

The Colorado River: History, Issues, and Solutions

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Abstract

Water is the lifeblood of this planet, and its conspicuously limited availability represents an inescapable link between humanity and the natural ecosystems it had thought to isolate itself from after millennia of advancement. Although roughly 70% of the earth's surface is covered by water, less than 0.01% of the earth's 1.4 billion km³ hydrosphere is readily available for human consumption. Only recently has the magnitude of this scarcity emerged at the forefront of global issues. Today, roughly 2.4 billion people, or 36% of the global population, live in water-scarce regions. Global analysis expects this number to rise to 4.8 billion people, or 52% of the projected population, by 2050. Such trends are far from limited to developing nations, as even the U.S. has begun to feel these effects in the current century. Few better examples exist in the country than the plight of the Colorado River.

The Colorado River, the single largest source of surface water in the arid southwestern U.S., is a vital resource and edifice of natural wonder to all who explore and follow its vast and twisted journey from the headwaters in the Rocky Mountains to the Gulf of California. And yet it represents something greater still: it has a history of regulation and over-consumption that can be seen as a microcosm of humanity's reliance on a seemingly unlimited resource in the face of growing water demand in this next century. This paper will examine the history of the Colorado River Basin, the laws and regulations that govern it, the crises the inhabitants of the Basin face, and the viable options for addressing them [1], [2].

Geographic Layout

The Colorado River, known to the Mojave as "Aha Kwahwat" and to the Spanish as "Rio Colorado" (literally "Red River"), runs roughly 1,440 miles (2,330 kilometers) from an elevation of 10,175 ft (3,101 m) in the headwaters at La Poudre Pass in the Rocky Mountain National Park in Northern Colorado to the Gulf of California between the Baja California peninsula and mainland Mexico [3]. On its journey the river runs from Colorado through Utah and Arizona before winding down the border between Arizona and California and crossing into Mexico. It has a mean gradient of 1.52 m/km, with most of its descent occurring in more than 165 distinct rapids areas, and a discharge ranging from 700 ft³/sec to 220,000 ft³/sec, averaging at about 17,850 ft³/sec (500 m³/sec) [3], [4].

The river's watershed Basin covers 246,000 square miles (640,000 km²) in the U.S., roughly 1/12th of the continental land mass, and 2,000 square miles in Mexico. It extends from 26° 50' to 27° 08' latitude south and 65° 17' to 65° 36' longitude west [5, 6]. More than half of this Basin is contained in the Colorado Plateau, an area of approximately 140,000 square miles surrounding the four corners region of Utah, Colorado, Arizona, and New Mexico. Because the Sierra Nevada Mountains on the West Coast prevent Pacific moisture from reaching the southwestern states, annual precipitation on the plateau is low, an average of about 10 inches per year [7]. As such, the river's flow of about 15 million acre feet (maf) annually is small compared to the 180 maf of the Columbia or the 440 maf of the Mississippi (See Figure 1) [5]. (One acre-foot is the amount of water required to cover one acre to a depth of one foot, approximately 326,000 gallons.)



Figure 1: The Colorado River Basin [10]

The region's temperature varies from -40 to 120 °F seasonally, but for much of the year the region is semiarid, with precipitation ranging from 6 to 60 in. annually. Like many desert rivers, such as the Nile River of Africa or the Tigris and Euphrates rivers of Asia, the Colorado River obtains its water from the snowmelt of the mountain ranges far removed from the dry, arid regions it crosses for most of its journey [8]. About 86% of the river's annual runoff originates within 15% of the watershed's area, in the Rocky Mountains of Colorado and the Wind River Range in Wyoming. Because small changes in precipitation can greatly impact the water supplies in this semiarid region, the variation coefficient for the Colorado is about 33% [9].

Most of the Basin's landscape is colorful and angular, with highly dissected canyon country with substantial topographic relief to the south and low-relief, wide valley plateau country to the north. The river is also characterized by rapid sedimentary erosion; boulders and weathering debris from canyon scouring are routinely swept downstream during flash floods during seasonal rainfall and held by dams or removed from the Basin. Evaporation far exceeds precipitation in the majority of the Basin's surface area, both making the river the primary water source in the region as well as increasing its salinity value from the increased mineral concentration in the remaining water [10]. As a result, although the Colorado River Basin is about the same size as that of the Columbia (258,000 square miles), the river's much smaller flow brings considerably higher levels of sediment; in 1917, before any large dams were constructed on the river, an estimated 500,000 tons of sediment in the river flowed past Yuma every day [5].

As the primary water supply for 25 million people in seven states (Colorado, Wyoming, Utah, New Mexico, Arizona, Nevada, and California), it is the main river system in the American Southwest, draining one-twelfth of the conterminous U.S. It is also one of the most thoroughly controlled rivers in the country, regulated by over 40 flow regulation structures, including the Hoover Dam [4]. As a result, more water is diverted out of the Colorado River Basin than any other Basin the US, with total out-of-Basin diversion of more than 5.2 maf, over a third of its virgin flow [5]. Today it supports the cities of Los Angeles, Las Vegas, and Phoenix, which could not develop and flourish in its absence [8].

History

Geologic History

Approximately 1.7 billion years ago, during the Precambrian era, North-South compression along the North American plate created the Colorado River Lineament, extending from northern Arizona to the Lake Superior Region. Since then the lineament has been activated a number of times, each instance slightly altering its orientation, while thin, sheet-like sedimentary deposits have piled on top. Deep-seated faults were reactivated in the Late Paleozoic to Early Mesozoic, roughly 320 to 240 million years ago (mya), uplifting the Ancestral Rocky Mountains and forming a series of uplifts and sedimentary Basins that allowed seawater in to later form salt deposits. It was not until the Laramide Orogeny, from the end of the Cretaceous to the late early Tertiary (roughly 144 to 60 mya), that the Rocky Mountains

formed; later during the Eocene, the mountains eroded and deposited sediments on the Colorado Plateau, then at a relatively low elevation. Only about 6 mya were the Rocky Mountains and the Colorado Plateau uplifted 4,000 to 6,000 feet to their current elevation [7].

Two contrasting views dominate the geologic history of the Colorado River. The first is that the river has been always maintained its current course since birth, and its current drainage system is approximately the same as the one it was born into. It was this view that John Wesley Powell, in his 1869 journey of discovery, would adhere to, and geologists would subscribe to for another 60 years: the denudation of the plateau country in Northern Arizona, the canyon cutting, and the uplift responsible for both all began in the Eocene epoch, between 33.9 and 55.8 mya [8]. Geologists in the 1930s and 40s, finding the interior-Basin deposits of Late Miocene and Pliocene age common along the course of the river, concurred with this theory and concluded that the entire river was no older than the late Tertiary [8].

In 1969, however, later evidence uncovered in the plateau country of Arizona, Utah, and Colorado, showed a major paradox: drainage systems ancestral to the present course of the Colorado River in its upper reaches existed in the Miocene and probably as early as the Oligocene (23-33 mya), while its lower reaches were no older than the latest Miocene or Pliocene. This paradox ultimately leads to the second view, fostered by E. D. McKee and the museum of Northern Arizona: like most rivers, the Colorado is continually changing and evolving based on factors like tectonism and climate change. In this view, the ancestral Colorado followed its present course as far as the eastern end of the Grand Canyon, but then continued southeastward, not westward, along the course of the present Little Colorado and Rio Grande rivers into the Gulf of Mexico. Sometime in the Pliocene, a youthful stream emptying into the newly formed Gulf of California eroded headward and captured the sluggish ancestral river in the eastern Grand Canyon area. It was at then, about 6 million years ago, that the river embarked on its present course and began carving the Grand Canyon [8].

This period of history regarding the Colorado River and the Grand Canyon is best conceptualized in three periods of tectonism: pre-rifting, rifting, and post rifting. The pre-rifting interval occurred between the beginning and the middle of the Tertiary, about 33-23 mya, when the Basin-range rifting in the western region got underway along the present course of the Colorado River. The terrain south and southwest of the Colorado Plateau began to erode, but the drainages at this time were tributary to a master stream that flowed primarily in northwest-trending strike valleys. The rifting interval occurred in the mid-to-late Miocene, roughly 13.5-5.3 mya, when the Basins in the western Cordillera sank so rapidly that through-flowing drainage was not able to maintain itself, resulting in widespread interior drainage. The formally high areas south and southwest of the plateau began to founder and the lower Colorado River began to form. The post-rifting interval, between 8-5 mya and the present, saw the end of rifting in the Basin, the opening of the Gulf of California, and transition from the interior drainage to the current through-flowing drainage system of the lower Colorado River. By 3.8 mya the river reached its present grade in the upper Lake Mead area, and by 1 mya (at the latest) it reached its present grade in the western Grand Canyon [8]. As a result, the Colorado River is a unique excavator for its age;

although the river's modern form is only about 6 million years old, over its lifetime it has excavated roughly 2 billion years of geologic history that line its cavern walls [11].

