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How the West Was Watered: A Case Study of the Colorado River

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Abstract

This case study is divided into two parts to explore the Colorado River and the tradeoffs involved in managing the river. In Part I, background information on the river basin is presented within the social, political, and environmental context of the system's complex management framework. In Part II, the class is tasked with completing a brief stakeholder analysis for the river that allows them to explore the tradeoffs involved in managing the Colorado River. Finally, students are asked to use their understanding of the river and its stakeholders to explore how the West will be watered.

Case Study Subject and Goals

Through a case history format, this case study aims to provide undergraduate level students with a solid understanding of the geography, history, and environmental and political context of the Colorado River system. Students will consider how growth in human population, agriculture, and hydrological development impact the river and its ecosystems. They will understand how water rights and allocations affect various stakeholders in terms of tradeoffs. Finally, the case study will promote reflection and discussion on the issues of water conservation, water management and rights, impacts of water use and climate change on freshwater ecosystems, and science and policy.

PART I

EIGHT THINGS TO KNOW ABOUT THE COLORADO RIVER AND BIODIVERSITY

1. Currently, almost all of the water in the Colorado River is diverted for use by farms and cities; none reached the sea before a tiny fraction of water pulsed to the Sea of Cortez in May 2014 as a result of a historic agreement between the United States (U.S.) and Mexico.
2. Climate change is reducing the supply of Colorado River water.
3. Urban growth is increasing the demand for Colorado River water.
4. Agricultural use of water is favored by a complex system of water allocations originally devised in 1922 and modified by international treaties, court cases, and federal laws and policies.
5. River management is the result of complex negotiations between the U.S. and Mexico, among seven U.S. states, and among stakeholders representing agricultural users, municipal users, native tribes and environmental groups.
6. The reduction of flow in the river has greatly reduced the extent and quality of riparian, wetland, and estuarine habitats. Invasive species have also altered these habitats and several native species are at risk of extinction.
7. Little water is currently allocated to support natural ecosystems.
8. Because approximately 90% of the Colorado River's water is diverted before it reaches the border, most of the economic benefits of water use are within the U.S. and most of the environmental consequences occur in Mexico.

The Mighty Colorado

The dominant river of the American southwest, the Colorado River cuts a wide swath through not only vast deserts and arid plains, but also through the lives of many people and species. It is a dynamic body of water, with headwaters in the snowpack of Colorado's Rocky Mountain National Park, outlet in the Gulf of California, and over 2,250 kilometers in between draining water from Wyoming, Utah, Colorado, New Mexico, Nevada, California, Arizona, and Mexico (Figure 1). Its mighty force carved out the Grand Canyon, nourished life in great deserts, and fed an expansive delta. In the last 100 years, the river has become tightly regulated and is used so completely that it now flows only rarely all the way to the sea.

For thousands of years, Native Americans have lived along the river and used its waters. Remains of elaborate canal systems indicate that many of these tribes had sophisticated water management practices to irrigate fields of crops, while other tribes relied extensively on the river's ecosystems for hunting and gathering. Many of these tribes, including the Mohave, Hopi, Ute, and Navajo, continue to use the river's water. The Cucupá have continuously fished, hunted, and gathered in the river's Delta region for millennia.

Spanish explorers provided the first written documentation of the river in the 16th century, with expeditions originating from the mouth of the river. In the first few decades of the 19th century, explorers from the eastern United States began to travel along the river. Parts of its course were not mapped until 1869, in two expeditions lead by John Wesley Powell. The flooding regime of the river and its turbulent waters made navigation difficult, but early settlers used skiffs and steamboats to transfer people and supplies. With the construction of two massive dams, the Hoover and Glen Canyon Dams, in the 20th century the river became navigable, fueling a population and development boom.

The more recent history of the Colorado River tracks the story of one of the fastest growing regions in the United States. The river's water has fueled development and growth through irrigation, hydroelectric power, and water supplies for the burgeoning cities of Denver, Phoenix, Tucson, Las Vegas, San Diego, and Los Angeles among others both in and outside of the river's basin. Over 40 million people in the U.S. and Mexico use Colorado River water every day, for everything from municipal to industrial uses. Water from the river plays an integral part in keeping over two million hectares of farmland in production in the U.S. and hundreds of thousands of hectares in Mexico (USBR 2012). In addition to irrigated agriculture, the regional economy is also built upon livestock grazing, mining, forestry, manufacturing, oil and gas production, recreation, and tourism, all supported by the water of the Colorado River.

Figure 1. Colorado River Basin By Shannon1 [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0-2.5-2.0-1.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons

The massive river infrastructure that delivers water to surrounding communities includes hydroelectric dams along with 12 major reservoirs on the river and its tributaries (see Figures 1 and 2) (Christensen et al. 2004). The two largest reservoirs, Lake Powell behind Glen Canyon Dam and Lake Mead behind Hoover Dam, comprise 85% of the river system's storage capacity and, combined, can store about four years of annual river flow (Christensen et al. 2004).

In transforming the river, humans have altered the spectacular natural ecology and hydrological features of the Colorado River, initially named "Rio Colorado" or "the Red River" by Spanish explorers for its reddish-brown, silty quality (USBR 2004). With the construction of dams and reservoirs, most notably the Glen Canyon Dam which trapped sediments that settled into the bottom of Lake Powell, the river has become tightly managed, with its flows regulated and clearer, more blue-green than red. The reduction of flow in the river has greatly reduced the extent and quality of riparian, wetland, and estuarine habitats—they are shadows of what they were 100 years ago—and the river's unique biodiversity has been significantly impacted. Invasive species have also altered these habitats and several native species are at risk of extinction. Part II of this case study explores many of the ecological consequences of changes in the river.

The Most Complicated Water System in the World: Management and River Policies

At the dawn of the 20th century, explorers had mapped the Colorado River, and as the promise of gold and fortune beckoned, populations in the American West expanded in extent and numbers. In 1902, with the settling of the West underway, the U.S. Bureau of Reclamation was instated to undertake the planning, construction, and implementation of numerous water diversion and storage projects in the western United States to promote this growth. In the 1910s and 20s, basin states began initial negotiations about the allocation of Colorado River water. In 1922, the Colorado River Compact was signed among seven U.S. basin states—a document that to this day allocates every drop of water in the river. Additional layers of interstate and international agreements, prior appropriation allocations, and federally reserved water rights for Native Tribes now comprise a "Law of the River," making the Colorado River the "most complicated water system in the world" (Gertner 2007; USBR 2011) (see Appendix 1.)

The Colorado River Compact divides waters of the river in the U.S. into two basins (the Upper Basin in Colorado, Wyoming, Utah, and New Mexico, and the Lower Basin in California, Nevada, Arizona). A treaty signed in 1944 by the United States and Mexico allocates some Colorado River water to Mexico. Using the volume of the "acre-foot" (one acre covered one foot deep in water or enough water to supply two households for a year, also equivalent to 1,230 million cubic meters), the Compact states that the Colorado's waters are to be divided between the Upper and Lower Basins, assigning 7.5 million acre-feet (maf) per year to each, while at the same time requiring that the Upper Basin deliver to the Lower Basin 75 maf over a moving ten year average. These two requirements in the Compact create one of the fundamental controversies of the Colorado River: when total flows over a 10-year period are less than what was contemplated in the Compact, which Basin must bear the shortage? Furthermore, within each basin, how will multiple states manage a potential water shortage? Meanwhile, the Treaty guarantees Mexico 1.5 maf per year, with the exception of years of "extraordinary drought" - a term not yet defined - when deliveries might be proportionally reduced to all other states.

The river's infrastructure supports the terms of the Compact (Figure 2). For example, Lake Powell's purpose is to store flows to ensure the Upper Basin's annual delivery requirement to the Lower Basin. Lake Mead stores water released from Lake Powell and regulates water deliveries for Lower Basin water users and Mexico. Water deliveries to users depend on water availability in reservoirs: Upper Basin deliveries depend on water in Upper Basin reservoirs and Lower Basin deliveries depend on water levels in Lake Mead. It is critical to note that during ideal conditions, the river's reservoirs store more than four times the river's annual flow, so the river's annual hydrology can be very different from the state of its reservoirs. Therefore, water users may start to experience shortages long after a dry period begins, but shortages may continue long after normal or wet conditions return.

