DOWNSTREAM IMPACTS OF DAMMING THE COLORADO RIVER

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INTRODUCTION

Dams are structures constructed across rivers to control their flows. The main objectives for building dams are to capture and store the surface flow from rivers and runoff from adjacent and upstream watersheds in artificial lakes or reservoirs and eventually release the stored water as needed. The system may be designed for purposes such as flood control, hydroelectric power generation, and providing freshwater for drinking and irrigation. Reservoirs may also serve as sanctuaries for fish and wildlife and for providing recreational activities such as swimming, fishing, and boating (Colorado River Research Group 2014). However, there are also many drawbacks to building dams that need to be considered. Dams displace people from their homes, flood productive areas, destroy ecosystems and /or impair services, inundate precious historical and cultural artifacts and eliminate important wildlife sanctuaries.

The subject of this paper is the Colorado River and the effects of its extensive damming projects on downstream ecosystems and the environment. The Colorado River is the major river in the arid and semi-arid southwestern United States and northwestern Mexico. It is a 1,470-mi (2,352-km) river with its main headwaters in the Rocky Mountain National Park in north-central Colorado. It is the international boundary for 17 mi (27 km) between Arizona and Mexico in the southwest (U.S. Bureau of Reclamation, Lower Colorado Region 2015). The Colorado River system, including the Colorado River, its tributaries, and the lands that these waters drain, is called the Colorado River Basin. It drains an area of 246,000 mi^2 (637,000 km^2) that includes parts of seven western U.S. states (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) and two Mexican states (Baja California and Sonora) (Fig. 1). Three-fourths of the Colorado River Basin is in federal lands comprised of national forests, national parks, and Indian reservations. The drainage Basin's total runoff is about 24,700 ft^3 (700 m^3) per second (Colorado River Commission of Nevada 2006, Colorado River Research Group 2014). The river is the primary source of water, which comes mostly from snowmelt in the Rocky Mountains, for a region that receives little annual precipitation.

For more than a thousand years, the Colorado River has been a central feature in the history and development of the southwestern part of the United States. During this period, management efforts in

Figure 1. Location of the Colorado River Basin in the U.S. Southwest and Mexico's northwestern corner.

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the Colorado River Basin embody society's struggle to overcome conflicts between competing interests over a shared water resource. First, there have been Native Americans who irrigated their crops with water from the river (Glenn et al. 1996). One tribe, the Cocopah Indians who reside in the delta region fished and farmed there for about 2,000 years. Unfortunately, the present Colorado River is often drained dry by upstream demands before reaching this part of Baja, California (Glenn et al. 1992, Zielinski 2010). In spite of this situation, irrigation is still one of the main uses of the Colorado River, especially on its lower portion where it supports one of the most extensive irrigated agriculture in the United States. Other equally important uses are generating hydroelectric power, and supplying drinking water to distant urban areas and other communities. For example, water from the Colorado River is diverted eastward across the Rocky Mountains to Denver and other cities in Colorado. The Colorado River Aqueduct carries water to the metropolitan area of Los Angeles, California, and the Central Arizona Project brings water supply to the Phoenix and Tucson areas in Arizona. In addition, the cities of San Diego and Las Vegas and many smaller cities, towns and rural communities in Arizona, Nevada, and California are dependent on the Colorado River for their water supply. All together about 35 million people in the U.S. Southwest and 3 million others in Mexico depend on the Colorado River for their water supply.

THE LAWS OF THE RIVER

In the 1800s, riparian states diverted water from the Colorado River and its tributaries without any restrictions. As diversions increased with time, however, a long battle over apportionment ensued. Today, the Colorado River is among the most controlled, most litigated and highly controversial rivers in the world. To reach this threshold, the Colorado River has to go through various stages of development in which each stage has been authorized or supported by a complex body of legal authorizations. The legal authorizations are in the form of compacts, federal laws, court decisions and decrees, contracts, and regulatory guidelines collectively known as the "Laws of the River" (Colorado River Commission of Nevada 2006), and they fall into six general categories: (1) International treaties; (2) interstate compacts; (3) federal statutes; (4) federal rules, regulations and operating plans; (5) federal court decisions; and (6) interagency and multi-party agreements (i.e., contracts between one or more public agencies and/or other parties). This collection of legal documents apportions the water into and regulates the use and management of the Colorado River in the seven U.S. basin states and the two Mexican states (Bureau of Reclamation, Lower Colorado Region 2015). The following is a synopsis of the most significant legal documents that constitute the "Laws of the River".

(1) **The 1908 Supreme Court decision of Winters vs. United States** (207 U.S. 564) is a court decision that recognizes Indian water rights regardless of whether a Native American tribe had previously used the water or not, with the rights established at the time when reservations were created. Further, the decision stated that the state in which the reservation is located must fulfill the particular tribe's water rights.

(2) **The Colorado River Compact of 1922** is an interstate compact that has the characteristics of a statute but the force of a contract, and it is interpreted according to the federal common law of contracts if Congress has consented to the agreement. This means when a compact is approved by Congress it becomes a law of the United States and as such it remains a legal document that must be construed and applied in accordance with its terms (*Texas v. New Mexico, 482 U.S. 124, 128* [1987]). This law is the cornerstone of the "Law of the River" and it represents the negotiated apportionment of the Colorado River water among the seven basin states in the USA and Mexican government in 1922. It defined the relationship between the upper basin states, where most of the river's water supply originates, and the lower basin states, where most of the water demands are. The compact divides the river basin into two areas, the Upper Basin (comprising of Colorado, New Mexico, Utah and Wyoming) and the Lower Basin (consisting of Nevada, Arizona, and California). The compact requires the Upper Basin states not to deplete the flow of the river below 7,500,000 acre-ft (9.3 km^3) during any period of 10 consecutive years. The compact enabled the widespread irrigation of the Southwest, as well as the subsequent development of state and federal water works projects under the U.S. Bureau of Reclamation. Such projects include the constructions of Hoover Dam and Lake Powell. However, there were some drawbacks to the decision. To begin with, the decision was made on the basis of rainfall patterns observed on wetter years before the treaty's signing in 1922, and the available amount falls short during dry periods. Also, the compact was not concerned with Indian water rights, nor did it include any provisions to protect the environment (Colorado River Research Group 2014). These had to be rectified later with new regulations.