Early Human History

The First Livestock

The first fundamental step in the anthropogenic regulation of the Colorado River resided on two principle factors: spreading demand for cattle and the federal designation of grazing land to maintain it. In the first 100 years since this country's independence, the federal government acquired most of the lands that now compose the American West; within the first 200 years, the government granted or sold roughly 1 billion acres of that land. Roughly 760 million acres, about a third of the nation's 2.3 billion-acre land area, remained public domain: national parks and forests, wildlife refuges, and Indian and military reservations. About half this public domain is in Alaska; the vast majority of the remaining 350 million acres are in the West, between the Rocky Mountain States and the Pacific Ocean. In the 11 western states, roughly 60 percent of all surface water originates on federal lands, including the Colorado River Basin [12]. Of the 246,000 square miles that compose the Basin in the US, 56% is controlled by the federal government (national parks and grazing land), 19% by private ownership, 16.5% by Indian reservations, and 8.5% by the states [9]. Roughly 60% of the Upper Basin and 52% of the Lower Basin is federally owned, not including Indian trust lands, military reservations, and state and municipal property [12].

Today nearly 250 million of the 350 million federal acres in the West are administered for cattle grazing, most by the Bureau of Land Management and the remainder by the Forest Service. No other activity uses more land area in the nation, contribute more towards altering the shape and texture of western lands, or consume more water [12]. Every ton of beef produced in this country requires approximately 7.5 million gallons; by contrast, every gallon of milk produced requires 16,000 gallons [13]. The magnitude of this fact, however, along with the other effects of the massive influx of livestock in the southwest, would not be recognized until the late 19th century [12].

In 1540 Spanish explorer Francisco Vasquez de Coronado brought the first livestock, including sheep, cattle, hogs, mules, and horses, an estimated 1,500 to 6,500 animals, into the American Southwest from Mexico. Historian Walter Prescott Webb theorized that many were set free because they became too weak or footsore to be of further use to their masters. Spanish and Mexican missionaries and settlers would later bring more livestock into the Southwest, and after the 1836 revolt the Texans appropriated more cattle from Mexican territory. The 1849 gold rush in California brought great demand for beef, and the mass exodus of cattle drives in the early 1850s from Texas across Arizona brought the first American ranches along the Santa Cruz River. Between 1850 and 1860, the Texas cattle population increased over 1000%, and after the Civil War cattle began appearing in even greater numbers in the Colorado River Basin. During this time, easterners and Englishmen invested heavily in livestock operations [12].

The Reclamation Movement

It was not until the mid-1880s that talk of overcrowding on the range began, in spite of the severe winter late in that decade. At this time between 720,000 and 1.5 million cattle inhabited the Lower Basin territory. But after the two consecutive dry years of 1891-1892 between one-half and three-quarters of the herds in Arizona were lost. This period also saw growing awareness to the fastest unalterable shift to the Lower Basin's landscape in recorded history: the millions of hooves from cattle destroyed significant portions of vegetation cover, increasing the severity of flooding and the subsequent sedimentation in the river. The grass cover disappeared and oak woodland zones moved uphill, only to be replaced by ocotillo, turpentine brush, and rabbitbrush spread by the cattle ingesting them [12].

Consequently, the 1890s also saw the Reclamation Movement, wherein the most easily dammed and diverted small streams were utilized to grow cattle feed [12]. Although the Colorado River had seen irrigation by local Native American tribes for some 2000 years prior, only in 1900 did such irrigation expand away from tributaries and headwaters to areas where it was more difficult to control, beginning with the opening of the Imperial Valley Canal in 1901 [5]. Such irrigation schemes were an attractive investment even to those with no interest in cattle, including John Wesley Powell, who was mostly interested in the social-engineering aspects of water, and the boomer of the Reclamation movement, William E. Smythe, who foresaw irrigation as mainly benefitting fruit and vegetable farmers. But it was the Newlands Reclamation Act of 1902 that set off a boom in water rights and canal building throughout the Basin [12]. Introduced by Rep. Francis Newlands of Nevada, empowered by Powell's mapping of dam locations and irrigation projects, and passed by President Theodore Roosevelt, the Act offered federal funding for irrigation projects in arid lands in the 20 states of the American west and created the United States Reclamation Service. Such federal loans were interest-free with long payback periods, making new water available and reduced the risks involved to developers [14]. This movement marked the first step towards the river's modern regulation.

The Warren Act of 1911 amended the Reclamation act, authorizing the Secretary of Interior to cooperate with private irrigation projects and execute contracts for conveyance and storage of non-project water in federal facilities with excess capacity. The Reclamation Extension Act of 1914 further expanded this opportunity, authorizing the Secretary of the Interior to designate and appoint a legally organized water user's association as a fiscal agent, under any reclamation project, to collect annual payments and charges for construction, operation, and maintenance of the project. Both the Reclamation Act and the Warren Act provided that no more water than enough to irrigate 160 acres would be furnished from any government project reservoir. Anyone holding more than 160 acres of irrigable land would be required to sell or dispose of any excess land to receive water [9].

Every stream in Arizona that could be tapped was sought after, and eventually the Act led to the damming of nearly every major western river [12]. The Roosevelt Dam on the Salt River in Arizona, the first major dam in the Basin and the world's tallest at 280 ft., was completed in 1911 [5]. By 1934, after the passing of the Taylor Grazing Act created the Grazing Service within the Department of Interior to

regulate rangeland use, all of the early federal water projects on the river system had been built, mostly in high country areas to benefit livestock interests [12]. By 1967, thirty different reservoirs in the Basin had an aggregate capacity of 72.5 maf, roughly five times the river's average annual flow [5].

The 1922 River Compact

This period of regulation brought with it a period of extensive corresponding legal development. This legal movement began with the call from the Lower Basin states to regulate the river's flow, remove flood hazards, generate electricity, and control its high salinity and silt load. These issues led the Upper Basin states (Colorado, New Mexico, Utah, and Wyoming) to call for a reservoir with a large storage capacity directly on the river, permitting rapid expansion of water use in the Lower Basin while forming the basis for claims of appropriated water rights in the more slowly developing Upper Basin. Consequently, a report submitted to Congress in 1922 recommending the construction of such a dam led to the drafting and signing of the Colorado River Compact [5].

The Colorado River Compact of 1922 divided the watershed into the Upper and Lower Basin States, divided at Lee's Ferry in northern Arizona, and established a state-oriented preference for agricultural and domestic uses over power generation. The legislators of every Basin state ratified the compact except Arizona's, who were unsatisfied with the Lower Basin allotment and refused to ratify the agreement until 1944. To circumvent this, the six ratifying states modified the requirement of a seven-state approval in 1925 and ratified the compact to become effective upon approval of the six states and the federal government. The compact became effective June 25, 1929 [5].

Although the compact did not allocate water amongst the individual states, it established five fundamental regulations [5]:

- 1) Both the upper and Lower Basin would have exclusive consumptive use of 7.5 maf per year, or enough to reach a total of 75 maf over a ten-year period.
- 2) The Lower Basin would be allowed to increase its consumptive use by 1 maf per year.
- 3) The Upper Basin states did not deplete the river flow below 75 maf during any ten-year period.
- 4) The United States of Mexico would have the right to use any surplus waters in the Colorado River System.
- 5) The Upper Basin would not withhold water and the Lower Basin would not require the unreasonable delivery of water.

The Boulder Canyon Project and The Hoover Dam

The need for allocation of consumptive use entitlement among the states incited the movement in Congress from 1923 to 1928 to authorize the construction of Boulder Dam and pass the *Boulder Canyon Project Act* of 1928 [5]. This ratified the 1922 Compact and authorized the Secretary of the Interior to act as the sole contracting authority of river water in the lower Colorado Basin. The Act also

authorized the construction of the Hoover Dam, which was completed in 1935 and has the largest reservoir (32 maf) in the US [5]. Flood control would be the first priority in the dam's operation, over water storage and power generation [15].

The Act also apportioned the Lower Basin's annual settlement (7.5 maf) among the three states: California was allocated 4.4 maf (58.7%), Arizona 2.8 maf (37.3%), and Nevada 0.3 maf (4.0%) [15]. In 1944, the US entered an international treaty with Mexico, allocating that country 1.5 maf annually or 1.7 in years of surplus [5]. In 1948, the Upper Basin states agreed on the Upper Colorado River Compact that annually appropriated to Colorado 3.88 maf (51.75% of the Basin allocation), Utah 1.73 maf (23.0%), Wyoming 1.05 maf (14.0%), New Mexico 0.84 maf (11.25%), and Arizona an additional 0.05 maf (0.7%). This later compact also permitted the upper states to divert more than their entitlement if return flows were sufficient to make the required delivery to the Lower Basin states and Mexico [15].

The net effect of these three legal allocations was the establishment of legal claims to the water through the entirety of the River Basin [15]. Remarkably, much of the river's allocation has been accomplished among interested parties through compact and legislation rather than litigation [16]. However, all such allocations were based on river data collected between 1906 and 1921, and it soon became clear such a time period may have provided more water to the system than the long-term average runoff [15].

The Colorado River Storage Project-Authority

In 1956, the U.S. Bureau of Reclamation enacted the Colorado River Storage Project, which provided a comprehensive water resource development plan for the Upper Basin. It authorized the construction of Glen Canyon, Flaming Gorge, Navajo, and Curecanti dams for river regulation and power production, as well as several irrigation projects in the region. The Glen Canyon Dam was constructed 300 miles above the headwaters of Lake Mead in 1964, with a reservoir and capacity only slightly less than that of the Hoover [5]. As a whole, the system today provides a storage capacity of roughly 34 maf, systematically released to meet the delivery requirements of the Colorado River Compact during low flow periods [9].