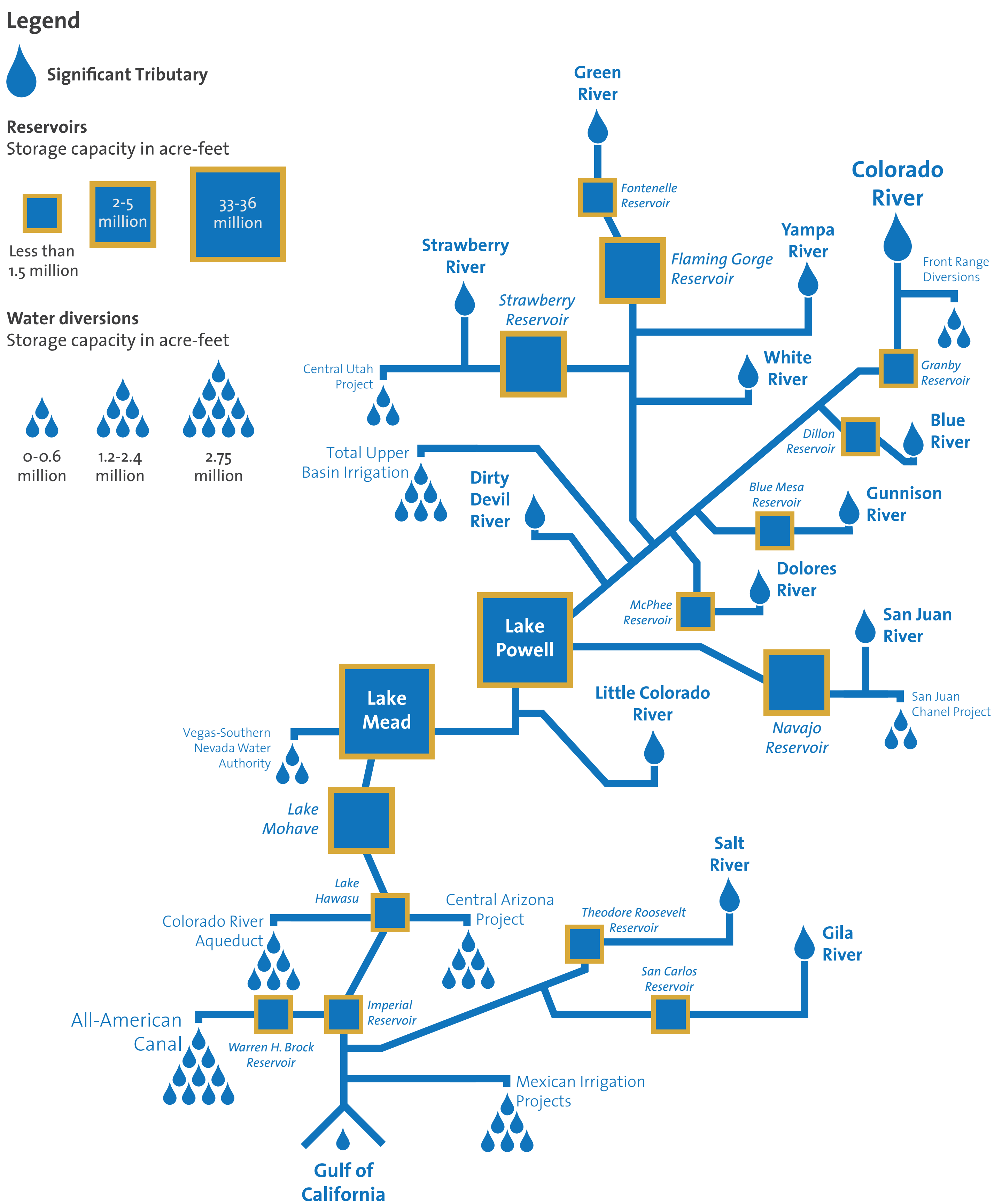

Figure 2: Infrastructure of the Colorado River (adapted from HCN Publisher, Ed Martston). Illustration by Nadav Gazit

A cast of main players orchestrates the tight river regulation (see Appendix 1), led by the U.S. Bureau of Reclamation, which builds and oversees the management of the Colorado River's water storage and delivery infrastructure, including Lake Mead and Lake Powell. It is important to note the international nature of this river: Colorado River management has been primarily a domestic issue for the U.S., while Mexico is significantly impacted by critical upstream policy and management decisions.

Status of Colorado River Allocations

While the legal framework that allocates Colorado River water is firmly established, the flows in the river itself vary, given the amount of melted snowpack in the headwaters. This variability can be extreme—the historic record shows that annual flows can range from four maf to 24 maf. This variation, in turn, is at the root of past and future concerns about how water is managed. For instance, streamflow measurements from 1886-1921 at Lees Ferry in Arizona at the dividing line between the Basins (24 kilometers below Glen Canyon Dam at the entrance to Grand Canyon National Park) were used to frame the terms of the Compact. However, recent research has shown that these were some of the wettest years for the Colorado River in the last century (Figure 3, Box 1), while recent years have matched the more typical drier periods in the known history of the river (Vano et al. 2014).

The disparity in river levels has resulted in conflicts over how to allocate scarce resources. For the majority of the last 40 years, the river has run dry before reaching the once expansive delta into the Gulf of California (Flessa et al. 2013), a phenomenon that has been replicated in many of the world's major rivers, including the Nile, Yellow, and Indus (Gleick 2003).

The Upper Basin states currently consume between 4.1 and 4.6 maf per year of their Compact entitlement of 7.5 maf. However, the Bureau of Reclamation concluded more than a decade ago that based on historic records of Colorado River hydrology, only 6.0 maf per year (including reservoir evaporation) is actually available to Upper Basin States in light of their obligation to deliver 75 maf over a ten year rolling average to the Lower Basin States plus half of the 1.5 maf per year delivery obligation to Mexico. Meanwhile, the Lower Basin has reached full use of its allocation, and even exceeded its allocation for several years in the 1990s – using excess water from the Upper Basin allocation to meet this demand. Two critical factors have been at play in the Lower Basin in recent years: a "use it or lose it" system of water rights and increasing urban demand, especially in areas that are outside the river basin. The initial formation of the Law of the River occurred when populations were low and during the era of manifest destiny, when agriculture was seen as the best way to provide livelihoods in the desert and settle the region, and rights were allocated to support farms. Despite brisk population growth in urban centers and concurrent increases in water demand,

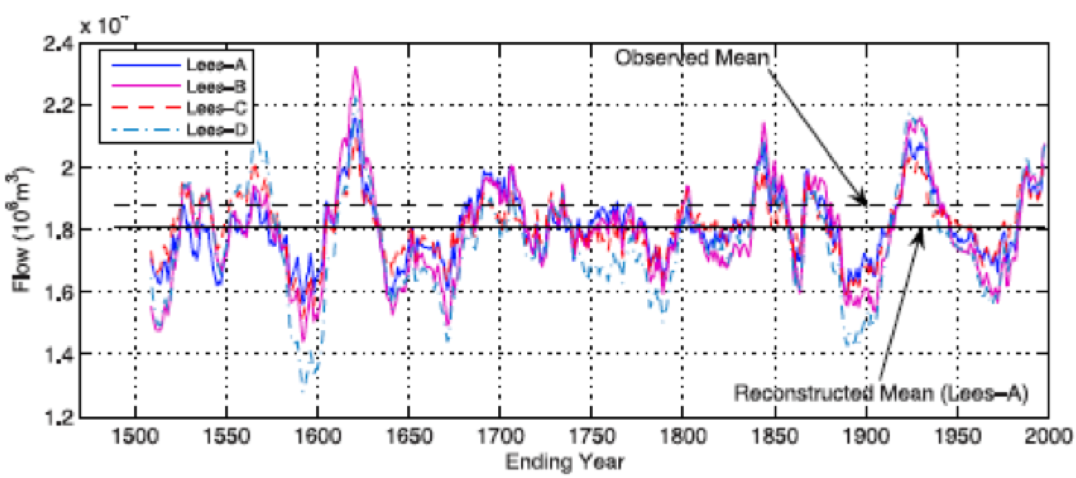

Figure 3: Time-series plot of the annual flow volume (in millions of acre-feet) for the Colorado River at Lees Ferry (Woodhouse et al. 2006).

agricultural water users still hold the vast majority of the Lower Basin's water rights and consume 70% of all the water in the basin (Morrison et al. 1996; Gertner 2007; Kuhn 2012; USBR 2012).

In Mexico, the region affected by the Colorado River is the area along the California and Arizona borders. The region includes urbanized areas such as the Mexicali-Calexico and the San Diego-Tijuana areas, but also major agricultural areas such as the Imperial and Mexicali valleys and important environmental features along the river corridor and its Delta.

A wide variety of crops are raised throughout the entire river basin, from hay in the Colorado Plateau to fruits and vegetables on the U.S./Mexico border. This irrigated agriculture is valued in the billions of dollars, and significant crops include vegetables and winter lettuce. The majority of water used in agriculture irrigates intermediate crops (those not directly consumed by humans, but by livestock) such as alfalfa and sudan grass that generate lower economic returns and is often exported.

Rapid population growth in the cities of the southwestern U.S. and Mexico has created new urban demands. For example, Las Vegas, one of the fastest growing cities in the U.S. in recent years with over two million people in the driest valley of the nation's driest state, gets 90% of its water from Lake Mead (notably, the city gets most of its electricity from the Hoover Dam) and has been using its full allocation for more than a decade. To provide water for an increasing population, Las Vegas' water providers have implemented aggressive water conservation policies and are pursuing development of groundwater extraction projects elsewhere in Nevada. Significantly, the majority of urban water use is outdoors, where water is used for landscaping, irrigating lawns, and filling swimming pools.