(3) **The Boulder Canyon Project Act of 1928** (*Public Law No. 642*) was enacted for a number of purposes, including: (a) ratifying the 1922 compact; (b) authorizing the construction of Hoover

Dam and related irrigation facilities in the lower Basin; (c) apportioning of the lower Basin's 7.5 maf among the states of Arizona (2.8 maf or 37.3%), California (4.4 maf or 58.7%) and Nevada (0.3 maf or 4%); and (d) authorizing and directing the Secretary of the Interior to function as the sole contracting authority for use of the lower Colorado River Basin water.

(4) T**he California Seven Party Agreement of 1931** is an accord that helped settle the long-standing conflict between seven California agricultural and municipal interest groups that use the Colorado River water. The seven principal groups are: Palo Verde Irrigation District, Yuma Project, Imperial Irrigation District, Coachella Valley Irrigation District, Metropolitan Water District, and the City and County of San Diego. The Agreement helped these groups reach consensus on the amounts of water to be allocated on an annual basis to each claimant. Even though the agreement did not resolve all water allocation issues, the regulations set forth have been incorporated and become parts of any major California water delivery contracts made since then.

(5) **The Mexican Water Treaty of 1944** put together an agreement on the use of the waters of the Colorado and Tijuana rivers and the Rio Grande. This agreement commits 1.5 maf of the Colorado River's annual flow to Mexico. This amount, however, is not a part of the 15 maf water allocated to the Upper and Lower Basin states of the United States. This treaty also allows for the lower Basin states to get an additional 1,100,000 acre-ft/year of water during periods of surplus water availability (U.S. Bureau of Reclamation 1948, Umoff 2008).

(6) **The Upper Colorado River Basin Compact of 1948** is an agreement that created the Upper Colorado River Commission that apportioned the other half of the annual Colorado River flow of 7.5 maf among the Upper Basin states of Colorado (with 3.86 maf or 51.47%), New Mexico (with 0.84 maf or 11.20%), Utah (with 1.71 maf or 22.8%), and Wyoming (with 1.04 maf or 13.86%). Arizona, also receives an additional 0.67% (or 50,000 acre-ft) annually for its portion that lies within the Upper Colorado Basin (U.S. Bureau of Reclamation 1948).

(7) **The Colorado River Storage Project of 1956** (*43 USC 620*) was an action designed to provide a comprehensive Upper Basin-wide water resource development plan that authorized the construction of Glen Canyon, Flaming Gorge, Navajo and Curecanti dams for regulating the river to produce power and store water for irrigation, recreation and other uses.

(8) **The Arizona v. California U.S. Supreme Court Decision of 1963** settled a 25-year-old dispute between Arizona and California. The dispute stemmed from Arizona's desire to build the Central Arizona Project to enable use of its full Colorado River apportionment. California objected and argued that Arizona’s use of water from the Gila River, a Colorado River tributary, constituted use of its Colorado River apportionment, and that California had developed a historical use of some of Arizona’s apportionment, which, under the doctrine of prior appropriation, precluded Arizona from developing the project. The Supreme Court rejected California's arguments, ruling that the lower Basin states have the right to appropriate and use tributary flows before the tributary co-mingles with the Colorado River, and that the doctrine of prior appropriation did not apply to apportionments in the lower basin (MacDonnell 2003). In 1979, the Supreme Court issued a **Supplemental Decree**, which perfected the rights referred to in the Colorado River Compact and in the Boulder Canyon Project Act. Those rights are entitlements essentially established under states’ laws, and have priority over later contract entitlements (Colorado River Research Group 2014).

(9) **The Colorado River Basin Project Act of 1968** (*Public Law 90-537*) authorized construction of a number of water development projects in both the upper and lower basins, including the Central Arizona Project (CAP) of Arizona. It also made the CAP water supply subordinate to California's apportionment in times of shortage, and directed the Secretary of the Interior to prepare, in consultation with the Colorado River Basin states, long-range operating criteria for the Colorado River reservoir system.

(10) **The Criteria for the Coordinated Long-Range Operation of Colorado River Reservoirs of 1970** (*Public Law 90-537 as amended March 21, 2005*) was issued to enable the coordinated operation of reservoirs in the upper and lower basins and set conditions for water releases from Lake Powell and Lake Mead.

(11) **Minute 242 of the U.S.-Mexico International Boundary and Water Commission of 1973** required the U.S. to take actions to reduce the salinity of the Colorado River water being delivered to Mexico at Morelos Dam.

(12) **The Colorado River Basin Salinity Control Act of 1974** (*43 USC 1571-1599, Public Law 93-320, as amended by Public Laws 98-569, 104-20, 104-127, and 106-459*) was issued as a means to comply with the United States’ obligations to Mexico under Minute No. 242. A major feature of the Act include construction of a brine discharge canal and a desalination plant for the treatment and conveyance of the Wellton Mohawk Irrigation and Drainage District discharge water (Title I of the Act). These facilities are meant to

enable the United States to deliver water to Mexico that have an average salinity of 115 parts per million (ppm) plus or minus 30 ppm over the annual average salinity of the Colorado River at Imperial Dam. The Act also authorized construction of four salinity control units and the expedited planning of 12 other salinity control projects above Imperial Dam as part of the basin wide salinity control plan (Title II of the Act).

(13) **The Grand Canyon Protection Act of 1992** directs the Secretary of the Interior to operate Glen Canyon Dam in such a manner as to protect against, and mitigate any adverse impacts on and improve the values for which the Grand Canyon National Park and the Glen Canyon National Recreation Area were established. The Act further directs that these actions be undertaken in a manner fully consistent with the other "Laws of the River" that govern the allocation, appropriation, development, and exportation of the waters of the Colorado River Basin.

(14) **The Arizona Water Settlement Act of 2004** (*Public Law 108-451*) was authorized by President George W. Bush. The legislation provided adjustments to the allocation of the Central Arizona Project (CAP) water and settled litigation between the United States and the Central Arizona Water Conservancy District concerning repayment for the CAP. It authorized the Gila River Indian community Water Rights Settlement and the southern Arizona Water Rights Settlement Act of 1982. It also provided funding to enable the Gila River Indian Community and the Tohono O'odham Nation to rehabilitate and expand water infrastructure to meet the needs of their reservations.