The Reserved Rights Doctrine

Although dozens of Native American tribes have inhabited the Colorado River Basin and its tributaries for centuries before the European occupation of the continent began, it was not until 1963 that the Supreme Court began deciding Native American claims to river water under the Reserved Rights Doctrine. As of today, many tribes have resolved water rights claims through settlement agreements on the Colorado and other rivers throughout the West [17].

The Arizona vs California Decision of 1964

During much of this time of development, Arizona was unsatisfied with the appropriation in the Lower Basin. In 1930 Arizona unsuccessfully sought to overturn both the Boulder Canyon Project Act and the Colorado River Compact, and in 1934 used National Guard troops to delay construction of Parker Dam. Although Arizona reversed its decision in 1944 and ratified the compact, the state's desires

had not changed. Arizona wished to build the Central Arizona Project to attain its full Colorado River apportionment, but California objected, arguing that Arizona's use of water from the Gila River (a Colorado River tributary) constituted its use of the apportionment. California further argued that it had developed a historical use of some of Arizona's apportionment, which, under prior doctrine, precluded Arizona from developing the project [5].

In 1952 Arizona initiated suit against California in the Supreme Court for confirmation of the 2.8 maf from the Colorado River along with all the water of the tributaries within Arizona. On June 3rd, 1963, the Supreme Court handed down its decisions on the two issues, the first involving the allocation of tributary waters in the Lower Basin [5]. The Supreme Court rejected California's arguments, ruling that Lower Basin states have a right to appropriate tributary flows before the tributary co-mingles with the Colorado River, and that the doctrine of prior appropriation did not apply. Because the Boulder Canyon Project Act applied only to the mainstream of the Colorado, Arizona's uses of the waters of tributaries within the state did not diminish the state's entitlement to 2.8 maf from the mainstream (373 U.S. 546).

The second major issue decided by the Supreme Court was the appropriate allocation of shortages when the mainstream supply is insufficient to sustain 7.5 maf annually. Ultimately they arrived at an appropriation that included the following key points (373 U.S. 546):

- California is limited to 4.4 maf per year, plus no more than half of any surplus over 7.5 maf, from the mainstream.
- Arizona is limited to 2.8 maf, plus one half any surplus, from the mainstream.
- Nevada is limited to 0.3 maf, plus 4 percent of any surplus if Nevada in the future should contract with the Secretary of the Interior for such water.
- The Secretary of the Interior has authority to divide the water of the mainstream in the Lower Basin by contract, subject to California's limitation.
- In the event of shortages, the Secretary of the Interior has discretionary power to allocate such shortages after satisfying these protected rights.

The Supreme Court also established two other key decision points: First, the Secretary of the Interior's discretion applies to allocation of shortages within a state, circumventing state law. Second, any reserved federal lands (Indian reservations, military reservations, national parks, etc.) are entitled to the necessary amount of water to fulfill their respective purposes (373 U.S. 546).

The Colorado River Basin Project Act of 1968

After the Supreme Court's decision, Arizona was finally authorized to create the Central Arizona Project (CAP) under the *Colorado River Basin Project Act* of 1968 (CRBPA). The project was a 541 km aqueduct canal that diverts roughly 1.5 maf per year from the Colorado River mainstream to sustain

nearly 1 million acres of irrigated farmland areas, as well as provide municipal water for metropolitan areas of Phoenix and Tucson. Today it is the largest and most expansive aqueduct system in the U.S. The Act also authorized construction of several new water development projects in both the upper and Lower Basins, including the Animas-La Plata Project, the Dolores Project, and the West Divide Project (P.L. 90-537 Stat 1004).

The Colorado River Basin Salinity Control Act of 1974

Although this period of regulation development formed the cornerstone of water supply control in the Colorado Basin, for much of the century the water quality remained uncontrolled. Although no adequate records on water quality exist prior to 1926, in 1967 the total salt load at Hoover Dam was roughly 10.4 million tons per year, nearly two-thirds coming from natural sources. Concern from the Mexican Government in 1961 over the unusually high salinity concentrations in the water from the Wellton-Mohawk irrigation project near on the Gila River near Yuma led to President Lyndon Johnson's formal commitment to the construction of a 75-mile canal to carry the highly saline water from the site directly to the Gulf of California [5]. This would not be enough to address the quality concerns of the future.

The first public act to regulate water quality was the *Colorado River Basin Salinity Control Act of 1974 (SCA)*, which authorized the construction of certain projects within the Basin to control the salinity level of the water. The program provided cost-sharing assistance to participating farmers to install on-farm irrigation system improvements to prevent heavily salted irrigation water from reentering the Colorado River. The Act also authorized the construction of the Yuma Desalting Plant to treat agricultural return flows from the Wellton-Mohawk Irrigation and Drainage District (P.L. 93-320 Stat 88).

The Environmental Quality Incentive Program (EQIP) replaced the Salinity Control Act in 1996, along with several other programs, including the Agriculture Conservation Program, the Water Quality Incentives Program, and the Great Plains Conservation Program. Created by the 1996 farm bill (P.L. 104-127), it provided cost-sharing, technical, and educational assistance to farmers through promoting environmental quality [18].

Current Status

The passing of all of these acts have made the Colorado River one of the most physically controlled and legally regulated watersheds in the country. Before regulation, the river's annual flow varied from less than 6 maf to over 20 maf; today the regulation system allows sufficient storage of water to maintain the flow during the dry season [5]. The Hoover and Glen Canyon Dams created Lake Mead (filled in 1935) and Lake Powell (filled in 1980), respectively, the two largest reservoirs on the mainstream and two of the largest reservoirs in the western hemisphere [10]. Together with Lake Mohave and Lake Havasu, these reservoirs are capable of storing roughly 53.6 maf, about four times the mean annual flow of the river [19], [20]. All of the acts and regulations that oversee the river and such structures within it form a modern code of conduct throughout the Basin simply known as "The Law of the River."

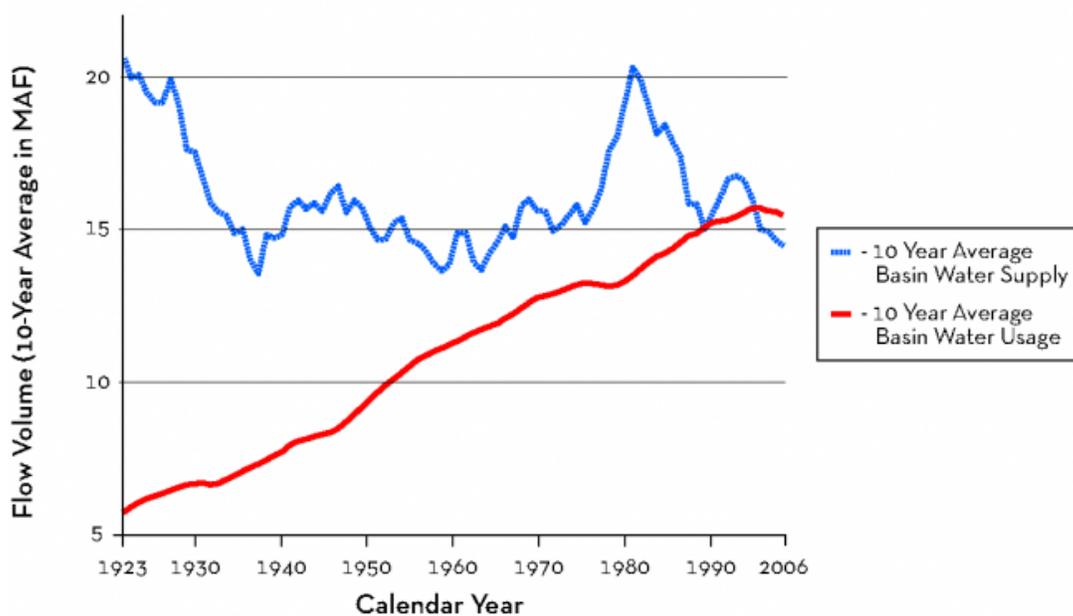
Today, within the Basin, the Colorado River supplies much of the water needs of 7.5 million people of seven U.S. states and 34 Native American tribes and 3 million people in two Mexican states as well as 25.4 million people outside the Basin [9], [21]. In addition to basic residential water demands, the River provides irrigation water to roughly 4 million acres within the US and 500,000 acres in Mexico, and generates roughly 12 billion kilowatt-hours annually through the numerous hydroelectric facilities within the Basin [21]. Such heavy reliance on the river makes any water supply issue an national priority.

Current Issues

Shortfalls

In spite of this century of development a plethora of issues still surround the river and impact all who depend on it, in terms of both supply and quality. In recent decades, the river has produced only about 13.5-15 maf per year, a far cry from the Compact's allocation of 17.5 annual maf [9]. In 2002 the total water demand officially surpassed the Basin's annual supply (see Figure 2) [17]. In 2005 the California Department of Water Resources estimated that California will face shortfalls of 4-9 maf per year by 2020. Utah will face a projected shortage of 186000 af by 2050, even after considering the 783000 af the state will save through conservation and conversion agriculture programs [9].