It is crucial to note that these water allocations for human uses do not take into account the needs of

Box 1. Drought, Climate Change, and the River

Recent research has examined the complex hydrological regime of the Colorado River and the implications of continued drought and climate change. River modeling by federal agencies and water managers is done using historical datasets on river parameters with the assumption that future flows will mimic those of the previous century. However, researchers are discovering that the years of data that formed the basis of the Colorado River Compact were among the wettest compared to the rest of the 20th century. Some scientists warn that this fundamental assumption may over-estimate the average stream flow by as much as 20% (Dettman 2004), and recent studies have projected a decrease in the natural water supply (USBR 2012). Furthermore, these particular years may have been the wettest in more than one thousand years. Data supporting this assertion has come from numerous tree-ring studies that reconstruct precipitation and river flow in the basin over time (Woodhouse et al. 2006; Woodhouse et al. 2010).

Since 1999/2000, the Southwest has been in the midst of a multi-year drought and the Colorado River had some of the lowest flows since stream flow gauges were installed. It is notable that this recent drought pales in comparison to some of the most severe droughts that have been documented in the southwest over the past 1,500 years—the most severe of which lasted 50 years (Woodhouse et al 2010). The water shortages occurring today may not be an aberration, but a return to a historical norm.

Furthermore, climate change is of particular concern for the Colorado River basin due to the sensitivity of the Rocky Mountain snowpack accumulation that feeds runoff, and will only exacerbate the problem of drought. Numerous studies have assessed the hydrologic and water resources impacts in the river basin, using a range of climate change scenarios including those recently set forth by the Intergovernmental Panel on Climate Change (2013). Many of these studies suggest vulnerability of the river to changes in precipitation and temperature-related effects, such as increased evapotranspiration, which could result in reduced stream flows of between five and 35% in the coming decades and depleted reservoirs (Christensen et al. 2004; Christensen and Leittenmeier 2006; McCabe and Wolock 2007; Rajagopalan et al. 2009; Woodhouse et al. 2010, USBR 2012, Vano et al. 2014).

biodiversity. In recent decades, stakeholders have begun to recognize the importance of freshwater flows for native species and riparian habitats and how Colorado River water allocations have negatively impacted biodiversity. Laws such as the Endangered Species Act were created to protect threatened and endangered species, and government and state agencies have worked to conserve some key habitat, through initiatives such as the Grand Canyon Protection Act of 1992. Numerous groups have emerged to advocate for nature as a stakeholder, including the Nature Conservancy, Sonoran Institute, ProNatura, Environmental Defense Fund, and Defenders of Wildlife. While in most cases, "nature" is not a recognized user of water in the system, especially in the context of the Law of the River and river allocation schemes, freshwater needs for biodiversity constitutes a critical demand on the river's water.

The River Allocation Dilemma

Due to natural flow variability, the 1922 Compact allocated more water than is actually available in the river (Box 1). As Upper Basin water users plan new projects to extract water from the river that belongs to them under the terms of the Compact, and as climate change promises to decrease flows in the river, the specter of a "Compact Call" is raised. If the Upper Basin states fail to deliver enough water, Lower Basin states may try to legally force Upper Basin states, through provisions in the Compact, to reduce consumption - a politically charged situation (Gertner 2007). While the specter of a Compact Call has not been raised since, water levels in Lake Powell and Lake Mead have dropped to levels just above limits that would trigger declaration of a water shortage. In 2007, spurred by a multi-year drought, declining reservoirs, and growing water demands, the seven Colorado River basin states in the U.S. took steps to begin to address the situation by signing a historic agreement that established additional guidelines in the instance of a water shortage in the Lower Basin (USBR 2007). The complex agreement specifies that if levels in Lake Mead drop below a set level, Arizona and Nevada will have to curtail their use of water, while California's allotment of 4.4 maf will be upheld, due to the terms of a series of Supreme Court cases dealing with disputes between California and Arizona over Colorado River water.

The dilemma is exacerbated by the fact that the allocation system gives little incentive to reduce water use as water is heavily subsidized and users tend to adopt "use it or lose it" policies that perpetuate rights secured on a first-come, first-served basis. New cities must purchase existing rights from agricultural districts that may be reluctant to trade these precious senior rights. New water users reliant on the basin's groundwater confront dropping water tables. Unless there is a limit to extraction, each new well puts further pressure on a declining resource.

PART II

"You could not step twice into the same river" - Heraclitus

WHAT ARE THE TRADEOFFS?

The water regulation regime of the Colorado River means tradeoffs for stakeholders. How do these tradeoffs impact others upstream and downstream?

Class Activity: Brainstorm a list of stakeholders in the Colorado River and their primary concerns. Then, read through the tradeoffs below and identify two key stakeholders who are affected by each tradeoff. How are they affected, and what are possible strategies for mitigating these impacts?

Optional activity: Use the Stakeholder Analysis NCEP module to identify key stakeholders and their concerns (available at ncep.amnh.org)

Water rights and the accommodation of new demands

The issue of water rights is central to the historical and current context of management of the Colorado River. As indicated in Appendix 1, the 'Law of the River' tightly controls how water is allocated amongst stakeholders. Within this allocation scheme, there are few options for securing additional Colorado River water. Las Vegas, for example, relies on banking, trading, reusing, and buying water rights to sustain its growth.

As noted above, agriculture is the main recipient of Colorado River water, but there is a growing need for municipal and industrial uses of water. The key water rights issue for the Colorado River is that rights were appropriated under the principles of prior appropriation (which means first in time, first in right, so that the oldest rights have priority over newer rights, and when there is not enough water to satisfy all rights, the newer rights will be cut off first). Agricultural districts were well established before many cities applied for water rights, creating a situation where cities are more vulnerable to shortages than farmlands. Colorado River water rights are permanent and cannot be renegotiated, and while they can be sold, there are restrictions on interstate trading. In addition, an individual farmer cannot sell water to an external user without the approval of their irrigation district, and districts are often wary of selling a resource whose value only increases over time. Despite these restrictions, water for growing urban populations is so valuable that cities throughout the Colorado River basin have purchased rights to Colorado River water from farms, a practice often criticized as "buy and dry" for the impact it has on the rural, selling communities. Some more innovative deals have been struck, such as those where cities pay farmers a contracted rate for the right to use the water during shortage years when the city would experience a water shortage due to the junior status of its rights. This "dry year lease" allows farming to continue in most years.

Out-of-basin transfers, where water is moved through massive pipelines, constitute a tradeoff as well, since water moves out of the system and is not returned to the Colorado River's streamflow. Water slated for use in homes and farms around Phoenix and Tucson, Arizona, travels along the 540-kilometer Central Arizona Project canal (built in 1985) from Lake Havasu through the Sonoran Desert. Other massive infrastructures are the 390-kilometer Colorado River Aqueduct in Southern California, the 112-kilometer San Diego Aqueduct, and the 200-kilometer Coachella Canal in California. The 136-kilometer All-American Canal provides water for the Imperial Valley of Southern California, a productive agricultural region that was once desert. Colorado's Front Range, including Denver, imports Colorado River water through mountain tunnels across the continental divide.

Furthermore, one of the most complex management issues facing the Colorado River is the legal definition, quantification, and allocation of Native American water rights claims. When the United States reserves public land for Native Americans, it implicitly reserves sufficient water to satisfy the purposes for which the land was reserved. This practice is known as the federal reserved rights doctrine, based on a 1908 U.S. Supreme Court case that confers senior water rights to Native American users in states that may be already using their full allocation of Colorado River water. Many of the unsettled rights involve large quantities of water, potentially impacting water uses around the basin and as well as long-term planning for the basin (Morrison et al. 1996; USDOJ 2014).

Salinity and water quality

The Colorado River system is naturally very saline—natural springs that feed the river's flow add more than half of the river's salt load. Many factors directly influence salinity in the basin: stream flow, reservoir storage, water resource development, salinity control methods (such as properly draining irrigation fields), climatic conditions, and natural runoff. Almost seven billion kilograms of salt are carried past the U.S. Geological Survey gauge below Hoover Dam each year. The flow of the river dilutes this salt, and depending upon the quantity of flow, salinity can be relatively dilute or concentrated, though salinity is cumulative and generally increases downstream, so salinity levels are highest in water being delivered to Mexico (USBRUC 2013).

Salinity levels are directly influenced by salt loading (as salt is carried from land into the river) and consumption of water flowing in the river system. While salt loading can come from natural runoff and runoff from human activities such as logging, mining, and urbanization, irrigated agriculture is the largest user of water in the Colorado River basin and a major contributor to the salinity of the system. Agriculture increases salinity by consuming water through evapotranspiration and by leaching salts from saline soils, a process where salt is extracted from soils by dissolving in water (Box 2). Municipal and industrial use increases salinity through the consumption of the water. The combined effects of instream, nonconsumptive water use and off stream consumption have had a significant impact on the river's salinity. The basin wide drought since 1999 has also had an influence on the present high levels of salinity of the Colorado River (USBRUC 2013).

