extending from India to Egypt. But on the island of Crete, where the Minoan civilization was flourishing, a new level of hydrologic infrastructure included the construction and use of aqueducts, cisterns, wells, fountains, bathrooms and other sanitary facilities, which might be recognized as a contemporary advance lifestyle. Capitalizing on these technologies, the Romans developed high engineering skills and extended these technologies on large-scale projects throughout their large empire.

After the fall of the Roman Empire, the concepts of science and technology related to water resources retrogressed. Water supply systems and water sanitation and public health declined in Europe. Whereas Islamic cultures, on the periphery of Europe, had religiously mandated high levels of personal hygiene, along with highly developed water supply, sewerage, and adequate sanitation systems, Europe acquired again high standards of water supply and sanitation only in the 19th century.

On the North American continent, the Lowland Maya civilization flourished from 1000 BCE to 1500 CE in and around the Yucatan Peninsula. Known for its sophistication in writing, art, architecture, astronomy, and mathematics, this civilization is still obscured by inaccessible forest, and many questions remain about its makeup. Although some scholars suggest that the Maya Lowlands contained small city-state centers ruled by warring elites, recent data suggest a regional network of densely populated cities with complex integrative mechanisms. Thus in contrast to the idea that settlements were supported by a relatively sparse rural population practicing swidden farming and limited role from intensive agriculture, recent research suggests that these populations were supported by a regional agricultural economy of great complexity.

The landscape included intensive agriculture that included a complex network of channels designed either to draw water away from natural streams toward infrequently flooded areas, or to drain those
same areas during major floods. Large and small channels intersected at regular intervals, forming nested grids within “channelized” fields.

Overall, it is important to note that a wide range of civilizations have modified waterflow for millennia, and in some cases with intensive practices. Thus our current activities are far from unique and in many cases, extension of the practices done by our ancestors.

WATER: PROBLEMS

All solutions of water problems may be sorted into nonstructural, structural, and mixed measures. Nonstructural measures include regulation and insurance. Structural measures consist of combinations of the four categories of structures:

- those that transfer water in space;
- those that change the water regime in time;
- those that change water power potential; and
- those that change water quality.

Modern water resources planning uses the principles of advanced economics in matching water demand and water supply by selecting and sizing a set of structures as the water resources system.

MAKING WATER PREDICTABLE: INFRASTRUCTURE

Of the top 10 urban centers, three California regions are found on a list that take more water from watersheds quite distant: Los Angeles, San Francisco, and San Diego. On a per capita basis, Los Angeles, San Francisco, and San Diego residents consume among the greatest amount of water from cross boundary sources (Table 2.3).

What are the ecological affects of these transfers? How do these centers of economic and political power affect the waters in the source waters and people who rely on them?

Without a doubt, one of the most famous example of cross-basin controversies comes from the conflict of the Los Angeles Aqueduct that imported water to Los Angeles from the Owens Valley as described in the opening of Chapter 2, but there are plenty of other examples—each with its own problematics (Fig. 2.21).

DROUGHT, MIGRATION, AND CONFLICT

Food security depends on reasonably predictable weather climates. Unfortunately, many believe the variation in weather is likely to increase as a result of climate change (longer droughts, higher frequency of extreme events, such as snow, floods, hurricanes). Although definitive conclusions that extreme weather events are increasing in frequency is partially understood, some indicators are starting to reveal themselves.

An extended drought in Syria caused migration to the city centers of the country. Becoming overwhelmed by the social services need, limited employment opportunities, and a relatively unresponsive government, devolved into a civil war, these problems and processes and the subsequent civil war in Syria is relatively undisputed. However, recent analysis suggest that the drought was part of a larger pattern of climate change in the region. If these results are robust, the war and associated refugees
Table 2.3 Cross-boundary water transfers and populations of large urban regions. Transfers refer to cross boundary transfers and are in units of liters/day/person (modified from McDonald et al., 2014).

| Urban Region | Country | Population (2010) | Transfer |
|--------------|---------|-------------------|----------|
| Los Angeles  | USA     | 13,223,000        | 673      |
| Boston       | USA     | 4,772,000         | 693      |
| Marumbai     | India   | 19,422,000        | 165      |
| Karachi      | Pakistan| 13,500,000        | 187      |
| Hong Kong    | China   | 7,053,000         | 347      |
| Alexandria   | Egypt   | 4,440,000         | 523      |
| Tianjin      | China   | 8,535,000         | 255      |
| Tokyo        | Japan   | 36,933,000        | 59       |
| San Francisco| USA     | 3,681,000         | 547      |
| San Diego    | USA     | 3,120,000         | 462      |
| Ahmandabad   | India   | 6,210,000         | 219      |
| New York     | USA     | 20,104,000        | 67       |
| Tel Aviv     | Israel  | 3,319,000         | 369      |
| Pretoria     | South Africa | 1,468,000     | 829      |
| Chennai      | India   | 8,523,000         | 133      |
| Algiers      | Algeria | 2,851,000         | 375      |
| Aleppo      | Syria   | 3,068,000         | 346      |
| Athens       | Greece  | 3,382,000         | 306      |
| Cape Town    | South Africa | 3,492,000     | 285      |