(15) **Water Rights Settlement between the State of New Mexico and the Navajo Nation** was signed on April 19, 2005, to resolve the claims of the Navajo Nation for the use of waters of the San Juan River Basin in northwestern New Mexico. The settlement was intended to adjudicate the Navajo Nation's water rights and provide associated water development projects for the benefit of the Navajo Nation in exchange for a release of claims to water that could potentially displace existing non-Navajo water users in the basin.

(16) **The Colorado Basin States Record of Decision** was signed on December 13, 2007 by the then Secretary of the Interior Dirk Kempthorne. According to the Secretary, the decision memorializes a remarkable consensus not only to solve current problems but also to prepare ahead of time for future droughts or surpluses rather than resorting to disruptive litigations. The decision implements new and interim operational guidelines to meet the challenges of the current drought in the basin, and the low-water conditions caused by continued drought or other causes in the future (Johnson and Kempthorne 2007, Colorado River Research Group 2014).

In addition to the laws, regulations and court cases on dam construction and maintenance, and water allocation, there are many laws and regulation related to power generation, sale, distribution, Indian water rights, and water quality control such as the **Hoover Power Plant Act of 1984** (*Public Law 98-381*) that authorized the Secretary of Energy to allocate and distribute the power generated at Hoover Dam, and a number of other legislative actions that settled Indian water rights (Colorado River Research Group 2014).

DAMMING OF THE COLORADO RIVER

For several million years the Colorado River flowed with little or no human interference. In its natural state, the Colorado River, especially during the pioneer and settlement period was viewed as a "natural menace" instead of an asset. Even then, the River had many invaluable ecological and environmental values as it flowed unimpeded to the Sea of Cortez, leaving vast areas of wetland behind and providing nutrient-rich fish habitat on its way (Glenn et al. 1996). In those times, the Colorado River ecosystem supported 32 species of endemic fish and 200 to 400 species of plants. The average pre-dam peak flow was 85,000 cfs while the highest flood in record was 210,000 cfs. The river also had temperatures that fluctuated between 0.2 to 28°C, salinity that ranged from 200 to 1300 ppm and a sediment load into the Grand Canyon that reached up to 62,800,000 tons/year, 20% of which came from the Paria and the Little Colorado Rivers (Topping et al. 2000).

It has taken only less than 100 years and the above "Laws of the River"' for the Colorado River to become comprehensively and commercially developed, dammed, desilted, diverted to irrigate crops, produce power, provide sites for recreational facilities, and serve as a source of water to distant cities, towns and other communities. Altogether, there are 14 large dams that stretch from Morelos Dam at the U.S.-Mexico border to Shadow Mountain Dam near the tip of the river's headwater in Colorado. The other 12 dams are unevenly spread (four in Colorado, five along the border between Arizona and California and two between Arizona and Nevada) along the 1,470 mile distance of the River. The capacities of the reservoirs in the main stem range between 18,400 acre-ft and 28,945,000 acre-ft with the total capacity of all the reservoirs summing up to 58,343,045 acre-ft. In addition, there are 19 dams in tributary streams (12 of them in Colorado, 5 in Utah and 1 each in New Mexico and Wyoming) with reservoir capacities that range between 54,920 acre-ft and 3,788,700 acre-ft and a total capacity of 9,821,250 acre-ft in the upper basin. The lower basin has 11 dams along tributary streams (10 of them in Arizona and 1 in New Mexico) with reservoir capacities that range between 51,360 acre-ft and 2,910,200 acre-ft, and a total capacity of 9,195,301 acre-ft. Most of the reservoir capacities are the original design capacities and do not account for any siltation and other aggradation and degradation that may have occurred since construction and operation (Colorado River Research Group 2014).

The largest dam, Hoover Dam, is the first major project in the Colorado River. It was built during the Great Depression and finished in 1935. The dam stood more than 700 ft tall and backed up the river for about a 100 miles upstream with an original reservoir capacity of 28,945,000 acre-ft. The construction of Hoover Dam is one of the most monumental engineering feats that have ever been built (Reisner 1987). The other great dam in the Colorado River Basin is Glen Canyon Dam. The construction of the dam was finished in 1963 and the stored water behind it forms Lake Powell which stretches for more than 200 miles upstream and controls the water flowing downstream. In terms of physical size, Glen Canyon Dam is one of the largest in the United States rising 710 ft over the bedrock and 638 ft above the original river bed. The original capacity of Lake Powell is second to Lake Mead and could hold 26,214,900 acre-ft. Altogether, there are more than 93 reservoirs in the upper and lower basins that tame the Colorado River. They cost huge amounts of money to build. Construction of the federal dams and associated water supply infrastructure costed $4.7 billion and $4.125 billion, respectively (Colorado River Commission of Nevada 2006). These expenses do not include costs for non-federal dams, which contribute significantly to the basin's water budget. Collectively, all dams in the Colorado River Basin can hold four to five times the river’s annual flow amount generating hydroelectricity and supplying irrigation and municipal water for over 35 million people in the U.S. and another 3 million people in Mexico (Schuster 1987, Colorado River Research Group 2014).

The Benefits of Damming the River

The Laws of the River described above relate to management of the Colorado River for multiple purposes. For thousands of years people have used dams on rivers to store water for irrigation and sometimes to generate power through water wheels and turbines. Being located in the semiarid Southwest which was sparsely populated, the use of the Colorado River for these purposes came late in response to the movement of people westward in the twentieth century. Since then, the Colorado River has been exhaustively dammed to become the lifeblood of the Southwest, fueling a $26 billion recreation economy that supports a quarter of a million sustainable recreation-related American jobs in Arizona, California, Colorado, Nevada, New Mexico, Utah, Wyoming, Mexico and beyond. Other purposes for extensive damming of the Colorado River include storage for drinking water supply, flood control, irrigation, hydroelectric power generation and transportation (Glenn et al. 1996, Colorado River Research Group 2014).