A significant negative impact of the salt concentration is economic. The last estimate of salinity damages in the Lower Basin alone was almost $300 million per year, primarily due to reduced agricultural crop yields, corrosion, and plugging of pipes and water fixtures (USBRUC 2013).

Salinity control projects have been implemented for decades, and salinity has been dramatically reduced since its 1970s highs. Much of the current salinity control in the river basin focuses on managing and minimizing salt loading into the river, primarily due to increased irrigation efficiency (Butler 2001). To achieve this goal, a variety of salinity control methods are used. Saline springs and seeps are collected for disposal by evaporation, industrial use, or deep-well injection. Other methods include both on-farm and off-farm delivery system and irrigation improvements, which reduce the loss of water and reduce salt pickup by improving irrigation practices, controlling soil erosion, protecting riparian areas, and by lining canals and ditches (USBR 2014a).

Salinity is not the only water quality concern in the Colorado River basin. Other issues of concern include reservoir eutrophication and algal impacts; natural bromide in the water and formation of potentially toxic or carcinogenic compounds with chlorination or ozonation during water treatment; selenium and trace elements from irrigation return flows and their impacts on endangered species; contaminants such as ammonium perchlorate and pharmaceuticals into Lake Mead; and ammonium, trace elements, and radiologicals from uranium mine tailings along the river (USBRUC 2013).

Box 2. The Story of the Salton Sea: No Easy Answers

The Salton Sea is California's largest lake, located just north of the productive agricultural area known as the Imperial Valley, part of the Imperial Irrigation District. However, the saline Salton Sea is no ordinary lake, owing to its complex history. The area is part of the Salton Sink that has intermittently held prehistoric lakes from spillover from the Colorado River. Prior to the turn of the 20th century, the area that is now the sea was a dry area where salt mining occurred. The present lake was created when heavy flow caused the Colorado River to breach a dyke in 1905 and then flood the area. Water flowed into the basin for two years before river flow was controlled—the lack of any drainage created a massive saline lake that is now saltier than the oceans (Salton Sea Authority 2014).

Today, the lake is replenished by agricultural runoff from nearby irrigated farmland in the Imperial and Coachella Valleys. Over the past century, the Salton Sea has become the "crown jewel of avian biodiversity" with over 400 bird species relying on its critical position along the Pacific Flyway. However, the Salton Sea is continuing to get saltier, which combined with other threats such as increasing nutrient levels from runoff and fluctuating surface levels, affects many species such as fishes and micro-organisms that support the diverse bird populations in the Salton Sea National Wildlife Refuge. To add to the dilemma, political roadblock is fast approaching, due to terms of an existing agreement among several agencies that manage Colorado River water. The agreement decrees that water transfers from the Imperial Irrigation District to San Diego and the Coachella Valley must begin in 2018. Human health consequences also loom, as the increasingly exposed lakebed produces dust that threatens air quality—a phenomenon that will increase when water transfers commence. In recent years, stakeholders including the Salton Sea Authority, US Bureau of Reclamation, California Resources Agency, and California Department of Water Resources, among others, have created various restoration plans for the sea. These plans range from the Salton Sea Restoration program, a $9 billion plan to restore a smaller but more manageable Salton Sea that includes habitat for birds and fish, to lower cost efforts to save an even smaller portion of the sea, financed by on site renewable energy projects (California Department of Water Resources 2014; Salton Sea Authority 2014). Given the high cost of the plans, progress has been slow to date and confined to small habitat restoration projects, while at the same time, costs of inaction continue to accumulate, to the tune of billions of dollars in health care costs, and reduced property values and agricultural productivity (Cohen 2014).

Riparian habitats and species

Riparian ecosystems are among the most diverse, dynamic, and complex biophysical habitats on the terrestrial Earth. Moreover, these ecosystems attenuate flooding, maintain elevated water tables, improve water quality, and thus provide valuable human and ecological services. Riparian corridors are also critical habitat for desert flora and fauna, providing oases of species richness and high productivity in otherwise dry environments. They are critical routes for migratory birds passing through desert regions on their way to nesting or wintering grounds. The integrity of riparian landscapes is maintained by disturbances. Because of its ecotonal nature and position in the landscape, riparian vegetation experiences disturbances associated with both aquatic systems (e.g., flooding generated by spring snowmelt and channel widening) and uplands (e.g., fire and wind throw) (All 2006).

Riparian zones in the western U.S. and Mexico have undergone remarkable changes over the past century through water diversion, groundwater decline, flow regulation, channelization, and dams that reduce flows and eliminate the normal pulse flood regime of dry-region rivers. The impact of these changes on riparian habitats has been exacerbated by spread of opportunistic invasive species. One such invasive is the salt-tolerant shrub saltcedar (*Tamarix ramosissima*), which along with a native salt-tolerant shrub arrowweed (*Pluchia sericea*), has largely replaced native cottonwood (*Populus fremontii*) and willow trees (*Salix gooddingii*) on the lower Colorado River. Loss of these native trees that depend on timed, seasonal flooding for germination, has degraded the habitat value of the riparian zone for wildlife (especially birds that use rivers as migration routes and nesting sites) and programs to restore native trees are underway (DiTomosa 1998; Stromberg 2001; Nagler et al. 2004). While intensive salt-cedar eradication removal programs use mechanical, chemical, and biological control agents, research indicates that a restoration of the natural flood pulse regime of the river may assist with regenerating native vegetation. Studies support the hypothesis that restoration of a pulse flood regime will regenerate native riparian vegetation despite the presence of a dominant invasive species, and suggest that natural resource managers and river operations specialists should examine the potential for providing beneficial floods on arid-zone rivers as a means of reestablishing native vegetation (Nagler et al. 2005; Tiegs et al. 2005; Glenn et al. 2013).

The Grand Canyon ecosystem was drastically altered by the Glen Canyon Dam: natural flash floods that would previously scour the canyon and deposit fertile sediment from tributaries originating in the Colorado Plateau no longer occur. Given the research indicating the restoration potential of pulse floods, managers began a program of experimental releases of man-made floods from Glen Canyon Dam in 1996, in efforts to mimic the natural flooding behavior of the river prior to the 1963 construction of the dam. Notably, these releases change the rate of water deliveries from Lake Powell to Lake Mead downstream, but not the total volume. The flows are part of an adaptive management strategy, building on the results from each test, intended to deposit sand up and onto eroded Grand Canyon sandbars and beaches, restore vegetation, and create habitat for endangered fishes as required by the Endangered Species Act. Scientists have conducted experiments during and following the floods to assess the impact of high water flows on key species and habitats in Grand Canyon National Park. These experiments have yielded mixed preliminary results, with increase in sandbar area and volume in some portions of the river and some erosion in others. Scientists are now testing more frequent high flow pulses to prevent erosion (USBR 2013).

Since the construction of the Glen Canyon Dam, the Grand Canyon ecosystem has also been characterized by cooler and clearer water, since the once warm water of the river now sits for long periods in Lake Powell. All of these changes have affected the native biota, such as the federally endangered humpback chub (*Gila cypha*) and razorback sucker (*Xyrauchen texanus*). The Colorado River contains one of the most unique collections of fish fauna in North America – with as many as three quarters of its approximately 32 freshwater species recognized as endemic (Minckley et al 1986; Minckley and Deacon 1991). More than 50 species of non-native species have been introduced into the upper parts of the river alone, where they compete with native fishes in areas where their ranges overlap (Upper Colorado River Endangered Species Recovery Program 2014).

Water managers have begun to understand how changes to the river have affected native species and protection and restoration initiatives are underway, including several major federal recovery and mitigation programs. Since 1988, the Upper Colorado River Endangered Fish Recovery System has worked to recover endangered Colorado River basin fishes. The Lower Colorado Multiple Species Conservation Program is a coordinated long-term effort to conserve and work towards recovery of endangered species and protect and maintain wildlife habitat in the Lower Basin. This is one of the largest conservation plans ever attempted. Both recovery efforts involve multiple stakeholders, from federal and state agencies to environmental groups and other private organizations. The driving legislation behind these initiatives is the Endangered Species Act, which calls for agencies to provide for the survival and recovery of threatened and endangered species through conservation and management initiatives, such as designating critical habitat and creating recovery and habitat conservation plans (USBR 2014b; Upper Colorado River Endangered Species Recovery Program 2014).

While the network of dams along the river has ecological consequences, they provide necessary services for many residents both in and out of the basin. The hydroelectric power facilities along the river and its tributaries generate approximately 12 billion kilowatt-hours annually that is used both inside and outside the basin, and the revenues from the dams underwrite programs ranging from salinity control to fish habitat restoration (Tillman and Anning 2014).

As highlighted in the next section, the river's management has significantly affected the riparian habitats and species in Mexico (some of the largest patches of riparian habitat remaining in the entire Colorado River basin), especially in the Colorado River Delta. However, as evidenced by numerous verdicts in U.S. courts, the U.S. federal government's claims of responsibility for species protection ends at the border, so even the Endangered Species Act does not require that programs such as the Lower Colorado Multiple Species Conservation Program incorporate the Delta into its planning process.