COLORADO RIVER BASIN WATER SUPPLY V. USE 10-YEAR AVERAGES FROM 1923 TO 2006



CLIMATE  CENTRAL

Figure 2: Basin Supply vs. Use [22]

Water Quality

Salinity

In addition to water shortages, an issue of water quality has permeated the Basin. Many saline sediments of the Basin were deposited in prehistoric marine environments, and since then salts contained within the easily-eroded sedimentary rocks have been dissolved and transported into the river system [21]. A heavy-mineral suite of hornblende-epidote-pyroxene (H-E-P) dominates the mineralogical composition of the region, making calcium, magnesium, sodium, chloride, sulfate, and carbonate the main constituents of the mineral quality of the river water [23], [21]. This mineral quality, commonly referred to as salinity or total dissolved solids (TDS), increases with its use and consequently increases further downstream [5]. Between its headwaters in Grand Lake, Colorado and the Imperial Dam on the California/Arizona border, the last point of major diversions in the US, the Colorado River water underwent a 21-fold increase in its TDS concentration, from 38 to 809 mg/L in 1972 [5].

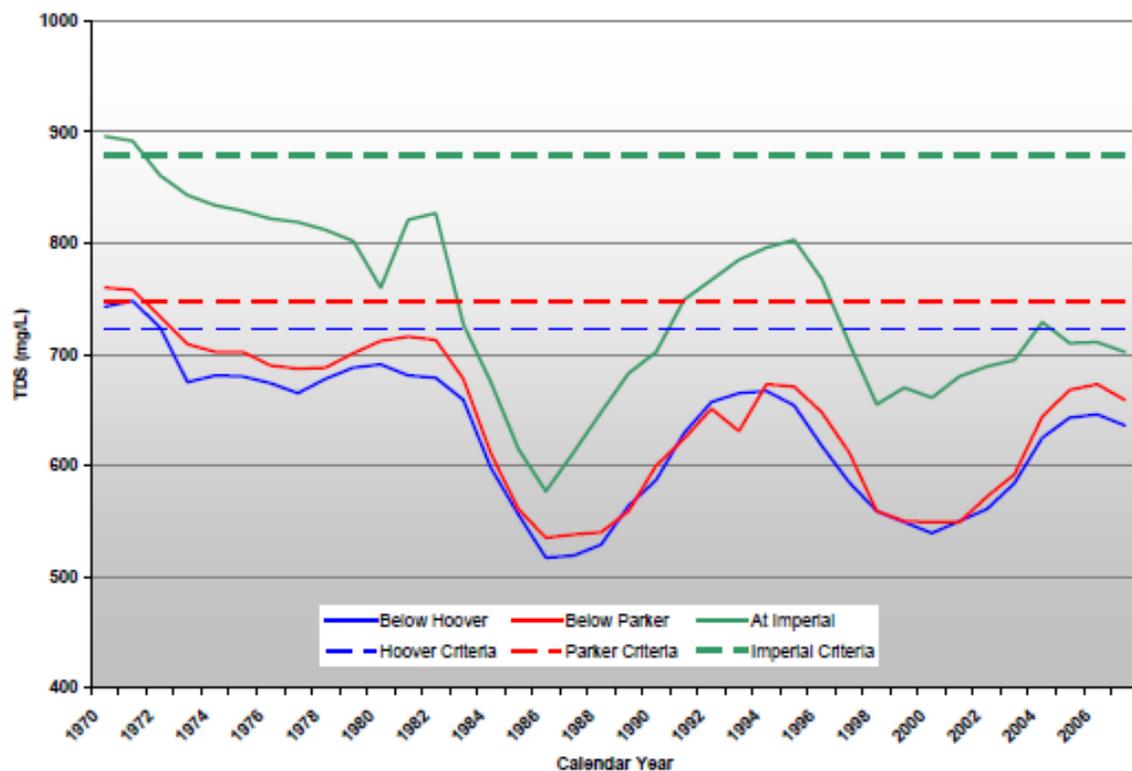


Figure 3: TDS Monitoring at Hoover, Parker, and Imperial Dams [21].

Salinity concentration varied widely prior to regulation as well as for the first few decades following the Compact. Analysis has shown that natural variations in the hydrologic cycle can cause fluctuations in the mean annual salinity concentration at the Imperial Dam of up to 350 mg/L TDS [21]. For most of the century of regulation, however, dam construction drastically reduced the annual sediment load of the river water. From 1925 to 1940, the mean annual suspended sediment load of the river near Grand Canyon was 195 million tons/year; from 1941 to 1957, it was 86 million tons/year [23].

Although much of the total salinity load in the mainstream occurs from natural weathering and erosion, about 34% originates from man-made sources, such as municipal and industrial consumption, irrigation, and evaporation from reservoirs. While dams decrease the salinity concentration of their downstream discharges, evaporation of still water increases the salinity concentration of the reservoirs; evaporation from Lake Powell and Mead alone increases the salinity about 100 mg/L at Hoover Dam [6].

Recent monitoring at the Hoover, Parker, and Imperial dams has shown an overall decrease in salinity concentration since 1970. However, since 2000 the concentration has been steadily rising again, reaching 702 mg/L in 2008 (see Figure 3) [21]. Such high salinity rates significantly reduce the agricultural productivity of the Basin and the stability of the river water for municipal and industrial use [6].

Perchlorate Concentration

A more water quality critical issue in the Colorado River, however, is that of rising perchlorate concentration. The perchlorate ion (ClO_4^-), most commonly present in rocket fuels, fireworks, and some fertilizers, has recently been detected as a salt (bound with ammonium, potassium, magnesium, and sodium) in ground and surface water supplies around the country [24], [25]. Most identified sources of perchlorate in the environment have been associated with military activities or defense contractors [26]. Such salts are highly water-soluble (see Equation 1) and can persist in water for many years [25]. As an iodide uptake inhibitor, it acts as a strong oxidizing agent but is very slow to react within the temperature and pH ranges of the natural environment [27]. Additionally, its negative charge prevents it from sorbing strongly to soils or minerals [25].



When consumed by humans it exerts a harmful decrease in the thyroid hormone output [27]. Because normal thyroid function is necessary for early neurological development, developing fetuses and newborns are the most sensitive to exposure [28].

In 1992 the U.S. Environmental Protection Agency (EPA), after reviewing and assessing the health effects of perchlorate, reached a no observable adverse effects level (NOAEL) of 0.14 mg/kg-day. This meant that in a 70 kg person, harmful thyroid effects begin at 49 $\mu\text{g}/\text{mL}$ and fatalities occur at 210 $\mu\text{g}/\text{mL}$. As a result of these findings, in 1997 the California Department of Health Services (DHS) established an 18 $\mu\text{g}/\text{L}$ threshold as the action level for ceasing water usage and initiating remediation [27]. More recently, in March 2004, California became the first state to set the public drinking water health goal of 6 $\mu\text{g}/\text{L}$ [29].

The EPA added perchlorate to its Contaminant Candidate List (CCL) for drinking water in 1998 [26]. Currently the EPA has recommended a regulatory level of 1 $\mu\text{g}/\text{L}$ in drinking water, but other federal agencies consider this level unrealistic and unwarranted [29].

Arizona, California, Nevada, and Utah are known to be substantially affected by perchlorate, partially due to their reliance on the Colorado River. In the Colorado River concentrations ranging from 8 µg/L to 3.7 g/L have been measured in 1998 [27]. By 2006 such concentrations narrowed to 5 to 9 µg/L [30]. The highest of these concentrations have been found in Lake Mead, where the California DHS in 1997 reported some regions with levels of 165 µg/L. Much of this concentration has been attributed to the runoff from the site of the former Pacific Engineering & Production Company of Nevada (PEPCON) rocket fuel plant in Henderson, Nevada, as well as the ammonium perchlorate manufacturer Kerr-McGee Chemical Corporation about 1 mile from the site [27].

While as yet there does not appear to be a widespread occurrence of significant levels in most of the US, perchlorate concentration still poses a major concern in the Colorado River Basin due to local population growth [26]. Indeed, this population growth is the primary cause of the river's water crisis.

Reasons for the Crisis

Population Growth

There are several fundamental reasons for this water crisis, but the most prominent is the rapid increase in the Basin's population over the past century. When the Colorado River Compact was written in 1922, the total population of the seven states within the Basin was 5.7 million people; by 2000, the population had increased by 800% to nearly 50 million, with about 30 million at least partially dependent on the Colorado River for their water supply [17]. Arizona's population increased by more than 130 percent from 1950 to 1966, more than five times the national rate [5]. Between 1990 and 2000, Nevada, Arizona, and Colorado were the fastest growing states in the nation [17]. Population analysts believe the growth rate for the Basin states will remain high at a 50% increase, reaching a projected 38 million people by 2025; in contrast, the predicted national population growth during that time will be 28% [17]. In Nevada, city planners anticipate a population growth from 1.8 million in 2000 to 3.5 million by 2020. Utah is anticipated to triple its water consumption over the next 50 years, from 645000 af in 2000 to 1.79 maf in 2050 [9].

Naturally, the rising population of the region brings a rising demand for water; each new family of five needs approximately 1 acre-foot of water annually to sustain their domestic needs [17]. Additionally, growing urban areas in the southwest seek an array of water-related services beyond fundamental municipal and household uses, including recreation and instream inflow to sustain riparian ecosystems [31].