The beneficial aspects of dams may be different on the basis of whether they are in reference to their effects upstream or downstream from the dam. Most upstream benefits may come in the form of aesthetics and providing recreational opportunities. The reservoirs behind the dams in the Colorado River are useful for boating, fishing, and other water sports. For example, the Glen Canyon National Recreation Area, mainly consisting of Lake Powell hosts more than 2.6 million visitors every year, many of them on houseboats and other pleasure crafts (Lowry 2003). Other upstream benefits are in the form of providing water supply for irrigating the extensive farms in the arid and semi-arid areas of the Southwest, and as drinking water for the continuously growing large cities such as Las Vegas, Phoenix, Tucson, San Diego, and Los Angeles, and the hundreds of smaller and dispersed communities in the region. These communities also benefit from the electricity generated by the hydroelectric power plants in the dams. The reservoirs behind the dams are also suitable habitat for fish, other aquatic wildlife, numerous riparian fauna and flora and a thriving ecological biodiversity.

Sometimes dams are built to provide critically needed downstream goods and services. Many dams are built to retain excess flow to protect downstream communities, agricultural farms and other installations from frequently damaging floods. Others, like the Glen Canyon Dam, were partly built to store and /or regulate erratic flow and guarantee its availability for equitable distribution among downstream users. Also, the stored water behind the dams in the Colorado River is used to generate more than 4200 megawatt of hydroelectricity that serves about 36 million people in the region (Thomas and Hecox 2013). Additionally, many reservoirs like those in the tributary streams in Arizona, Colorado, New Mexico, Utah, and Wyoming and some of those in the main stem of the Colorado River are used to store water to irrigate about 4 million acres of desert land and to provide water for residential, commercial and industrial uses (Colorado River Commission of

Nevada 2006). For example, the Central Arizona Project supplies needed water to the growing metropolitan areas of Phoenix and Tucson and many other communities in Arizona, while the All-American Canal provides water for the Imperial Valley of southern California, a productive agricultural region converted from a desert wasteland. Without water from the Colorado River huge swaths of arid and semi-arid land would not have been reclaimed to produce the variety of agricultural products that helped make the deserts of Arizona and California become a breadbasket of the southwestern U.S.A.

The Drawbacks of Damming the River

With the damming and expanded use of the Colorado River, there have been profound changes occurring in the basin. New societal demands for water and energy are on a collision course with vested legal rights and past commitments. This has become more serious with time when rapid population growth (both through internal growth and migration), and mammoth economic forces operating in the area are converging to competitively exploit both the water and hydropower being produced in the Colorado River Basin. Such a scramble for these resources has significant quantitative and qualitative implications. To deal with these problems and properly manage the operation of the Colorado River, the various congressional and judicial laws and regulations described above under the "Laws of the River" have to be issued and become operational.

Effects on the amount of stream flow

The first 10 laws and regulations under the "Laws of the River" are exclusively related to the quantitative control and distribution of the Colorado River. All came during a period when the public's awareness of environmental issues was not strong enough to require qualitative changes in the management of the River. Dams such as Hoover, Glen Canyon and others in the main stem and the tributary streams were built mainly for water storage, hydroelectric power generation and flood control. Because of significant retention of water in the reservoirs or lakes behind dams such as the Glen Canyon Dam, there are considerable reductions in the regular and peak flows downstream. Figure 2 illustrates these phenomena by comparing the pre- (1921-1963) and post-Glen Canyon Dam (1964-2015) average monthly flows at Lee Ferry. The graph shows a difference of 30,000 cfs (that is, a 60% decrease) between the pre-dam (50,000 cfs) and the post-dam (20,000 cfs) peak flows. It should be noted that the post-dam flows do include the six times releases of experimental high flows that ranged from 37,000 to 45,000 cfs lasting from 24 to

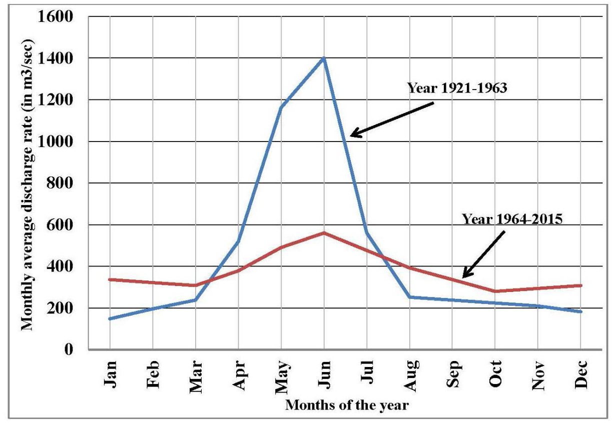

Figure 2. Comparison of pre-dam and post-dam monthly average flows of the Colorado River at Lee's Ferry, Arizona.

168 hours. The purpose of the high flows and their variations in rate and duration is to see the effects of their changes on downstream sediment removal and riparian restoration.

The quantitative impact of damming the Colorado River and the post-dam state of its water resources is more pronounced in the delta area where stream flow completely disappears for months (May, June and July in particular) during the warm season . This is demonstrated using the total monthly flows for one year at locations close to the delta at miles 17 and 24 (or kilometers 27 and 38) from the mouth of the River (See Fig. 3). The closer the river gets to its mouth the drier it becomes because most of the remaining stream flow going down to Mexico is consumed in the lower Colorado River Basin in the U.S. and the Mexicali farms in Mexico (Michael et al. 2001). The absence of water in the delta is the cause for the near disappearance of the Cocopah Indians from their ancestral land. Their status is summarized by Onesimo Gonzales, a village chief of the Cocopah Indians, when he said in 2001:

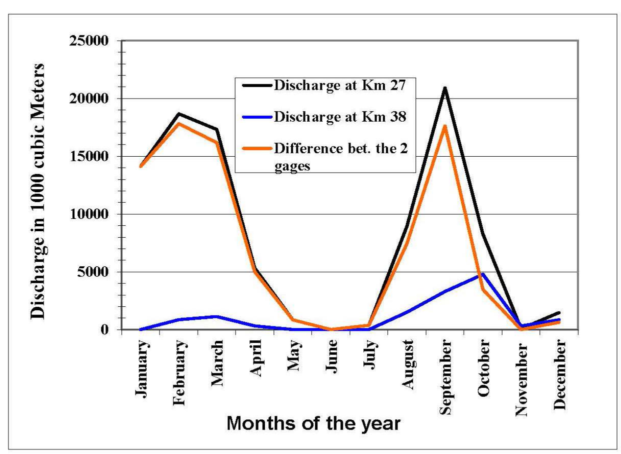

Figure 3. Average monthly discharge of the Colorado River at kilometers 27 and 38 from the border in Mexico for 1997.