Colorado River Delta

Some of the most pronounced tradeoffs in the way the river is regulated are the consequences for the Colorado River Delta. Before its damming and diversion, the Colorado River emptied virtually its entire flow into the Gulf of California, also known as the Sea of Cortez (Dettman et al. 2004). These massive freshwater flows created a landscape of wetlands and forests that the famed conservationist Aldo Leopold described as "a hundred green lagoons" when he visited in 1922. Since that time, major impoundments caused first by Hoover Dam (Lake Mead filled from 1935-1957) and then by Glen Canyon Dam (Lake Powell filled from 1964-1981) desiccated the Delta. Except for a few limited occasions, no water flowed beyond Morelos Dam at the border in Mexico from 1960 until 1980 as these reservoirs filled (Pitt et al. 2000; Zamora-Arroyo et al. 2008). Even during wet years, water was simply captured behind the dams rather than transmitted to the Delta and the sea (Glenn et al. 2001) (see Figure 4 for water levels at the international border.) Since the river no longer reached the ocean in most years due to upstream withdrawals, key riparian, wetland, and intertidal habitats that normally sustain bird populations, fisheries, and coastal fishing communities were compromised (Gleick 2003). The balance between freshwater flows and saltwater intrusion was also altered, further affecting riparian species.

Residents in the Delta region are primarily fishermen, farmers, and workers employed in service industries for these professions. Agricultural irrigation currently dominates the water usage agenda in northern Mexico, and the Colorado River provides water to hundreds of thousands hectares of irrigated farmland (Glenn at al. 2013). Most fishing income in the past was derived from the shrimp industry; however, this industry has been decimated in recent years both by overfishing and lack of the fresh water influx that shrimp are dependent upon. Fishing is dependent on habitat quality and the intensity of fishing effort, whereas farming relies strongly on availability of irrigation water. Human vulnerability to fluctuations in ecosystem productivity in these areas is pronounced for the Gulf fisheries (All 2006).

Increased public interest in environmental issues over the years has substantially boosted attention to the Delta from governments, non-governmental organizations and environmental groups on both sides of the border. Scientists are working to understand and reconstruct the relationship between Colorado River freshwater flows and the health of the estuary. Aragon-Noriega and Calderon-Aguilera (2000) show a statistically significant positive correlation between river flow and the relative abundance of postlarvae of the shrimp Litopenaeus stylirostris in the years 1993–1997. Rowell et al. (2005) used oxygen isotopes in fish otoliths to determine that Colorado River flow is important in providing brackish water nursery habitat for the Gulf corvina (*Cynoscion othonopterus*), a commercially valuable and endemic fish in the upper Gulf of California. The results also supported the hypothesis that declines in commercial landings of Gulf corvina can be partially attributed to reduced river flow and that increased flow would increase nursery habitat and likely benefit recruitment.

Notably, the Colorado River Delta in Mexico has shown resilience and has revegetated somewhat following 20 years of water flows from the U.S. Lake Powell, the last major impoundment built on the river, filled in 1980. Since then, flood flows in the main channel of the river, released by managers in the United States when flows exceed available storage capacity and uses, have occurred in El Niño cycles, and have returned native trees and other vegetation to the riparian corridor, as the pulses led to the germination of willow and cottonwood seeds. In addition, environmental organizations working in the Delta began to purchase water from local farmers to irrigate nascent restoration sites, indicating the significant restoration potential for the Delta should some freshwater flows be regularly restored. The native riparian vegetation provides a migration route for endangered southwestern willow flycatchers (*Empidonax traillii*) and other migratory birds moving north from Mexico for summer nesting. The Delta is an important stopover point on the Pacific Flyway with 55% of the total bird species in North America breeding, wintering, and/or migrating through the area (Zamora-Arroyo et al. 2008). Many studies report that these flows have improved the ecology of the intertidal zone and the marine zone in the Upper Gulf of California (Glenn et al. 1996; Pitt et al. 2000; Nagler et al. 2005; Glenn et al. 2007).

More recently, a historic agreement, five years in the making, between the U.S and Mexico resulted in the release of the largest pulse of water into the Delta in decades, to be followed by a smaller permanent annual flow to sustain the ecosystem. The initial two-month long flood, enough water to reach the Gulf of California according to sophisticated models, was designed to simulate a natural spring flood, trigger germination of

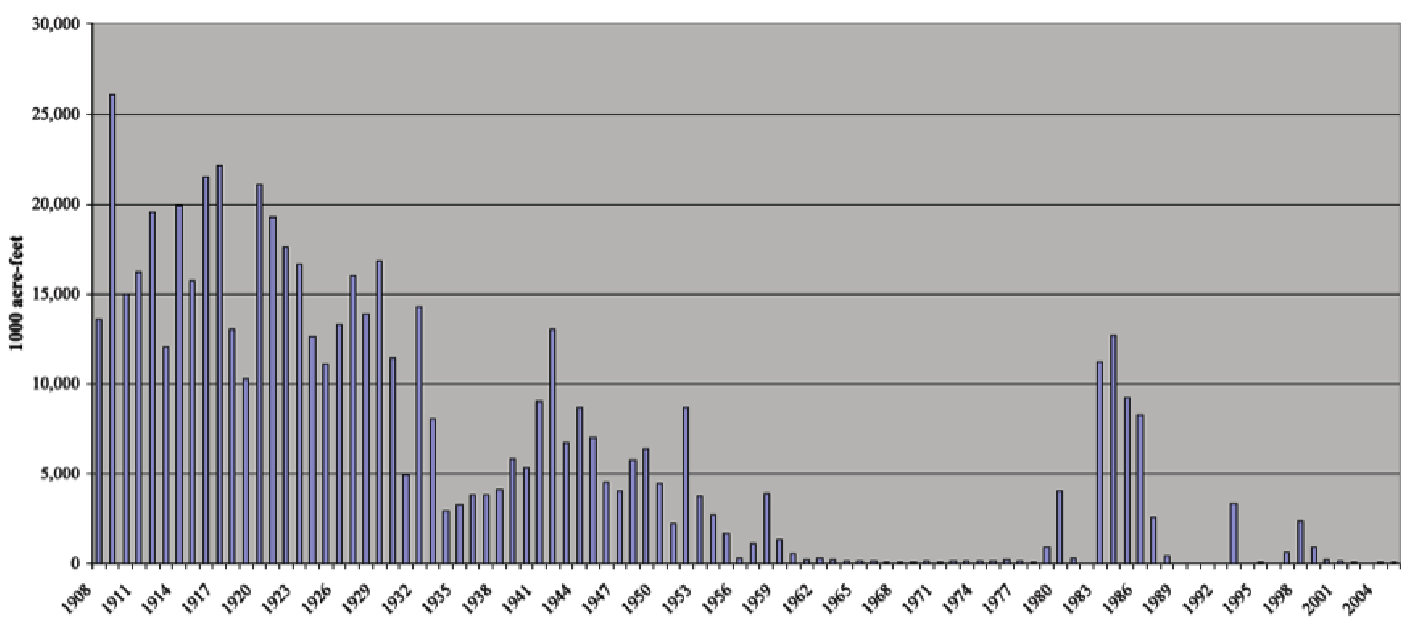

Figure 4: Colorado River Annual Flow Volume Below Major Dams and Diversions, 1908-2005 (Wheeler et al. 2007).

native seeds, and create new wetlands, while the annual flow is designed to maintain this new growth (Glenn et al. 2013). The pulse flow, about one percent of the river's historical flow, was released from the Morelos Dam on March 23, 2014. According to the terms of the agreement, scientists will carefully assess the hydrological, ecological, and operational consequences of the new water deliveries by stakeholders, and continue to write the story of the Colorado River Delta (Water Education Foundation 2014; Witze 2014).

Groundwater

Surface water is derived from precipitation and can be diverted. Groundwater, however, accumulates from precipitation, irrigation, or river seepage that is absorbed into the ground and is collected in underground aquifers over thousands of years. Groundwater – both renewable and nonrenewable - can then be accessed through wells and is also a major contributor to surface water flows. In addition to supplying surface water, the Colorado River provides groundwater to surrounding areas.

In the arid West, only a small portion of groundwater can be recharged through precipitation. Continuous withdrawals can cause water tables to drop, aquifers to collapse, and lands to sink, resulting in loss of valuable water storage resources. In addition, groundwater pollution can be more severe than surface water pollution, as the normal cleansing mechanisms at work in surface waters are not present in ancient aquifers threatened by agricultural runoff, dumping of wastewater, and industrial and hazardous waste. Salinity, in particular, is one of the most devastating forms of groundwater pollution in the Colorado River basin, derived from salt percolating down from agricultural fields (Morrison et al. 1996).