**FIGURE 2.21**
Boston water system.
represent an important framework: that climate change may mediate conflict and cause climate-change refugees.

**SHRINKING PIE?**

With an increasing demand on water resources, it is tempting to think of water as a Malthusian-like resource, where the ‘development’ of water supplies might be linear and population growth (or demand) for water is increasing exponentially. If framed this way, water is a fixed resource. Thus we view water allocation as a zero-sum game—water used for one use preclude other uses. Some argue that the nonhuman, ecological values are destroyed by water development projects, whereas others complain that their livelihoods are threatened by environmental regulations designed to protect natural systems. We face a pragmatic choice, but potentially false dichotomies are not always helpful (Fig. 2.23).

Instead of thinking about water as a limited resource and allow the politics of scarcity to dominate the discourse, I argue that we can base our relationship with water as participants in an ecological play, where political and economic processes coexists with inland water ecosystems, and our goal is to learn how they align. Without being naive, we are not going to ignore the real and fundamental conflicts in society, but try to take a broad view by understanding the science of water. With this framework, we would predict that conflicts of interest in water resources activities will increase the required administrative, arbitration, and market decisions to resolve conflicts using a discursive approach, which we will expand upon on Chapter 14.
FIGURE 2.23
“No water, No jobs,” Common road signs along Interstate 5 running through the San Joaquin Valley. These are symptoms of a complex power struggle for the control and potential use of water in California (Source: Arnett Young).

EVOLUTIONARY PLAY: A NEW REGIME
SOCIAL AND ENVIRONMENTAL JUSTICE

Who would have known that the oil price shocks in the 1970s could potentially displace nearly 20,000 people from the Kayan, Kenyah, and Penan communities in Sarawak rainforests some 50 years later?

To further increase the portfolio, Malaysia also began evaluating sites for hydroelectric generation and identified the rivers in Sarawak as early as the 1960s, but concrete planning only occurred after 1979 when the country identified its vulnerability to oil supplies, and realized that the correlation between energy and development suggested that for the country to grow, more energy generation capacity was key (Fig. 2.24).

Finally, as a justification for most dams, the flood risk for downstream residents is usually reduced. However, it might be more accurate to say that risks are displaced by new ones. With “flood protection”, the floodplain is colonized. However, the capacity of the dam to prevent flooding is often overstated because of extreme with unknown frequencies. When this happens, the residents of the floodplain experience unanticipated flooding. Of course, there are other examples where the dam fails completely and then the losses tend to be catastrophic. In might be better to say that the flood risk is altered. This is particularly useful when you consider the impact of the Bakun dam on the Dayak, whose settlements were flooded by the dam. After public opposition originally halted the dam projects in the early 2000s, Malaysia turned its attention to the Bakun dam, which was slated one of the 11 dams after the Baram dam was completed. The Bakun hydroelectric dam, completed in 2011, serves an excellent example of the failed promises of big dam projects: displaced residents remain antagonistic to their resettlement and dramatic changes to the river’s ecology are undocumented.

In the case of the Bakun Dam, the indigenous people displaced by the project struggle to eke out a living over a decade after they were resettled (Fig. 2.25). About 10,000 people were resettled to the town of Asap in 1998, surrounded by areas licensed for oil-palm plantations. Dayak people expected to be compensated with land and housing, but the discrepancy between the actual compensation is
dramatic. Instead of getting two houses, each family got one. Instead getting 22 acres of land, they received 3 acres. Many went into debt to pay for additional housing. Many received only three acres of rocky, sloped or sandy soils that are too small, of too poor quality to generate a living, and too far from Asap to manage effectively. On their traditional lands, the Dayak could fish in the river, hunt,
and gather forest products. In the resettlement areas, they have no access to forests. They went from a food-secure to food-insecure status.

For the Dayak people of the Baram, the lessons learned by the resettlement of the Bakun River watershed provides a dire warning—of failed promises for compensation, loss of social cohesion, and the irreversible forfeiture of cultural heritage.