Our River is gone. No more fishing. Trees are dead. No one plants. The wells are dry (Rosenblum 2001).

This is in sharp contrast with Aldo Leopold's observation when he traveled there in 1922 and found that

The River was everywhere and nowhere, for (it) could not decide which of a hundred green lagoons offered the most pleasant and least speedy path to the gulf (Leopold 1949).

The Colorado River has been steadily declining between the time of Leopold's observation when it was green and lash and that of Gonzales' lament on its ecological demise. Now, the Colorado River delta is a remnant wetland that has become the subject of growing scientific and political concern. The recent literature on the ecology and restoration of the delta of the Colorado River emphasizes the importance of natural and anthropogenic sources of water for sustaining delta habitats (Glenn et al. 1992, 1996, 1999; Zengel et al. 1995; Morrison et al. 1996; Valdés-Casillas et al., 1998; Luecke et al. 1999; Pitt et al. 2000).

Figure 4 shows the steady increase in the average demand for water in Colorado River Basin. With the rapid development of the Southwest, the demand (consumption) for water had surpassed the average flow of the River in the late 1990s and the average supply early in the 2000s (Colorado River Research Group 2014). This milestone seems to have gone mostly unnoticed, while proving to be incredibly salient, as it increases vulnerability for drought. It is because of these situations the Colorado River was recently named the nation's Most Endangered River by a leading river conservation organization, the American Rivers, primarily because the Colorado is operating at a dangerous water deficit. The bottom line is that more water is being taken out along the river's arid path than is obtained from annual rain and snow melt on its headwaters (see Fig. 4). In conclusion, the overall demand for the Colorado River water exceeds the supply and if the Colorado River were a business it would be operating "in the red."

Effects on downstream sediment accumulation

Another important quantitative impact of damming the Colorado River is on sediment deposition, accumulation and removal along the main stem of the River, especially in its Grand Canyon portion. Fine sediment is very important to the health of the Grand Canyon. In fact, the reduced supply and transport of sediments is considered to be the primary factor responsible for the degradation of the post-dam Grand Canyon ecosystem. Sediments provide both nutrients and substrate for plants to grow, habitat for fish and wildlife, and serves as beach for recreational use by visitors into the Canyon. The construction of the Glen Canyon Dam has brought major changes to the ecosystem of the Colorado River downstream of the dam, especially by trapping behind the dam all the sediment that comes from the 107,838-mi^2 watershed area above the dam. Prior to the dam, there were distinctly high and low flow periods that coincide with seasonal and annual climatic variations. Low flow periods accumulated sediment in alluvial plains via erosional and aeolian depositional processes (Topping et al. 1999), which minimized long-term erosion to existing sandbars in the Canyon. High

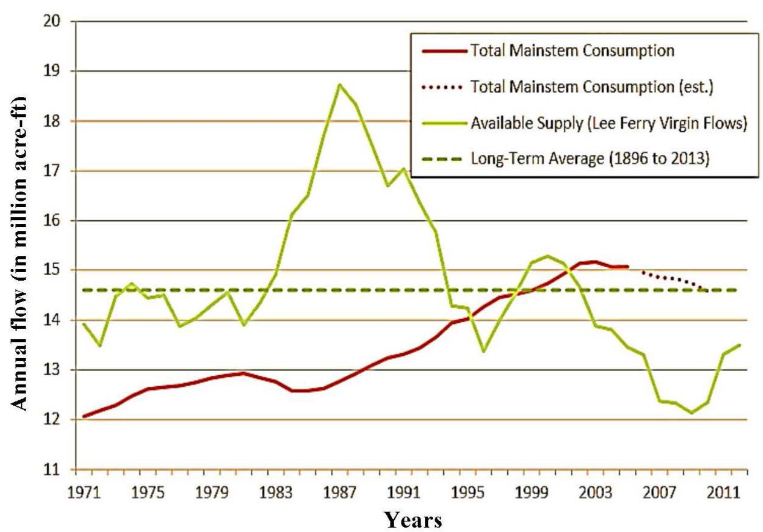

Figure 4. Average Supplies versus demands on the Colorado River main stem (10-year averages) (after Colorado River Research Group 2014).

flow periods coincided with monsoonal rains and spring snow melts. The floods redistributed stored sediment from the river channel and surrounding floodplains to build sandbars. Dam-controlled flow patterns with sediment entrapment behind the dam have altered the natural processes that created the Grand Canyon through erosion processes (Topping et al. 2000). Deficiency of sediment below the dam is undisputed, but less certain is the dynamics of sediment storage and transport within the system. A series of High Flow Experiments (HFEs) have been tried to see if occasional high-flow regimes can change the sediment dynamics. So far these HFEs have proven to achieve long-term desirable restorative effects throughout the Canyon, but may cause localized aggradation in some areas and degradation in others (Grams et al. 2015). What is certain is that a half-century of controlled flow from Glen Canyon Dam, along with restricted sediment supply have resulted in net sediment loss over time in the Grand Canyon as a whole.

Effects on downstream water quality

In addition to having an adequate quality water supply, the economic and social well-being of major cities and rural communities in the Colorado River Basin are inextricably linked with the environmental health of the River. The latter in return has been significantly affected by the extensive damming of the Colorado River and the rapid development that followed. There are many qualitative factors that influence the health of a river. The factors may be physical, chemical and biological in nature. The post-dam downstream physical changes in the Colorado River are manifested in the form of low stream flows and the changes in sediment accumulation as described previously. There are also changes in water temperature especially immediately below the dam. The water temperature regime there is typically altered and is largely determined by the depth from which the released water is pulled out of the reservoir. Deeper water is typically colder. Also the river water temperature downstream from Glen Canyon Dam varies with time and distance from the dam. The temperature is warmer in warmer months and colder in colder months, and the temperature warms with distance from the dam and the post-dam temperature fluctuation is much lower than those before dam construction (Zamani 2015). The changes in temperature can lead to drastic ecological changes because cold water, when released into naturally warm water ecosystems can have devastating impacts on natural fish and mussel populations. This happens because many organisms have evolved with a specific temperature regime and are not suited to adapt to altered temperatures.