But the heaviest demand, especially in the Lower Basin, comes from agriculture, which consumes about 80% of the river's total supply [9]. The demands for water in the Lower Basin are roughly 10 times greater than those in the Upper Basin, mostly due to agricultural development, as agriculture in the Lower Basin is almost entirely dependent on the Colorado River (see Figure 4) [15]. This demand is augmented by a general shift in the agricultural sector from arid land crops for human consumption towards high-water-demand crops, primarily alfalfa, feed grains, and cotton, due to a combination of global trade, the expansion of artificial irrigation works, and U.S. farm subsidies [17].

On top of this, all the larger cities (Phoenix, Tucson, and Las Vegas) are in the Lower Basin; the vast and growing urban concentrations of Los Angeles and San Diego, while not in the Basin, also rely heavily on the river for electric power and water [5]. The largest user is the Imperial Irrigation District (IID) in southern California, which alone accounts for approximately 2.87 maf annually, almost 20% of the river's average annual flow. Consequently, in spite of the Compact's allocation of 7.5 maf to both areas, the Bureau of Reclamation estimated in 2001 the Lower Basin's annual use to be about 8.0 maf (including return flows but not the Mexican requirement) and the Upper Basin's to be about 4.5-5.0 maf [9].

Effects on Salinity

Population growth has also affected the salinity levels of the river. The two basic causes of salinity increases in streams are salt loading and salt concentration. Salt loading is the discharge of mineral pollutants into the river system from industrial wastes and irrigation return flows, and increases in salt concentration result from the consumptive use of water [5]. As a result of the latter source, salinity concentration is generally inversely proportional to the flow rate [9]. With greater demand on the water supply, salinity concentrations are anticipated to increase overall with even greater magnification downstream.

Fallacies in the 1922 Compact

The effects of population growth on the River have been further augmented by the modern inadequacy in the 1922 Colorado River Compact. The Compact was based on a gross overestimation of reliable annual water supply due to limited observational record [9]. According to tree-ring analysis of the local vegetation, the period of 1905-1925 was the wettest period in 400 years of record, with an

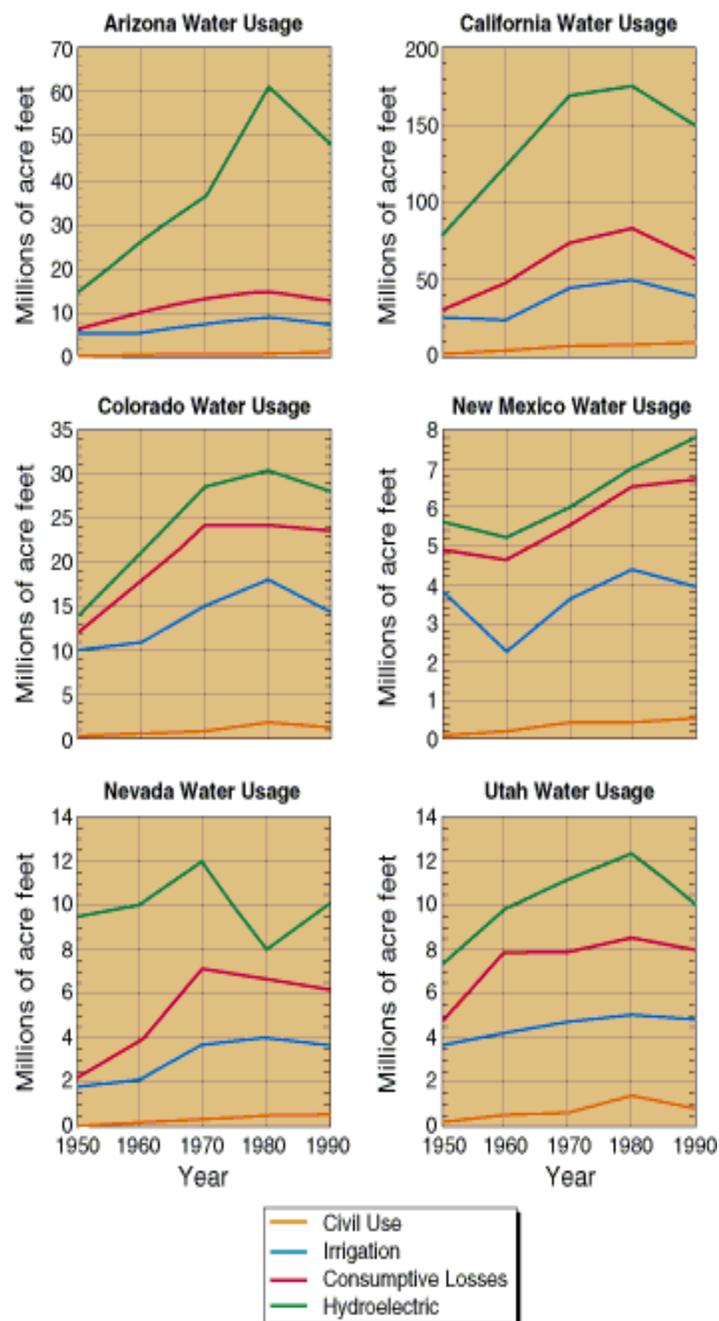


Figure 4: Historic Water Use in Basin States [42]

average annual production of 18.0 maf and average annual flow of 16.4 maf at Lees Ferry [9], [17]. The signatories at the time believed the assumed variations in the river flow, far narrower than the actual range, would average out over a matter of 10 years and fulfill the downstream requirement. Since the signing of the compact, the average annual flow has been about 14.3 maf, with the lowest recorded flow in 1934 of 5.6 maf. But much of the recent population growth has occurred during the wetter-than-average period from 1975 to 1999, presumably based to some degree on public complacency of water availability (see Figure 5) [9].

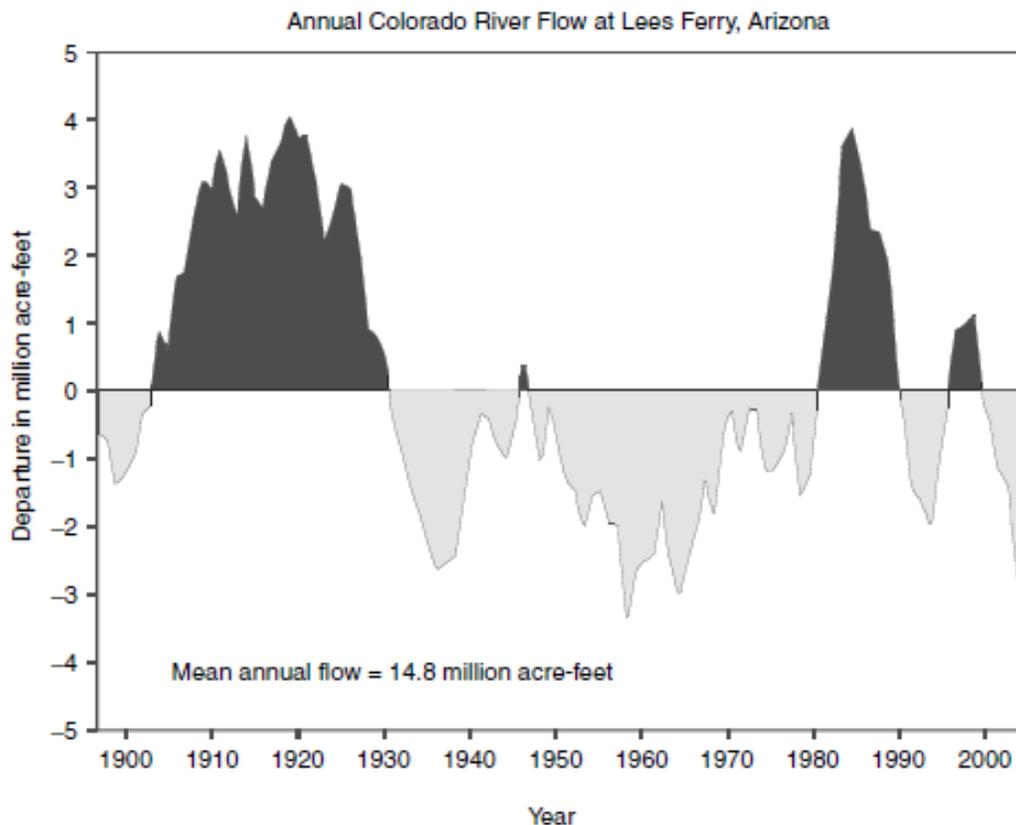


Figure 5: Annual Flow at Lees Ferry [9]

Additionally, modern interpretation of the Compact has uncovered technical ambiguities that would not have been considered at its time of writing. As discussed earlier, the Law of the River confers some dictates for the distribution of shortages during droughts, but to date such provisions have not been evaluated in relation to stakeholder needs. The first such ambiguity in the Compact presents itself in the dictation that *“The States of the upper division will not cause the flow of the river at Lee Ferry to be depleted below an aggregate of 75 million acre-feet for any period of 10 consecutive years...”* In theory this allows the Upper Basin to deliver less than 7.5 maf in some years as long as it delivers 75 maf over a ten-year average, giving it considerable flexibility with how much water it withholds in times of drought. Because the recent Long Range Operating Criteria by the Department of the Interior removed the flexibility of withholding water in any given year and required annual deliveries of 8.25 maf, both

Basins would suffer shortages in the long run. One should consider developing revisions to this criteria to make the annual delivery requirement more flexible to more equally distribute the burden of shortages [17].