Groundwater in the Lower Basin is already over drafted above natural recharge levels, which has direct impacts on levels of groundwater surfacing in the Colorado River Delta region. This is compounded by the already overdrawn Mexicali aquifer, which provides water for Mexican farmers. In some areas where water from the Colorado River is imported, groundwater is heavily used, but not always regulated. Any solution to these conflicts is complicated by the fact that the problem of groundwater management is after-the-fact: unregulated water is often over-appropriated before overdraft consequences are evident. Any action therefore will require individual stakeholders to give up water rights, so any attempts to regulate groundwater would be expected to face opposition from agricultural interests fearing pumping restrictions and local water districts opposing oversight (Morrison et al. 1996). A recent study, using satellite data to track groundwater depletion in the Colorado River basin from 2004 to 2013, found such significant losses in the basin during these drought years (equivalent to two full Lake Meads) that the depletion may threaten the long term ability to meet future allocations of surface water (Castle et al. 2014). Startlingly, the study found that groundwater was filling the gap between demands and the annual renewable surface water supply, and given its decline, this groundwater supply is nonrenewable, indicating that the available stock of freshwater in the basin is in significant decline.

HOW WILL THE WEST BE WATERED?

This case study has given an overview of the complex social, political, and environmental framework that follows the Colorado River along its course.

> **Class Activity**: Given this information and your own creativity – break into groups and brainstorm ways that the West will be watered in the future. How does climate change affect this process? What other factors may come into play in the future? Specific discussion points are given below.

The realities of increasing demands on finite water resources mean challenges ahead for the southwestern U.S. and there are no easy answers. The modern history of the Colorado River has been marked by the principle of building more infrastructure to sustain economic growth, but is transitioning to an era of increasing institutional flexibility such as the use of markets to transfer water to accommodate new water needs including those of freshwater ecosystems. However, the challenges ahead may require a more comprehensive approach. Possibilities lie in new policies, cooperation, technologies, and tired and true conservation.

Agricultural and urban conservation initiatives

The powerful U.S. Bureau of Reclamation has shifted from dam–building to resource management. The agency recently released a report on the supply of and demand for Colorado River water that explored various options for meeting future demands, ranging from increasing supply and reducing demand (through reuse and conservation measures), to modifying operations to reduce evaporation, to transferring and banking water throughout the system (USBR 2012). Despite the inherent uncertainties in projecting climate change and population growth, this report makes clear that the West is urgently facing a water crisis. The report projects that by 2060, river supplies will fall short of demand by about 3.2 million acre-feet—more than five times the amount of water annually consumed by Los Angeles (Figure 5).

There are significant opportunities for water conservation in the biggest water-consuming sector of agriculture. Morrison et al. (1996) estimate that improvements in irrigation efficiency or shifts in cropping patterns can free significant amounts of water for ecological or other purposes. For Arizona, the authors estimate that upgrading half of all irrigated cotton and major vegetable and citrus crops to drip or other micro-irrigation techniques, and upgrading half of irrigated alfalfa, wheat, and barley crops to more efficient irrigation methods could save on the order of 445,000 acre-feet of water per year. Combined with other conservation approaches, an approximately 1.24 maf could be saved per year, comparable to the groundwater overdraft in Arizona. However, the benefit of water conservation is not always clear-cut: some water used for agriculture drains back to the river and is used by others downstream, though repeated withdrawal of water for agriculture and return drainage can increase the river's salinity downstream.

Urban conservation will also be part of the way the West will be watered. Successful efforts to curb domestic water use permanently will include a combination of economic incentives, efficiency standards and regulations, voluntary retrofits of appliances for example, and public outreach that together promote the use of water-saving technologies and behaviors. Since outdoor water use accounts for the majority of domestic water use, technologies and behavior change also need to apply to landscaping and other outdoor water uses. These initiatives, however, are dependent upon a stabilized rate of population growth—a complex challenge that requires urban planning and growth management tools.

Any water conservation measures in the home, business, and agriculture are complicated by the "use it or lose it" structure of the Colorado River allocation scheme—though stakeholders are now working collaboratively to make adjustments to this system, within the confines of the Law of the River, through tools like economic incentives and properly designed water pricing and tax structures. As an example of an innovative approach to modifying the rigid allocation structure, the four largest cities (Los Angeles, Denver, Phoenix, and Las Vegas) that depend on the Colorado River for their drinking water started piloting an innovative conservation plan that pays farmers, industries, and municipalities to reduce their water use. Called the Colorado River System Conservation Program, the $11 million fund is designed to keep the levels of Lake Mead and Lake Powell high enough to avoid a declaration of water shortage, which would trigger politically sensitive reductions in water deliveries. Las Vegas for example, has many incentives to participate, given its dependence on Lake Mead. Lake levels have dropped close to the top of the city's uppermost water intake pipe, and while the city has been constructing a third intake tunnel deeper in the reservoir since 2008, the clock is running out on the other two intake pipes that may be high and dry in coming years (Postel 2014).

Discussion Question 1:

Are these conservation efforts feasible? What other conservation opportunities may be available? Where would conservation efforts have the most impact? How can stakeholders and managers promote water conservation?

Market-based re-allocation

Most of today's new water demands are met through

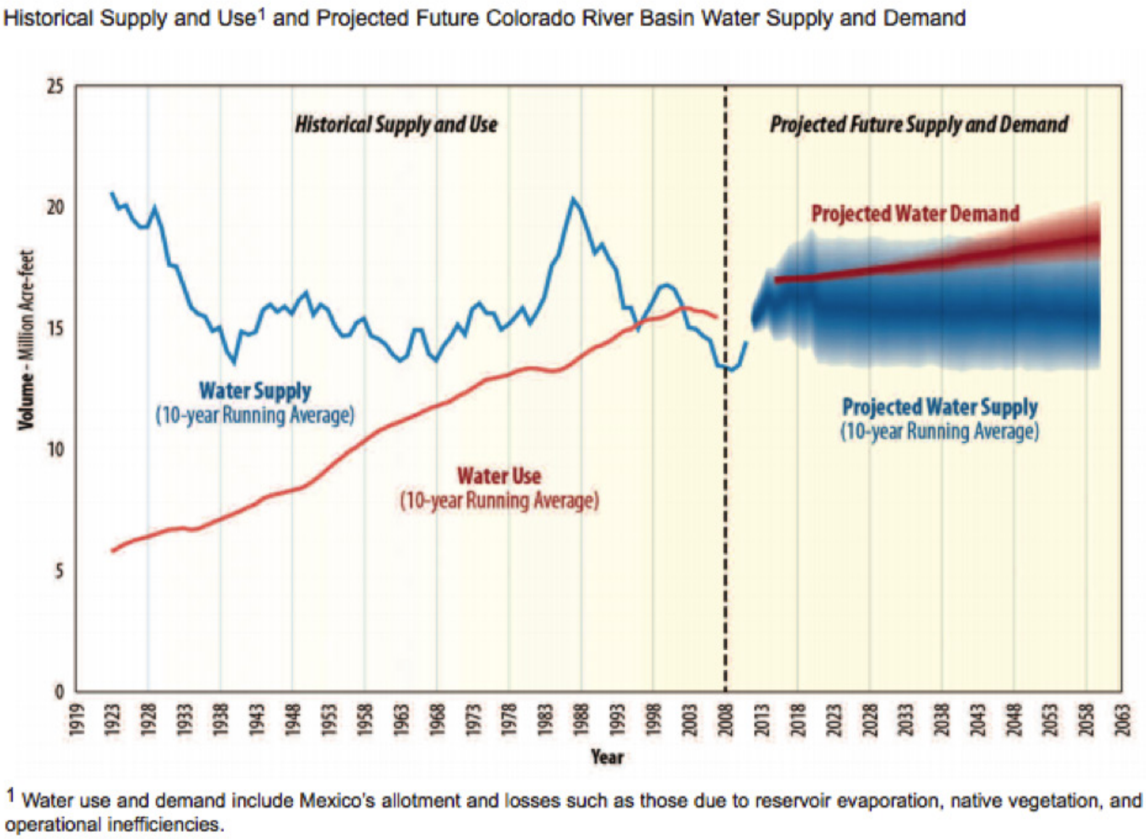

Figure 5: The range of projected future water supply and demand in the Colorado River basin, modeled on various management scenarios in the coming years, shows future imbalances and an uncertain future water supply (USBR 2012).

re-allocation of existing rights through market mechanisms, in other words, the selling and buying of water. Some transactions have transferred the water rights themselves, while most of today's transactions are based on long-term leases of water, allowing the holder of the water right to continue to own that property. In some cases, water can be "banked" or stored for use in another year in one of the Colorado River system's large reservoirs. In the Lower Basin, banked water is "taxed" by 5%, which creates a system benefit: more water is in storage for all consumptive users.

Voluntary water transfers can move water from low valued uses, such as alfalfa farming to higher valued uses, such as drinking water, yet this is contingent upon stakeholder agreement as part of the Law of the River.