One other important downstream impact of damming the Colorado River has to do with chemical-related changes to water quality. The chemical quality in the Colorado River Basin for this paper may be expressed in terms of salinity. Salinity, also referred to as total dissolved solids (TDS), is defined as the mass of dried ionic constituents that pass a 2μm filter, and is quantified in-river as either a concentration (mass per unit volume) or as a load (mass per unit time), or in parts per million. The numerical threshold Standards in the Colorado River, which increase downstream range from 723 ppm at Hoover Dam to 879 ppm at the Imperial Dam near the Mexico border (Morford 2015). The sources for salinity in the Colorado River may vary from place to place and can be natural or anthropogenic in nature. The natural sources may be saline springs, saline rock weathering and surface runoff (which amounts to 47% of the Colorado River salinity), while irrigation, reservoir evaporation, and mining and industry are the main anthropogenic sources of salinity, contributing 37%, 12%, and 4% of the total salinity load in the Colorado River, respectively (Bureau of Reclamation 2013). Altogether, the Colorado River transports between 7 and 9 million tons of salt annually to the Gulf of California depending on climatic control and salt mitigation practices within the basin. This amount is expected to increase in the future because of increased human use. Even now, the lower Colorado River contains about 2,000 pounds of salts per acre-foot. It is no surprise then that the Bureau of Reclamation estimates that salinity contributes more than $306 million per year in economic damage along the Colorado River Basin, with roughly half of it caused by agricultural activities (Borda 2004). To cope with the problem, the Bureau of Land Management (BLM), the Natural Resources Conservation Service (NRCS) and the Bureau of Reclamation (BOR) spend $32 million annually to prevent 1.3 million tons of salts from entering the Colorado River (Bureau of Reclamation 2013). The primary prevention methods include implementation of best management practices in irrigation districts, erosion control on public lands, and reduction in point source inputs from natural geologic sources. Salinity control is also achieved on rivers by regulating salinity discharge such as by pumping from different depths in large dams. As show in Figure 5, the long-term effect on salinity of the Glen Canyon Dam is beneficial as it has greatly reduced the salinity peaks as well as its wide fluctuations starting with the Dam operation in 1964. In spite of the slight fluctuations from year to year, the overall salt concentration in the Colorado River below the Dam has been decreasing with time.

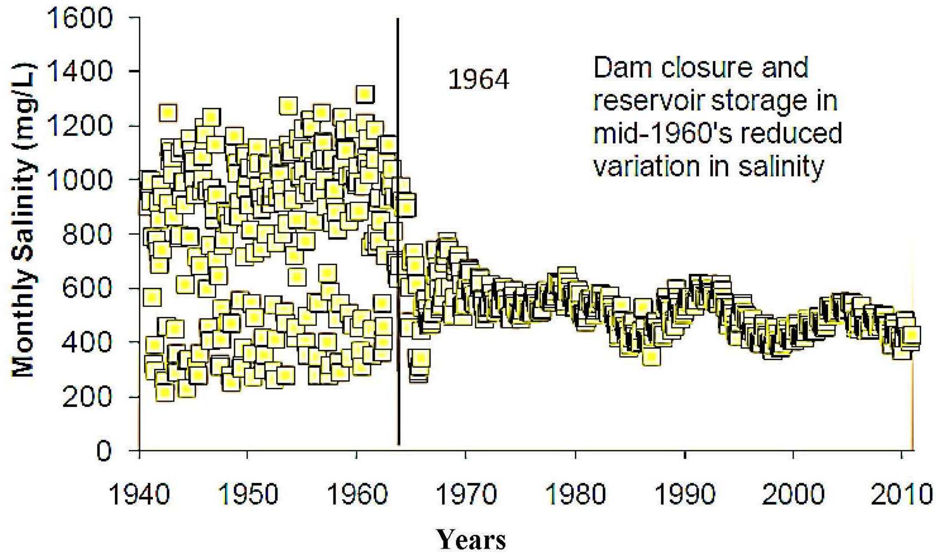

Figure 5. Effects of Glen Canyon Dam on Colorado River salinity at Lee Ferry (Bureau of Reclamation 2013).

With construction of the dams, the Colorado River has gone through various critical changes that affected the biota in the River. Prior to damming of the River, water rushed through canyons in various amount and at various speeds to continuously aggrade and degrade all aspects of the stream channel. High velocity waters scoured canyon walls cleansing debris along their paths, removing sediments containing harmful trace minerals that when accumulated become toxic to the system (Glen Canyon Institute 1998), while at the same time changing the depth and magnitude of the canyons. The extreme fluctuations in the flow of the Colorado River in the pre-dam period provided good habitat for carp, catfish, razorback and bluehead suckers, humpback and bonytail chub, speckled dace and the Colorado squawfish, most of which are endangered today (National Park Service 1998). With construction of the dams, however, the Colorado River has significantly reduced its water quality and aquatic habitat. For example, the changing natural temperature range of the pre-dam water (32°F to 80°F) became a relatively constant temperature of 46°F after the dam was built (USBR and USDOI 1996). Also, the river downstream of the dams such as that below the Glen Canyon Dam became practically devoid of nutrients because most of them are bound to sediments, and become trapped in the reservoir behind the dam. Also, otherwise harmless trace metals and salts, such as selenium, arsenic, and mercury, when trapped in stationary sediments can become harmful substances. Such chemicals eventually become incorporated into the plankton and zooplankton, and are distributed throughout the food web to have significantly damaging effect on the flora and fauna along the River. The damming of the River and the changes in the water quality and flow characteristics of the River have stimulated introduction of exotic species such as various species of trout and other game fish, like striped, large, and small mouth bass, black crappie, walleye, bluegill sunfish, and channel catfish (National Park Service 1998) that outcompete weakened endemic species which are often specialists whose specific niche has been destroyed. Because of such situation many of the native fish species and other aquatic organisms have become threatened or endangered.