Further issues arise with interpreting the Compact in regards to storage and evaporation. The Compact states: *“The States of the upper division shall not withhold water, and the States of the lower division shall not require the delivery of water, which can not reasonably be applied to domestic and agricultural uses.”* Whether or not underground storage for future agricultural and domestic use qualifies as domestic use is still a subject of debate. Evaporation losses and bank seepages further complicate the calculation of required deliveries to Mexico: while the Lower Basin states tend to interpret the compact to require 0.75 maf to reach Mexico annually, it would require the Upper Basin to deliver this amount plus any ‘extra’ to provide for evaporation and channel losses during transfer [17].

The 1963 *Arizona vs. California* Supreme Court decision gave the Secretary of the Interior primary authority over allocating water flow among Lower Basin states. The 1968 Colorado River Basin Project Act (CRBPA), however, made Central Arizona Project’s priority junior to some other Lower Basin users, giving the CRBPA control of how shortages are apportioned in the Lower Basin. Currently the Secretary has no explicit guidelines by which to declare a shortage in the Lower Basin, as the exact numbers based on the elevation in Lake Mead, which the Bureau of Reclamation long ago chose to use as the primary indicator, have never been determined [17].

Effects of Climate Change

Ultimately, one cannot overlook the effects of climate change on the quantity and quality of water resources. One of the numerous effects of climate change involves the growing evaporative demands for water with rising temperature. With such high demands on water in the Basin, even minor alterations in the evaporation rate can severely impact the supply. Traditional methods of managing floods and droughts may be inadequate to address such new variations in hydrology, whether they involve alterations in water quality that threaten water systems, changes in atmospheric dynamics that shift storm tracks, or the loss of snowpack in mountainous regions. Such concerns are especially prevalent in the majority of water systems that cross international boundaries, as politics will further complicate the response to such threats [32].

Climate change is of particular concern in the Colorado River Basin due to the sensitivity of snow accumulation in the Rocky Mountains that generates roughly 70% of the annual runoff. Recall that precipitation in the semi-arid region of the Basin averages only 40 mm/year, yet the average flow from 1906-2000 varied widely from 5.3-24.0 maf, averaging at 15.1 maf. General Circulation Models (GCMs) of the atmosphere predict the global mean annual air temperature to increase between 1.4 to 5.8 °C over the next century. Studies over the past few decades predict the effects of this increase on streamflows in semi-arid regions to include increased rain to snow ratios, increase in winter runoff, decrease in summer runoff, earlier and faster snowmelt, and increased rates of evaporation [33]. In 2006, the Bureau of Reclamation estimated evaporation from current reservoirs cost the system 20% of

the river's total production, with an annual loss of 1.04 maf at Lake Mead alone, a margin expected to increase with climate change. Currently evaporation from Lake Powell on a single 3-day period would satisfy the domestic water needs of 17,000 western homes for an entire year. Annually the lake loses 730,000 af to evaporation, enough to supply the domestic needs of 3,650,000 people, nearly the entire population of Phoenix, for that time [17].

In 2004 researchers at the University of Washington, Seattle composed a series of Parallel Climate Model (PCM) scenarios to predict the effects of climate change on the Colorado River Basin for three different future time periods: 2010-2039, 2040-2069, and 2070-2098. These scenarios were based on the comparison of simulated hydrologic and water resources scenarios derived from U.S. Department of Energy and the National Center for Atmospheric Research and observed historical climate records from 1950-1999. Their results for Periods 1, 2, and 3 predicted a 3, 6, and 3% reduction in mean Basin annual precipitation and a 14, 18, and 17% decrease in annual runoff, respectively. Releases from Glen Canyon Dam to the Lower Basin (as mandated by the Compact) were met in only 59-75% of the years for these predicted periods; consequently, annual hydropower output was also significantly reduced for these scenarios. Accounting for increases in evapotranspiration, the net effect of such discrepancies would be a reduction in runoff ranging from 8 to 20% [33].

The 2002 Drought

In spite of such analysis and a history of shortfalls in the river's mean annual flow, Colorado River managers did not expect significant shortages in the Lower Basin to occur until after 2030 [9]. The historic drought (a drought being defined as two or more consecutive years of below-average stream flow) in 2002 drastically altered this perspective [34]. From 2000 to 2003, the annual flow averaged only 9.85 maf, with only about 6 maf in 2002, the second lowest year of production since the Bureau of Reclamation began recording in 1906 [17]. During this recent drought, unregulated water inflow to Lake Powell in years 2000, 2001, 2002, 2003, and 2004 was 62, 59, 25, 51, and 51% of average, respectively, and the cumulative flow deficit (departure from long-term mean) was almost 11 km³, approximately 2 years of average stream flow [17], [34].

The reserves in Lake Mead and Lake Powell have reflected this crisis in tandem as well. The 2002 inflow to Lake Powell was the lowest recorded since the lake began filling in 1963 [35]. Due to a below-average snowfall in March 2004, the mainstream inflow for Lake Powell was only 50% of average. Lake Powell was at capacity (24 maf) in 1999; by April 2004 the lake was at 42% capacity (10.2 maf), a level not seen since 1971 during the lake's first filling period. Meanwhile, Lake Mead declined 23 m to 59% capacity, losing over 17 km³ of volume, approximately 3 years of California's water allocation [9], [34]. Other small reservoirs in the Upper Basin were at 50-70% capacity in 2004 [34]. Based on current demand, the average annual inflow will refill the system storage by about 3% per year. In spite of unregulated inflows to Lake Powell topping 105% in 2005 and 102% in 2008, the drought that began in 2000 is currently entering its 11th year with little chance for turnaround in sight [9].

Powell's elevation is more susceptible to weather patterns than Mead's: Powell recovers faster during wet periods and drops faster during droughts [36]. Even if California ceases taking surplus flows, as they have been since October 2003, and the releases from Lake Powell are limited to the 8.23 MAF annual minimum, Lake Mead will continue to decline [36].

Between 1923 and 2004, eleven droughts have occurred in the Basin. Although this recent drought was one of the two worst in the past 80 years for portions of the Upper Basin (the other occurring during the late 1980s to the early 1990s), tree-ring analysis in the region suggests it is the seventh worst on a 500-year record. The largest drought on scientific record occurred at the end of the sixteenth century and lasted for at least 20 years, roughly 2.5-4 times the magnitude of the recent drought. Although the recent drought was far milder and followed a fairly high stream flow period, streamflow monitoring research suggested it was significantly impacted by the increased water demand caused by population growth in the region. Such analysis proves that even mild hydrologic drought can be amplified to extreme conditions by overuse of the water supply [34].

Although the shortfalls in the river's water supply were felt before the 2002 drought, today they are especially prevalent. There is no time left to prepare for long-term water shortages, for they are already occurring throughout the Basin. While simply waiting for the ever-diminishing water supplies to inevitably drive people out of the Basin to more fertile land would be the simplest solution, a more viable solution must be available through a combination of comprehensive resource planning and new management practices.

Solution Modeling

General Approach

The grim magnitude of water shortages facing the Colorado River Basin is augmented by the urgency of developing a viable new system of managing and allocating what water resources remain. No more suitable areas for damming in the Basin exist; the Colorado River is already the most dammed river in the nation, and the number of dams already exceeds the law of diminishing returns. Importing water by constructing trans-Basin pipelines is also infeasible, both economically and politically [17]. Simply put, the population within the Basin has breached its water capacity, and the states within must make major adjustments to living with less water.

Any new "Law of the River" or amendments to existing statutes must account for factors the previous century of regulation failed to. One must address the requirements of drought planning for both the current drought and any that occur in the future. In regards to long-term planning, one must compose a comprehensive new plan for water allocation that accounts for the newly-discovered ranges in flow variability while eventually allowing reserves in Lake Mead and Lake Powell to accumulate to pre-drought levels. Additionally, this new plan must account for any effects climate change may pose to current and future water resources [17].

Achieving consensus among stakeholders cannot occur without strong central leadership to facilitate it. Even in 1922, long before the wave of modern complexities accompanied by population growth, then Secretary of Commerce Herbert Hoover had to provide aggressive leadership during the negotiation of the Compact to reach an agreement among the Basin states [17]. Such leadership would likely have to include the U.S. Bureau of Reclamation, which controls releases from the reservoirs to the Basin, the U.S. Chamber of Commerce, which oversees trade between states, and the state representatives that manage intrastate stream activities [37]. As it stands the Basin states have yet to reach a comprehensive resolution on how to divest the burden of shortages during a drought, but all stakeholders share the common interest of avoiding continuous internal conflict [17].

Further complicating the matter is the mentality of far too many policymakers within the area that fails to grasp the scope of the shortage. Upper Basin states, particularly Colorado and Utah, are still discussing developing water resources at pre-drought levels. Many city developers in the area are hesitant to any conservation practices under their “use it or lose it” mindset, referring to situations in which surface water rights have to be used to maintain future rights to that water; if cities conserve now, they may have to find other sources during future growth periods. Because most cities are rightly anticipating future growth, they focus on developing new supplies as long as possible. In spite of some Basin states currently pursuing municipal conservation of water, overall water use and demand in the states has increased with new development. Any change to the “Law of the River” must accompany a change in this policy [17].