Moreover, in the Bakun and Baram river watersheds, the people of Sarawak have poignantly demonstrated the socioecological disruption. For the time being, the construction of the Baram Dam has been halted. But dam plans seem to have several bouts of reincarnation, so the long-term outcome will probably always remain uncertain.

The alignment with environmental scientists to provide better information to stakeholders to make informed decision about the environmental benefits and costs of development is a good example, demonstrating that compromises are possible even by governments with limited democratic control.

The conflict between development goals to build dams for hydroelectricity and indigenous peoples in Sarawak was set in motion in the 1970s. The justification for hydroelectric development has been a dominant narrative in developed and developing countries for decades (Fig. 2.26). However, counter narratives have arisen as ecologists have documented how dams change river geomorphology, water quality, habitat value, and access.

The evaluation of projects for their potential social and environmental impacts is evaluated through SEIA reports in Malaysia. Yet Sarawak Energy Berhad, the state energy monopoly, claimed that the assessment could not be completed because of protests, releasing the following statement:

*Sarawak Energy’s ability to commence and complete the feasibility studies and SEIA reports to ensure community issues and points of view are taken into account have been disrupted by the ongoing protests. While we respect the right of individuals and organizations to express their point of view, it should be done in a manner that is lawful and does not place their safety or the safety of others at risk. The behavior of the NGOs protesting at Baram in the past has breached both these basic principles.*
In the case of the Dayak communities, the alignment between social and environmental justice and ecological protection converges on the ‘Stop the Baram’ campaign (Fig. 2.27). Evidence is on their side: socio-ecological impacts of the dam would be devastating for their way of life and dramatic changes to the river ecology. With international support from Rivers International and thoughtful engagement with various groups of interest, the Dayak effectively used the media and a blockade to force the government to (temporarily) shelve the Baram Dam.

When announcing the government’s decision, Chief Minister, Datuk Patinggi Tan Sri Adenan Satem, articulated a view that the Baram protesters would regret their victory:

*There have been many protests and blockades by the people who voiced their disagreement to the building of the Baram dam. If you don’t want the dam, fine. We will respect your decision. I hope you understand the impact for refusing it, as you will be missing out on related projects which are beneficial, such as roads and other necessities.*

*One day, you will find that not building the dam has given some disadvantage and as a result of this, you suffer. That is in your own hand. It is your decision.*

To keep these development projects going, the Malaysian government now has pinned its hopes on construction on one of the other 12 dam projects—Baleh Dam located in the upper Rejang basin in central Sarawak. The rainforest in this part of Southeast Asia has some of the highest rates of plant and animal endemism, i.e., species which are found only in that region, and the ecological damage from the proposed dam will be considerable, even though the severity of its impact cannot be known at this time. As the Dayak people’s successful resistance to the Baram River dam project reveals, those who live within the Baleh watershed will need to be vigilant and persistent in their opposition if they hope to protect the human and ecological communities that inhabit that region.
NEW RULES AND INSTITUTIONS: A REGIME FOR MANAGING INLAND WATERS

A civilization may be conceived as a collection of various infrastructures. The 25–30 main purposes in water resources activities compose a large part of these infrastructures, e.g., drinking and irrigation water, hydroelectric and transportation, fisheries and recreation, etc. Controversies between water resources development and protection of the environment will increase until new methods for their resolution are designed. Aging of hydraulic structures and water resources systems already poses many difficult problems for their revitalization. Pressures mount to extract maximum benefits from existing systems before building new ones. Society will continue to press for the decrease of some risks from water-related structures. Cleaning polluted water environments, especially aquifers, will be on the main agenda of water activities in the first half of the 21st century.

Water and water rights will be considered as market commodities. Priorities in using sources of water may switch due to the impact of various types of pollution. The climatic change phenomenon will have a large influence on water resources planning and development in future civilizations.

It is this context that we begin our journey into inland waters. The stage for the species in these systems present an evolutionary stage and ecological play. Following the conceptual framework of for aquatic systems from Fig. 2.28, we will insert social systems into the framework and consider how we as humans are part of these systems, as we develop our knowledge of water science and ecology of inland waters.
NEXT STEPS

CHAPTER STUDY QUESTIONS

1. As human population densities increase, water supplies become more complex. Describe some of the drivers that make complexity a requirement.

2. Agriculture and aquaculture rely on freshwater sources of water. How does water supply and quality affect these two food sources. What are the commonalities and differences in water use and management between agriculture and aquaculture?

3. Water can be thought of as an ecosystem service for transportation. What are the pros and cons of thinking of water in this way?

4. What are the limits of hydropower?