Elimination of flooding in the post-dam period at first led to proliferation of riparian vegetation downstream from the Glen Canyon Dam. The reason for the abundant growth of the vegetation on the sandbars and canyon walls is due to the Colorado River not having seasonal flooding (USGS 1996). As a result, plant diversity along the corridor significantly increased due to the alteration of the Colorado River. As the years passed, however, the sandbars have become eroded since the river is unable to provide the strength and silt to constantly move or create the sandbars. The situation decreased the health and vigor of the vegetation for a while until the high flow experiment (HFE) of 1996.That artificial flood was successful in rebuilding the sandbars by providing the amount of flow and sediment concentration needed to rebuild them (Brinkley 1996). Since then, there have been five more HFEs to continue rebuilding the sandbars and provide food and substrate for healthy riparian vegetation growth and to provide suitable habitat for other riparian organisms in the Colorado River within the Grand Canyon.

CONCLUSIONS AND RECOMMENDATIONS

Since the early 1900s, the Colorado River Basin states have been concerned about the increasing demand for the Colorado River water and its fair allocation among its claimants. This became more serious with increasing population growth and the greening of the desert and other expansive economic and social developments in California and Arizona that demand for more water. The signing of the Colorado River Compact in 1922 served as the beginning for easing the concern. But it has taken more than15 additional laws, compacts, regulations and court cases to arrive at the current management level, which still is not perfect. There are some weaknesses in the "Laws of the River," which demand additional regulations, agreements and commitments to meet new challenges and address unmet demands to arrive at a more fair and equitable distribution of the dwindling river water among the seven U.S. and two Mexican states.

Clearly, there needs to be changes in the way the water is apportioned among the claimants. With the recurring drought in the Southwest and the presence of climate change (Christensen et al. 2004) and its worsening situation until it gets better, the management of the River must be dynamic and based on objective reality to fairly allocate what is there rather than what ought to be. Decisions must be based on current science, use current technology and be adaptive in nature to minimize disagreements among stakeholders and safe guard and optimize the apportionment of an essential but scarce resource. Secondly, given that the water is used for multiple purposes such as irrigation, hydroelectric power generation, drinking water supply for a rapidly growing population, industrial, recreational and other uses, there needs to be a clear understanding, resolved collaboration and partnership among all interested parties in determining priorities of use and its proper apportionment. In addition, there needs to be a standing committee of the sharpest minds selected to represent all stakeholders in a fair and equitable manner. The committee may be chaired by a highly knowledgeable and neutral person from a federal agency to ensure fairness. Decisions must be made in a multi-objective, collaborative, holistic, sustainable, adaptive and evidence-based manner to avoid conflicts and resolve issues in an amicable, fair and just manner. Under such a situation, there is a good chance for groups even those sharply in conflict with each other to come to a compromise and accept a mutually acceptable management of the Colorado River ecosystem and its critical water resources.

REFERENCES

BRINKLEY, J. 1996. Grand Canyon flood has experts gushing. The Orange County Register. Online. Lexis Nexis Academic Universe. April 13, 1996.

BORDA, C. 2004. *Economic Impacts from Salinity in the Lower Colorado River Basin*. Technical Memorandum Number EC-04-02. Bureau of Reclamation. Denver, CO

CHRISTENSEN, N. C., A. W. WOOD, N. VOISIN, D. P. LETTENMAIER, and R. N. PALMER. 2004. The effects of climate change on the hydrology and water resources of the Colorado River Basin. *Climate Change* 62:337-363.

COHEN, M. J., J. CHRISTIAN-SMITH, and J. BERGGREN. 2013. *Water to Supply the Land: Irrigated Agriculture in the Colorado River Basin*. Pacific Institute, Oakland CA.

COLORADO RIVER COMMISSION OF NEVADA. 2006. *"Laws of the Rivers": the Legal Regimes of Major Interstate River Systems of the United States.* Colorado River Commission of Nevada, Las Vegas, Nevada.

COLORADO RIVER RESEARCH GROUP. 2014. *The First Step in Preparing the Colorado River's Water Budget: Technical Report*. Colorado River Research Group <www.coloradoriver researchgroup.org>.

GLEN CANYON INSTITUTE. 1998. *Glen Canyon Institute: US Water News* <http://www. Glencanyon.org/USWaterNews.htm>. Last visited: November 2, 1998 5:06pm; Last updated: September 24, 1998.

GLENN, E. P., R. S. FELGER, A. BURQUEZ, and D. S. TURNER. 1992. Cienega de Santa Clara: Endangered wetland in the Colorado River delta, Sonora, Mexico. *Natural Resources Journal* 32: 817-824 .

GLENN, E. P., C. LEE, R. FELGER, and S. ZENGEL. 1996. Effects of water management on the wetlands of the Colorado River delta, Mexico. *Conservation Biology* 10:1175-1186.

GLENN, E., R. TANNER, S. MENDEZ, T. KEHRET, D. MOORE, J. GARCIA, and C. VALDÉS. 1998. Growth rates, salt tolerance and water use characteristics of native and invasive riparian plants from the delta of the Colorado River, Mexico. *Journal of Arid Environments* 40:281-294.

GLENN, E. P., J. GARCIA-HERNANDEZ, C. CONGDON, and D. LUECKE. 1999. Status of wetlands supported by agricultural drainage water in the Colorado River delta, Mexico. *Horticultural Science* 34:16-21.

GRAMS, P. E., D. BUSCOMBE, D. J. TOPPING, M. A. KAPLINSKI, and J. E. HAZEL, JR. 2015. Use of flux and morphologic sediment budgets for sandbar monitoring on the Colorado River in Marble Canyon, Arizona. *Proceedings of the 3rd Joint Federal Interagency Conference*, April 19-23, 2015, Reno, Nevada.

INGEBRETSEN, R. J. 1998. A sedimental journey: A Grim Prospect for Lake Powell. *Hidden Passages: Journal of the Glen Canyon Institute*.

JOHNSON, R., and D. KEMPTHORNE. 2007. *Record of Decision Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead*. Department of the Interior, Washington D.C.

LEOPOLD, A. 1949. *A Sand County Almanac and Sketches Here and There*. Oxford University Press, Oxford, NY.

LOWRY, W. 2003. *Dam Politics: Restoring America's Rivers*. Georgetown University Press, Washington D.C.