Long-Term Water Resource Planning

To compose a new “Law of the River,” or simply resolve the ambiguities of the current one, the involved parties must draw upon a new framework of resource supply and demand that accounts for present parameters. While no single method of resource planning will ever be universally applicable to the ever-growing plethora of water resource crises around the world, one concept has received considerable attention in recent years for just such issues. In the early 1980s the Global Water Partnership developed the concept of Integrated Water Resources Management (IWRM) as “...A process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.” [38] With so many different stakeholders, each with their own uses of water and land, stretched out over a broad ecosystem vital to the sustainability of the region, the Colorado River Basin would appear to be a pristine subject for this concept.

The IWRM approach is anchored on three basic pillars: Enabling Environment, Institutional Framework, and Management Instruments, while explicitly avoiding the classical fragmented approach for water resources management. Implementing the concept requires enabling an environment of appropriate policies, strategies, and legislative framework while establishing a shift towards sustainable appropriation in the political, social, economic, and administrative systems responsible for delivering water services at different levels of society. Policymakers must broaden their perception of water and

take into account its involvement and value in both the planet's life support systems and socio-economic development. Successful management therein will have to incorporate three basic efforts: i) securing water and water-dependent services (i.e. food production), ii) avoiding degradation of water and land resources and ecosystem integrity, and iii) foreseeing and assessing changes in climate, population, and socio-economic conditions. Major initial reforms to water governance are not essential, as simple plausible first steps are often sufficient to catalyze this paradigm shift (see Figure 6) [38].

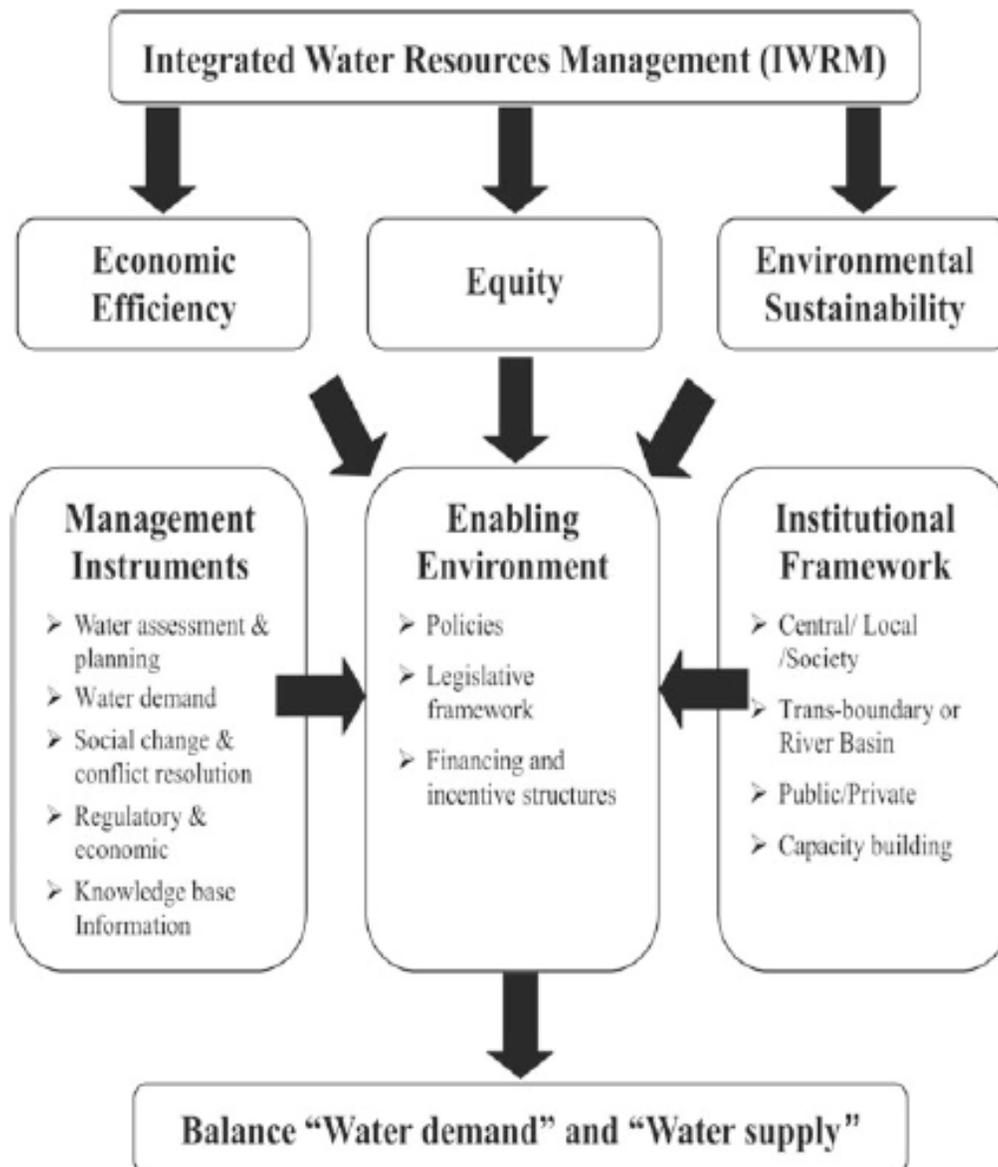


Figure 6: The IWRM Outline [38]

The IWRM approach offers a series of critical benefits, including greater utility from a given amount of water through adjusted allocations, enhanced water supply through water conservation strategies, more intensive recycling of water through planned sequencing of various uses, improved

water quality through monitoring and data collection, and inclusion of a wider range of Basin stakeholders into decision making. Although it involves a highly challenging and complex approach that draws decisions from a sinuous amalgam of interests and issues, the development of a computer-based decision support system (DSS) to accommodate the IWRM approach and assist decision makers will mitigate the frustration incurred by the process. The modern DSS, built upon 40 years of information technology, can draw upon a wealth of water resource data for analysis and apply it towards crafting viable decisions, all while storing previous decision implementation to account for changes in data and applications in future policy (see Figure 7). The management of the Colorado River Basin will be able to evolve and adapt with the same flexibility and endurance as the very river it governs [38].



Legend: IWRM = Integrated Water Resources Management; GW = Groundwater; ANN = Artificial Neural Network; MOP = Multiobjective Programming; MCDA = Multicriteria Decision Analysis; AI = Artificial Intelligence.

Figure 7: Decision Support System for IWRM. [38]

Not every comprehensive method of water conservation and appropriation requires an elaborate plan of stakeholder consensus. Indeed, some of the most effective and time-efficient methods are those implemented on the local or personal level, requiring only the common practice of consumers. Such short-term methods are especially vital in surviving periods of drought, like that which the Basin states currently face.

Residential Use

The first step in water conservation occurs in basic residential consumption. Water consumption is inevitably higher in hot, arid regions like the Colorado River Basin. In 2004 per capita water use was 160 gallons per day in Tucson, 226 gallons per day in Phoenix, and over 240 gallons per day in Las Vegas; in contrast, the U.S. per capita consumption that year was 100 gallons per day [17]. Options for domestic conservation include requiring low flow toilets and showerheads, implementing water reclamation or gray water systems beyond current industrial uses, and requiring xeriscaping, a water-prudent landscaping method created by the Denver Water Department in 1978, in public areas [39], [17]. Simply eliminating ornamental uses of water, such as public fountains, is also a worthwhile consideration [17].

Underground Storage

Evaporation from the river system constitutes another major source of waste, one rarely considered. Underground water storage could mitigate such losses as an alternative to surface reservoirs, with minimal losses to seepage. The Arizona Water Bank is currently engaged in such a project to store millions of acre-feet in underground aquifers [17].

Agricultural Shift

Inevitably, however, one cannot discuss water conservation in the Colorado River Basin without addressing the agriculture of the area. More than half of agricultural water is used to irrigate non-food, water-intensive crops like alfalfa for cattle feed and cotton, which are far more suited for the rainy climates in the southeastern U.S. [17]. In Arizona alone, crop irrigation accounts for over 90% of the state's annual water consumption; of the 6 maf used for cropland irrigation, 2.5 are used on high-value intensive crops (cotton, vegetables, field fruits, citrus), while 3.5 are used on low-value extensive crops (feed grains and forages) [5]. Just as demand for cattle feed led to the regulation of the Basin, only a fundamental shift in such agriculture can bring about a sustainable future for the region.

Although the most common concern with shifting agricultural water to urban use is the impact to local economies, only a small percentage of agricultural water needs to be conserved to provide for municipal needs. In most areas, saving 7-10% of agricultural water doubles the availability for urban use. Large savings could be generated simply by shifting from inefficient flood irrigation to drip irrigation on existing crops. Shifting just 50,000 acres (1.35% of the lands irrigated by the Colorado River) of alfalfa from sprinkler to drip irrigation would save nearly 200,000 af of water annually, enough to sustain 1 million people for that time [17]. In Arizona, upgrading half of its irrigated crop systems to the more efficient method would save roughly 445,000 af of water annually [40]. While most small farmers will not consider it economically viable to install drip irrigation systems, cities that subsidize the farms for such systems could gain access to the water saved, state law permitting [17].