Technological solutions and augmentation

A cutting edge water management project using reclaimed water for municipal purposes is operating in Orange County, California. The Orange County Water District has reduced their dependence on groundwater and imported water (including from the Colorado River) by diverting highly treated wastewater that is currently discharged into the ocean to groundwater basins for reuse. Before it is distributed, the treated water undergoes an advanced treatment process that includes

Discussion Question 2:

How do we supply these "new" demands from urban areas and for biodiversity needs? What are the consequences of moving water from agricultural use to urban use? What should be done for farmworkers, agribusinesses, and county tax revenues? Does it make sense to take agriculture out of production in order to water lawns and fill swimming pools? Given your understanding of the Law of the River, what re-allocation schemes are feasible? Now, imagine that the law could be changed. What changes regarding allocations and water rights should be made? How would these changes impact other stakeholders?

two membrane filtration systems - microfiltration and reverse osmosis, and treatment by ultraviolet light and hydrogen peroxide. Once purified, the water is sent to spreading basins to seep into the ground, like rain, blending with groundwater that is then withdrawn for drinking water and other purposes. The Orange County Water District has decades of experience reusing purified wastewater that is injected into wells to serve as a saltwater intrusion barrier to prevent coastal wells from being contaminated with seawater. The reclaimed water project has been operational since 2008 and produces enough water to meet the daily needs of 600,000 residents in Orange County (Groundwater Replenishment System 2014). Innovative approaches such as the Groundwater Replenishment System, which is slated for expansion in the coming years to meet the needs of 250,000 more residents, will be increasingly necessary as water stress increases.

In the face of persistent drought in the basin, the seven Colorado River basin states in the U.S. have begun to study opportunities to augment water supply in the region, looking at everything from desalination of brackish and ocean water, to weather modification such as cloud seeding to increase precipitation, to the importation of freshwater in bags through ocean routes, to the construction of pipelines to import water from other regions of the continent (Southern Nevada Water Authority 2008, USBR 2012). These augmentation projects have varying associated legal, political, and environmental issues—they may not necessarily be inexpensive or easy to implement, but some of them show promise and will continue to be pursued as water supplies tighten in coming years. For example, in Yuma, Arizona, the U.S. Bureau of Reclamation constructed a desalting plant designed to remove minerals from nearby agricultural runoff. Construction of the plant was completed in 1992, but due to both complications from a plant flood and the surplus supply conditions, it has only been sporadically operational. Given the recent drought and increasing demands, interest in the augmentation potential of the plant has increased (USBR 2014c). However, it is important to note that the runoff that would be processed is what sustains the nearby Cienega de Santa Clara wetland in Sonora, Mexico, in the Colorado River Delta. In this scenario, water that may be "saved" through desalination would constitute a tradeoff in terms of reduced flows into critical wetlands that provide habitat for endangered and threatened species.

Discussion Question 3:

How feasible are these technological solutions and augmentation strategies? What are the costs and benefits of these approaches? How does water conservation fit as an augmentation strategy? How might water managers make decisions about different strategies and what political considerations would come to play?

Policy and science

Much of the Law of the River—the Compact, the federal and state statutes, interstate compacts, court decisions, and other operating criteria and administrative decisions that define the river's overall governance —was established in the past and it is clear that the situation has changed dramatically in the intervening years. Volumes of new scientific information have been made available since then: the scientific knowledge base of Colorado River hydrology and climate rivals, and may exceed, comparable knowledge bases for any of the world's river systems. It is time to re-evaluate the body of policy concerning the river. Multiple stakeholders have called for a comprehensive study and policy review that is informed by science and planning principles and marked by collaboration and cooperation between US and Mexico, states, and stakeholders at all levels (National Research Council 2007).

Tradeoffs and river management

As outlined in Part II, the management of the Colorado River results in complex tradeoffs. The river is a managed river and will remain so. The question is what it will be managed for and how to do it right in the years to come.

Currently, it's well managed for agriculture and power generation, managed adequately for cities, and badly managed for nature and biodiversity. As demands rise and supplies tighten, stakeholders will need to revisit questions about how the river is managed.

Discussion Question 4:

How does policy adjust to changing realities and new scientific information? Scientific discovery tends to occur faster than policy change – how can stakeholders keep abreast of change? Students can discuss the revised estimation of water yield since the Compact, the recognition of the value of biodiversity since the construction of major Colorado River infrastructure, or the emerging understanding of the impact of climate change on the river and its users. Imagine if the Law of the River could be re-evaluated and re-negotiated. What aspects might be changed? How would this impact other areas of the basin and other stakeholders?

Discussion Question 5:

Are all the many uses of the Colorado River compatible? If not, what should the priorities be and why? Are there fair ways to move water from one use to another? Which stakeholders have the power to make these changes?

Binational cooperation

In general, the history of the management of the Colorado River has been primarily U.S. based, to the detriment of Mexico in terms of water quality and habitat quality, especially in the Delta. Most of the economic benefits of Colorado River management have been north of the border while most of the environmental costs have been south of the border. The International Boundary and Water Commission, an arm of the U.S. State Department, governs the relationship between the U.S. and Mexico on the Colorado River. Border water controversies cover a wide range of environmental and economic issues, including habitat and biodiversity conservation, water quality and water to support agricultural and economic development. In the past, the U.S. and Mexico might try to address those issues separately or through limited bi-national programs, but as border cities and economies have grown more interdependent, so has the need to find solutions that satisfy constituencies on both sides of the border. A solution to a problem on one side of the border likely will have repercussions, sometimes negative, on the other side. It is clear that bi-national cooperation will be essential for restoration of habitat in key riparian areas and the Colorado River Delta.

The historic agreement to provide a pulse and annual flows to the Delta is an example of how cooperation can result in a win-win. In order to "free up" water from the tight allocation system to flow to the Delta, representatives from the U.S and Mexico crafted an agreement whereby in exchange for flows into the Delta that come from Mexico's 1.5 maf allocation, the U.S is providing financing for the leak-prone water supply system in the Mexicali Valley. The water saved through these improvements, combined with water committed from Mexico's existing allocation, and water purchased by environmental organizations working in the Delta, is a down payment on a restored Delta (Jenkins 2014).

Discussion Question 6:

Imagine if the river were completely within the U.S. Would the Delta be better protected or restored? Discuss the Colorado River as an example of the difficulties and possibilities of cross-border environmental policy. How can nations avoid zero-sum outcomes with regard to water management? Are there are interests on both sides of the border that can be served through a collaborative approach to river management?

Facing the Challenge of the 21St Century

Every drop of Colorado River water is already appropriated, and its value will only increase. The river's complex regulatory framework, rooted in almost 100 years of legal and social history, and constantly under revision, is what makes this system so extraordinarily complex. As demands mount and tradeoffs grow even more complex, sound water policy will require innovative thinking, consensus building, and an integrated planning process.

The complex story of how the West was and will be watered is directly related to the past and future of the West itself. While the history and ecology of the Colorado River basin make it unique, the system also illustrates many of the challenges faced by water managers all over the world. How do we minimize the environmental impact of dams, pollution, and overuse? How do we balance the needs of all the species that inhabit the basin and depend upon its freshwater resources? Because the Colorado is so well studied and carefully monitored, the lessons learned by its managers are widely applicable to other river systems – and clarify the tradeoffs that water management involves.

QUESTIONS FOR FURTHER DISCUSSION

1. Reflect on the title of this case study, "How the West Was Watered." Which stakeholders were watered? Which stakeholders were de-watered?
2. Compare the discussion in Part II to the 150 different proposals for balancing the water budget of the Colorado River considered by the U.S. Bureau of Reclamation in their report "Colorado River Basin Water Supply and Demand Study" (USBR 2012). Do you agree with the report conclusions about the most promising proposals? Then read "Colorado River Drought Forces Painful Reckoning for States", published in January 2014 by The New York Times (http://www.nytimes.com/2014/01/06/us/colorado-river-drought-forces-a-painful-reckoning-for-states.html) and discuss the future of water in the Southwest. How will supplies continue to meet demand? Discuss the complicated issues of water conservation versus supply augmentation. Topics can include issues such as desalination, transfer of water rights and banking of water in reservoirs.
3. Read "Drought – and neighbors – press Las Vegas to conserve water", published in April 2014 by The LA Times (http://www.latimes.com/nation/la-na-las-vegas-drought-20140421-story.html#page=1). Given the precarious situation for this city that is entirely dependent on the dropping water levels of Lake Mead, how is the state of water resources in the city affecting planning for and development of the region? Can this challenge be overcome by linking land-use planning to water planning? How might this linkage work?
4. Research the story of how Tucson was able to break the historical rise in per capita water via a combination of water pricing, city ordinances, use of xeriscaping, and other conservation strategies combined with public awareness campaigns.
5. Read Box 2 above. Who are the main stakeholders in the restoration of the Salton Sea? For example, what is the close relationship between agriculture and the lake? If farmers are transferring their water rights to urban areas, how will the Salton Sea be affected? Research the concerns of those supporting and opposing the restoration, including conservationists (http://www.latimes.com/opinion/op-ed/la-oe-0918-morrison-salton-sea-krantz-20140918-column.html#page=1), farmers (http://news.nationalgeographic.com/news/2014/02/140218-salton-sea-imperial-valley-qsa-water-conservation/) and taxpayers (http://www.cvindependent.com/index.php/en-US/news/environment/item/1297-saving-the-sea-the-government-takes-baby-steps-to-preserve-the-salton-sea).
6. Read "Exporting the Colorado River to Asia, through hay" published January 2014 by National Geographic (http://news.nationalgeographic.com/news/2014/01/140123-colorado-river-water-alfalfa-hay-farming-export-asia/). What is virtual water? How is the river water used to produce hay in the Yuma and Imperial Valleys an additional tradeoff to be considered in managing the Colorado River, especially it comes to the issues of water rights and new markets for river water?
7. Read "New Hope for the Delta," published in January 2014 by High Country News (https://www.hcn.org/issues/45.18/new-hope-for-the-delta/print_view), and discuss the deal making that lead to the historic 2014 release of water into the Colorado River Delta. A photo essay by High Country News documents the historic flood pulse in rich detail (https://www.hcn.org/articles/colorado-river-delta/), and the story made international news (http://www.latimes.com/nation/la-na-ff-colorado-river-delta-20140323-story.html and http://www.dailymail.co.uk/news/article-2750254/Dramatic-

photographs-capture-mighty-Colorado-River-kissing-sea-time-50-years-coast-Mexico-dams-intentionally-unleashed.html)