LUECKE, D. F., J. PITT, C. CONGDON, E. GLENN, C. VALDÉS-CASILLAS, and M. BRIGGS. 1999. *A Delta Once More: Restoring Riparian and Wetland Habitat in the Colorado River Delta*. Environmental Defense Publications, Washington, D.C.. 51 pp. <https://www.edf.org/sites/default/files/425_delta.pdf>

MACDONNELL, L. J. 2003.*Arizona v. California*: Its meaning and significance for the Colorado River and beyond after fifty years. *The Arizona Journal of Environmental Law and Policy* 4(1):88-129.

MICHAEL J. C., C. HENGES-JECK, and G. CASTILLO-MORENO. 2001. Water balance for the Colorado River Delta. *Journal of Arid Environments* 49:35-48.

MORFORD, S. 2015.*Salinity in the Colorado River Basin*. <https://watershed.ucdavis.edu/education/classes/files/content/page/6%20Morford-Colorado_Basin_Salinity.pdf> accessed on August 23, 2015.

MORRISON, J., S. L. POSTEL, and P. GLEIC. 1996. *Sustainable Use of Water in the Lower Colorado River Basin.* Pacific Institute for Studies in Development, Environment, and Security and the Global Water Policy Project Report. Pacific Institute for Studies in Development, Environment, and Security, Oakland, California.

NATIONAL PARK SERVICE. 1998. National Park Service. <http://www.nps.gov/htdocs4/glca/watergo.htm> .Last Visited: October 19, 1998

PITT, J., D. F. LUECKE, M. J. COHEN, E. P. GLENN, and C. VALDÉS-CASILLAS. 2000. Two countries, one river: Managing for nature in the Colorado River Delta. *Natural Resource Journal* 40:819-864.

REISNER, M. 1987. *Cadillac Desert*. Penguin Books Publishers, New York, New York.

ROSENBLUM, M. 2001. Fighting over the last drops of the Colorado: Water wars: A series on the world's most precious resource. *Sunday Gazette-Mail*, May 20, 2001 <https://www.highbeam.com/doc/1P2-18994661.html>.

SCHUSTER, R. J. 1987. *Colorado River System: System Overview*. US Bureau of Reclamation. Denver, Colorado.

THOMAS, S., and W. E. HECOX. 2013. *Overview: Colorado River Basin Water Demand and Supply Imbalance*. The 2013 Colorado College State of the Rockies Report Card Water Friendly Futures for the Colorado River Basin. Colorado College, Colorado Springs, Colorado.

TOPPING, D. J., D. M. RUBIN, J. M. NELSON, P. J. KINZEL, and J. P. BENNETT. 1999. Linkage between grain-size evolution and sediment depletion during Colorado River floods. Pp. 71-98 *in* R. H. Webb, J. C. Schmidt, G. R. Marzolf, and R. A. Valdez, eds., *The Controlled Flood in the Grand Canyon.* American Geophysical Union, Washington, D.C. DOI: 10.1029/GM110p0071.

TOPPING, D. J., D. M. RUBIN, and L. E. VIERRA. 2000. Colorado river sediment transport 1: Natural sediment supply limitations and the influence of Glen Canyon Dam. *Water Resources Research* 36(2):515-542.

VALDÉS-CASILLAS, C., O. HINOJOSA-HUERTA, M. MUNOZ-VIVEROS, F. ZAMORA-ARROYO, Y. CARRILLO-GUERRERO, S. DELGADO-GARCIA, M. LOPEZ-CAMACHO, E.P. GLENN, J. GARCIA, J. RILEY, D. BAUMGARTNER, M. BRIGGS, C. T. LEE, E. CHAVARRIA-CORREA, C. CONGDON, and D. LUECKE. 1998. *Information Database and Local Outreach Program for the Restoration of the Hardy River Wetlands, Lower Colorado River Delta, Baja California and Sonora, Mexico*. Instituto Tecnológico y de Estudios Superiores de Monterrey (ITESM), Campus Guaymas, Guaymas, Sonora, Mexico. 102 pp.

UMOFF, A. A. 2008. *An Analysis of the 1944 U.S.-Mexico Water Treaty: Its Past, Present, and Future*. <http://environs.law.ucdavis.edu/volumes/32/1/umoff.pdf> Accessed August 24, 2015.

U.S. BUREAU OF RECLAMATION. 1948. *Upper Colorado River Basin Compact of 1948*. Bureau of Reclamation, U.S. Department of the Interior, Washington D.C.

U.S. BUREAU OF RECLAMATION. 2005. *Quality of Water - Colorado River Basin Progress Report No. 22*. Upper Colorado Region, Salt Lake City, Utah.

U.S. BUREAU OF RECLAMATION. 2013. *Quality of Water- Colorado River Basin Progress Report*

No. 24. Upper Colorado Region, Salt Lake City, Utah.

U.S. BUREAU OF RECLAMATION, LOWER COLORADO REGION. 2015. *The Law of the River*. <http://www.usbr.gov/lc/region/g1000/lawofrvr.html>. Internet; accessed August 17, 2015.

U.S. BUREAU OF RECLAMATION and U.S. DEPARTMENT OF THE INTERIOR. 1996. An *Assessment of the Environmental Impact Statement on the Operations of the Glen Canyon Dam*. U.S. General Accounting Office Report to Congres sional Committees.

ZAMANI, K. 2015. *Effect of Glen Canyon Dam on the Temperature Regime of Colorado River.* <https://watershed.ucdavis.edu/education/clas ses/files/content/page/5%20Zamani%20Effect Glen_Canyon_Dam_on_CO_Temperature.pdf> Accessed: August 23, 2015.

ZENGEL, S., V. MERTETSKY, E. GLENN, R. FELGER, and D. ORTIZ. 1995. Cienega de Santa Clara, a remnant wetland in the Rio Colorado delta (Mexico): Vegetation distribution and the effects of water flow reduction. *Ecological Engineering* 4:19-36

ZIELINSKI, S. 2010. The Colorado River runs dry: Dams, irrigation and now climate change have drastically reduced the once-mighty river. Is it a sign of things to come? Smithsonian Magazine, October 2010. <http://www.smithsonianmag.com/science-nature/the-colorado-river-runs-dry-61427169/?no-ist>