Such is not to say a general shift in agriculture would not be a vital source of conservation. Shifting 25% of Arizona's irrigated cotton and alfalfa areas to higher-value citrus and vegetable crops

could save roughly 362,000 af, and following 15% of such areas could save an additional 433,000 af annually. Comparable savings are possible in the California and Mexico regions of the river as well [40].

Demand-Side Incentives

Short of enacting statewide law to enforce any of these water conservation methods, economic incentives are perhaps the most provocative method on the public level. Adopting a water use policy wherein the cost of water per unit increases with the quantity delivered, together with a revision of the basic rates so that they more accurately reflect the full costs of water service and the annual supply, would cause customers to adopt a more conservative application of water for personal use. Lawn watering, for example, accounts for as much as 60% of private use in residential areas, and a modest decrease in this use would be of enormous relief to local supply [5].

However, agricultural subsidies, municipal incentives, and state and federal policies aimed at promoting economic growth have largely insulated water from market forces, causing dramatic variability in its price. Allowing market forces to drive water prices would incite widespread conservation efforts, while allowing state water policy makers to consider rate structures or creative pricing plans to control demand. Some of these techniques include surcharges on water use for municipalities, pump fees for both new and established pumps, and declining block pricing. Additionally, a market-based allocation system or formal structure would empower states to more readily buy or lease water beyond their Compact allocation and provide a flexible, if short-term, mechanism for dealing with drought impacts [17].

Recent Policy

Recent progress has been made in the legislative front to develop some of these interim guidelines. In May 2005, the Secretary of Interior tasked the Basin states to develop a consensus plan to mitigate drought in the Basin and directed the Bureau of Reclamation to develop guidelines for Lower Basin shortages and the operation of Lake Powell and Lake Mead, particularly during low reservoir conditions. Later that year, the USBR initiated a National Environmental Policy Act (NEPA) to develop such guidelines, accounting for water conservation, considering reservoir operations at all operational levels, and establishing operational guidelines for an interim period to gain operational experience to inform future management decisions. Four key elements emerged from these decisions: 1) a shortage strategy for Lake Mead and the Lower Division States, 2) coordinated operation of Lake Powell and Lake Mead, 3) mechanism for shortage and delivery for conserved water in Lake Mead, and 4) modified and extended elements of existing Interim Surplus Guidelines (ISG). In 2007 the Final Environmental Impact Statement (FEIS) addressed each element in the broad range of alternatives. A diverse body of stakeholders, including the Basin States, Native American Tribes, environmental nongovernmental organizations (NGOs), federal agencies, and the general public, helped develop these alternatives and submit a consensus alternative, signifying a historic agreement on this issue [41].

This preferred alternative was composed of four key proposals, corresponding to those above:

- 1) A publication of the discrete levels of shortage volumes associated with Lake Mead elevations to conserve reservoir storage and provide water users and managers in the Lower Basin with greater certainty to know when, and by how much, water deliveries will be reduced during low reservoir conditions.
- 2) A fully coordinated operation of Lake Powell and Lake Mead to minimize shortages in the Lower Basin and avoid risk of curtailments of use in the Upper Basin.
- 3) An Intentionally Created Surplus (ICS) mechanism to provide for the creation, accounting, and delivery of conserved system and nonsystem water to promote water conservation in the Lower Basin.
- 4) Extension of the term of the ISG and modify those guidelines by eliminating the most liberal surplus conditions, leaving more water in storage to reduce the severity of any future shortages.

A Record of Decision (ROD) was issued in December 2007, officially adopting the Interim Guidelines for Lake Powell and Lake Mead. These guidelines were crafted to include operational elements that respond to any potential impacts from climate change and increased hydrologic variability during the interim period and encourage efficient use and management of Colorado River water and enhance conservation opportunities in Lake Mead through the adoption of the ICS mechanism. The coordinated operation element, for example, allows Lake Powell releases to be adjusted to respond to low reservoir storage conditions in Lake Mead. The Basin states have since agreed to address future controversies concerning the Colorado River through consultation and negotiation before litigation. The guidelines are in place through 2026 and include a provision that requires the Secretary of the Interior to initiate a formal review of their effectiveness by the end of 2020 [41].

Secretary of the Interior Dirk Kempthorne officially signed the ROD on December 13, 2007, calling the Interim Guidelines the most important agreement among the seven Basin states since the 1922 Compact. Analysis of the implementation of these guidelines during that time period will provide valuable insight to both the impacts of climate change on the Colorado River Basin resources and the most effective policies for future solution modeling in the region [41].

Conclusion

In spite of its long geologic history, the Colorado River Basin has undergone some of its most dramatic changes within the past two centuries. The westward expansion with its cattle drives permanently altered the vegetative landscape and flow of its tributaries, and the 1922 Compact and the century of regulation that followed made the Colorado the most dammed and controlled river in the western hemisphere. This regulation has brought unparalleled economic and population growth that could not exist otherwise in the semiarid region, and to this day the vast network of dams and reservoirs on the river remains a marvel of modern engineering and interstate commerce.

Simultaneously, the Colorado River presents a unique paradox in the face of the global water crisis: in spite of such extensive regulation it faces monumental shortages that threaten the livelihood of all depending on it. Although local agriculture is especially sensitive to water shortages, municipal and residential consumers will soon feel the effects as well. As if to add insult to injury, previously minor issues with water quality, such as salinity and perchlorate concentration, are becoming increasingly prevalent in the wake of dwindling supply. While the simple laws of supply and demand facilitated the majority of this shortage, the effects of global climate change have amplified these effects through increased evaporation and decreased snowmelt accumulation in the headwaters at Grand Lake. This widespread reliance on a renewable yet limited resource has inevitably led to the demand outweighing supply and the unavoidable fact that such consumers must simply learn to live with less.

As with any shortage of a vital resource, effective management of Colorado River water can only manifest from a comprehensive set of laws and regulations that account for factors of availability and legal ambiguities that previous statutes failed to. Additionally, such laws and regulations must be accompanied by a general shift in agriculture practices towards the farming of crops more suited to thrive in the region, as well as a set of new water conservation practices in private residential use.

Although the recent 2002 drought in the Basin severely hindered productivity in the Basin with water shortages the affected states continue to recover from today, it prompted the policymakers of the region as well as an array of environmental groups to work with the USBR to take decisive action on the matter. Taking into account the fallacies of the 1922 Compact and the potential impacts from climate change on the supply of Lake Powell and Lake Mead, this new set of Interim Guidelines is expected to assist in creating both a mentality of water conservation as well as the basis for new solution modeling in the Basin.

Appendix I: Timeline of Human History on the Colorado River

1540 – Coronado brings the first livestock into the river basin from Mexico.

1849 – The Gold Rush in California incites the first great cattle drives across the Colorado River Basin.

1850 – The First American ranches are founded along the Santa Cruz River.

1890 – The Reclamation Movement begins, damming and diverting the easiest of small streams in the basin to grow cattle feed.

1901 – The Imperial Valley Canal is constructed, symbolizing the first major diversion of water on the river's tributaries.

1902 – The Newlands Reclamation Act is passed, initiating a vast array of canal building in the basin.

1911 – The Warren Act amends the Reclamation Act, authorizing the Secretary of Interior to cooperate with private irrigation projects and execute contracts for conveyance and storage of water in Federal facilities with excess capacity.

1911 – The Roosevelt Dam is constructed on the Salt River in Arizona, the first major dam in the basin.

1914 – The Reclamation Extension Act is passed, authorizing the Secretary of the Interior to designate and appoint water use associations as fiscal agents to collect payment and charges for reclamation projects.

1922 – The Colorado River Compact is signed, dividing the watershed into the Upper and Lower Basin states and establishing a series of regulations for each state's consumption of river water.

1928 – The Boulder Canyon Project Act is passed, ratifying the 1922 Compact and authorizing the Secretary of the Interior to act as the contracting authority of river water in the Lower Basin.

1935 – The construction of the Hoover Dam is completed.

1944 – The U.S. enters an international water treaty with Mexico, allotting the country 1.5 maf annually or 1.7 maf in years of surplus.

1952 – Arizona initiates suit against California for confirmation of 2.8 maf.

1956 – Colorado River Storage Project is incepted, authorizing the construction of several irrigation and hydroelectric power projects in the region.

1961 – President Johnson formally commits to the construction of a 75-mile canal from the Welton-Mohawk irrigation project to the Gulf of California.

1963 – The Supreme Court hands down its decision on Arizona vs. California, ruling in favor of Arizona.

1963 – The Reserved Rights Doctrine is passed, allowing Native American claims to river water to be heard.

1964 – The Glen Canyon Dam is constructed.

1968 – Colorado River Basin Project Act is passed, authorizing Arizona to create the Central Arizona Project and the construction of several new water development projects in both the upper and lower basins.

1974 – The Colorado River Salinity Control Act is passed, authorizing construction of the Yuma Desalting plant and other projects within the basin to control the salinity level of the water.

1996 – The Environmental Quality Incentive Program is passed, replacing the Salinity Control Act.

2002 – Water demand officially exceeds supply.

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