8. How has the 'Law of the River' affected the native people of the Colorado River Delta? Read and discuss "In the Colorado River Delta, waters – and prospects – are drying up" (http://www.latimes.com/news/nationworld/world/la-me-newcolorado25-2008may25,0,1536281.story) and "Grabbing the Colorado from "the People of the River" (http://newswatch.nationalgeographic.com/2012/12/19/grabbing-the-colorado-from-the-people-of-the-river/).

APPENDIX 1: LAW OF THE RIVER, ALLOCATION REGIME, AND MAJOR PLAYERS

Law of the River

The Colorado River has been subjected to extensive negotiations and litigation. As a result, a complex set of federal laws, compacts, court decisions, treaties, state laws and other agreements has been developed, known as the "Law of the River". Principal documents forming the Law of the River are:

- Colorado River Compact of 1922
- Boulder Canyon Project Act of 1928
- Mexican Treaty of 1944
- Upper Colorado River Basin Compact of 1948
- Colorado River Storage Project Act of 1956
- 1963 US Supreme Court decision, Arizona v. California
- Colorado River Basin Project Act of 1968
- 1970 Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs
- Minute 242 of the 1973 International Boundary and Water Commission
- Colorado River Basin Salinity Control Act of 1974
- Grand Canyon Protection Act of 1992
- 2001 Colorado River Interim Surplus Guidelines
- 2007 Colorado River Interim Shortage Guidelines
- Minute 319 of the 2012 International Boundary and Water Commission

Allocation Regime (USBRUC 2005)

Water quantity
Colorado River water was apportioned by the Colorado River Compact of 1922, the Boulder Canyon Project Act of 1928, the Water Treaty of 1944, the Upper Colorado River Basin Compact of 1948, and the United States Supreme Court (Arizona v. California et al. 1963). The Colorado River Compact divided the Colorado River Basin between the Upper and Lower Basins at Lees Ferry (just below the confluence of the Paria River), apportioning to each use of 7.5 maf annually. In addition to this apportionment, the Lower Basin was given the right to increase its beneficial consumptive use by one maf per year. The compact also contains provisions governing exportation of Colorado River water. The Water Treaty of 1944 obligates the United States to deliver to Mexico 1.5 maf of Colorado River water annually, absent treaty surplus or shortage conditions.

Upper Colorado use
The Upper Colorado River Basin Compact of 1948 divided and apportioned the water apportioned to the Upper Colorado River Basin by the Colorado River Compact, allocating to **Arizona** 50,000 acre-feet annually, with the remaining water allocated to Upper Colorado River Basin States as follows:

- **Colorado** 51.75%
- **New Mexico** 11.25%
- **Utah** 23%
- **Wyoming** 14%

Lower Colorado use
States of the Lower Colorado River Basin did not agree to a compact for the apportionment of waters in the Lower Colorado River Basin; in the absence of such a compact Congress, through Secretarial contracts authorized by the Boulder Canyon Project Act, allocated water from the mainstem of the Colorado River below Lees Ferry among California, Nevada, and Arizona, and the Gila River between Arizona and New Mexico. This apportionment was upheld by the Supreme Court, in 1963, in the case of Arizona v. California. As confirmed by the US Supreme Court in 1963, from the mainstem of the Colorado River (i.e., The Lower Basin):

- **Nevada** was apportioned 300,000 acre-feet annually and 4% of surplus water available;

- **Arizona** was apportioned 2,800,000 acre-feet annually and 46% of surplus water available; and
- **California** was apportioned 4,400,000 acre-feet annually and 50% of surplus water available.

Mexico

The Water Treaty of 1944 obligates the United States to deliver to Mexico 1.5 maf of Colorado River water annually, absent treaty surplus or shortage conditions.

Major Players In Colorado River Management

- US Federal Government
  - US Bureau of Reclamation
  - US Army Corps of Engineers
  - Bureau of Indian Affairs
  - National Park Service
  - US Fish and Wildlife Service
  - International Boundary and Water Commission
  - Western Area Power Administration

- Government of Mexico (national, state, and local)
- State and City Governments (Upper and Lower Basin) in US
  - *Upper Basin*
    - Upper Colorado River Commission
    - Colorado River Water Conservation District
    - Utah Division of Water Resources
    - Wyoming Water Development Commission
    - New Mexico Environmental Department
  - *Lower Basin*
    - Arizona Department of Water Resources
    - Central Arizona Water Conservation District
    - California Department of Water Resources
    - Colorado River Board of California
    - Nevada Division of Water Resources
    - Colorado River Commission of Nevada
    - Southern Nevada Water Authority
    - Colorado River Salinity Control Forum
    - Colorado River Basin Ten Tribes Partnership

GLOSSARY

Acre-foot: A common water industry unit of measurement. An acre-foot is 325,851 gallons, or the amount of water needed to cover one acre with water one foot deep. An acre-foot serves annual needs of two typical California families.

Aquifer: Underground formation of water-bearing permeable rock, sand, or soil; an aquifer stores groundwater.

Allocation: Systematic distribution of water rights in this case.

Augmentation: Increasing stream flow through various means to "develop" water beyond what is supplied in normal river operations.

Alluviation: The process of sediment or gravel accumulating in a flowing water body.

Biodiversity: The variety of life on Earth at all its levels, from genes to ecosystems, and the ecological and evolutionary processes that sustain it.

Brackish: Mixed salt and fresh water, less salty than seawater.

Compact Call: If the Upper Basin states are unable to deliver the quantity of water required by the Colorado River Compact, Lower Basin states may legally force Upper Basin states, through provisions in the Compact, to reduce consumption - a politically charged situation

Desalting: Removing salt from water by evaporation, distillation, reverse osmosis, nanofiltration, etc.

Ecosystem: A community of organisms and its environment, functioning as an ecological unit.

Ecotone: Transition area between two adjacent ecological communities usually exhibiting competition between organisms common to both.

Endemic: Exclusively native to the biota of a specific place.

Erosion: Wearing away of the earth's surface by running water, wind, ice, or other geological agents.

Eutrophication: Over-enrichment of a body of water with nutrients, resulting in excessive growth of organisms and depletion of oxygen concentration.

Evapotranspiration: Process of transferring moisture from the earth to the atmosphere by evaporation of water and transpiration from plants.

Groundwater: Water beneath the Earth's surface, supplying rivers, springs, and wells.

Headwaters: Source or upper part of a stream or river.

Hydrological: Pertaining to water, its properties and movement through the Earth's land and atmosphere.

Invasive Species: A species that spreads widely and causes ecological or economic harm.

Irrigation: Applying water to crops, lawns or other plants using pumps, pipes, hoses, sprinklers, etc.

Isotope: Different forms of atoms of the same element.

Lower Basin: Portion of Colorado River below Lees Ferry in Arizona.

Native: A species that is indigenous to a region: the species lives there or has lived there historically, but was not introduced there from elsewhere.

Otolith: A bone-like structure found in the inner ear of many species of fish that allows scientists to estimate age.

Riparian: Relating to or living or located on the bank of a natural watercourse (as a river) or sometimes of a lake or a tidewater.
Runoff: Water that drains or flows off the surface of the land.
Salinity: The amount of salt in water.
Saltwater intrusion: When saltwater moves into the freshwater zone of an aquifer, making the water unfit for drinking.
Snowpack: Layers of ice and snow accumulated on the ground that persists through winter and melts in the spring and summer.
Stakeholder: Any individual, group or organization having a valid interest in a field or matter.
Trihalomethanes: Produced when water is disinfected with chlorine and the chlorine reacts with naturally occurring organic matter found in most freshwaters.
Upper Basin: Portion of Colorado River above Lees Ferry in Arizona.
Water Rights: The legal right to use water from a water course or body of water.
Xeriscaping: Planting native and drought-tolerant plants, shrubs, and groundcover that require relatively low amounts of water.

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