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Downstream Effects of Damming the Colorado River

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Abstract

This paper deals with downstream riverine ecosystem effects of damming the Colorado River. The construction and operation of dams in the Colorado River have multiple benefits that include having increased water for irrigation and domestic supply, generation of hydroelectric power energy, providing improved aquatic recreation and wildlife habitat, and flood control. Damming the river has also some drawbacks. The storage of water behind dams has inundated and buried under invaluable cultural and historical artifacts. The damming and the extensive stream flow diversions for irrigation and water supply have also prevented the river water from reaching the delta area for months and sometimes for an entire year. In addition, damming the river has resulted in decreased sediment accumulation, especially in the Grand Canyon, and high level salinity and other chemical accumulations in the lower irrigated parts of the basin. Some efforts being made to ameliorate the negative effects of damming include periodic high flow experiments at Glen Canyon Dam to improve sediment dynamics, fish and wildlife habitat and the overall ecosystem along the Colorado River within the Grand Canyon. Another improvement effort being made is desalination of irrigation effluents in the lower Colorado River to improve the quality of water going to Mexico.

Keywords: Colorado River management, effects of damming a river, laws of the river, sediment dynamics, water shortage, water quality.

INTRODUCTION

Dams are structures built across rivers to collect and store surface flow from rivers and runoff from surrounding watersheds in reservoirs for eventual release when needed. The main purposes for building dams are to provide resilient and secure water supply for drinking and irrigation (Singh 2017), to control and minimize damage from floods, to increase aquatic recreation, to improve habitat for aquatic and riparian wildlife, and to generate hydroelectric power. But, there are also serious disadvantages of building dams. Dams can inundate residential and productive agricultural areas, destroy ecosystems and drawn historical and cultural remains and force people to abandon their ancestral homes, eliminate important wildlife sanctuaries and impair the aesthetic qualities of affected areas.

This study deals with the Colorado River and the effects of its damming on downstream ecosystems and the environment. The River is the most important source of water in the arid and semi-arid southwestern United States and northwestern Mexico. The river is 2,352-kilometers long with its main headwaters located in the Rocky Mountain National Park in north-central Colorado and Wyoming, and ending up in the Gulf of Mexico. Along the way, it forms 27 kilometers of the international boundary between Arizona and Mexico (U.S. Bureau of Reclamation, Lower Colorado Region 2016). The main stem of the Colorado River, its tributaries, and the surrounding watersheds together are called the Colorado River basin. The Basin has an area of 637,000 km^2 spreading in seven U.S. southwestern states (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) and two Mexican states (Baja California and Sonora) (Figure 1).

Figure 1. Location of the Colorado River Basin in the US Southwest and Mexico's Northwestern corner (https://www.centralbasin.org/).

Seventy five percent of the Colorado River basin is in federal lands consisting of national forests, national parks, and some Indian reservations. The total runoff rate from the entire drainage basin' is about 700 cubic meters per second (Colorado River Research Group 2014). About 90% of the Colorado River flow originates from the Upper Basin, above Lee Ferry mostly from precipitation that falls as snow in the three states of Colorado, Utah and Wyoming. However, more than 80% of the stream flow is lost as it travels downstream along the drier lower basin states of Arizona, Nevada and California through evapotranspiration, water diversion for irrigation, recharge to the ground, and withdrawal for domestic water supply (Hundley 1986; Colorado Foundation for Water Education 2016; Miller et al. 2016).

For hundreds of years, the Colorado River played a significant role in shaping the history and economic development of the southwestern United States. It started with Native Americans who used the water from the Colorado River Basin to irrigate farm crops (Glenn et al. 1996). One Native American tribe, the Cocopah Indians who reside in the Colorado River delta thrived through farming and fishing for about 2,000 years. Their activities were all in harmony with the environment and with little or no adverse effects on the riverine ecosystem. The latter started to change with the settlement of the pioneer Euro-American population during the last two hundred years. The new comers used the Colorado River water to develop extensive irrigated farms and built large communities with their insatiable demand for water. This unfortunately has led to the draining almost dry of the Colorado River before reaching the delta, and thus depriving the Cocopah Indians their main source of living (Zielinski 2010). In spite of the latter, irrigation still remains as the main economic stay upstream from the delta. Other equally important uses of the Colorado River water are providing drinking water supply to various communities, and generating hydroelectric power. For these purposes, 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 transports water for irrigation and domestic supply to the Phoenix and Tucson metropolitan areas in Arizona. Similarly, 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 50 million people in the U.S. Southwest and 3 million others in Mexico depend on the Colorado River for their water supply, while about 70% of the River's water is taken out to irrigate over 20,000 km^2 of cropland in the basin (Zielinski 2010; Miller et al. 2016).

THE LAWS OF THE RIVER

In the 1800s, many growing communities along the Colorado River diverted water from the River and its tributaries without any restrictions. As diversions increased with time, however, an unending battle over apportionment of the Colorado River water ensued. Today, the 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 guided by one or more of the regulatory mechanisms summarized below. The authorizations are in the form of compacts, federal laws, court decisions and decrees, contracts, and legal guidelines collectively known as the "Laws of the River" (Colorado River Commission of Nevada 2006). The authorizations fall into one of 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 regulates and assigns the uses and management of the Colorado River water among the seven U.S. basin states and the two Mexican states (U.S. Bureau of Reclamation, Lower Colorado Region 2016). The following is a synopsis of the most significant legal descriptions that together 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. The rights are considered to have been established at the time when the reservations were created. Furthermore, the decision stipulates that states in which reservations are located must fulfill the particular tribe's water right needs within their respective states.

(2) **The Colorado River Compact of 1922** is an interstate agreement that has the characteristics of a statute but the enforcement of a contract; it is interpreted according to the federal common law of contracts whenever there is a congressional consent to the agreement. This means, the agreement was approved by Congress and has become the law of the land. As such it remains the legal document for court decisions such as the case of *Texas v. New Mexico, 482 U.S. 124, 128* (1987). In a sense, the Compact has become the cornerstone of the "Laws of the River" as it represents the negotiated apportionment of the Colorado River water among the seven Basin states in the USA and the two Mexican states. It defines the relationship between the upper basin states (comprising of Colorado, New Mexico, Utah and Wyoming), where most of the river's water supply originates, and the lower basin states (consisting of Nevada, Arizona, and California) in the USA and the two Mexican ones, where most of the water demands occur. The compact requires the Upper Basin states not to deplete the annual flow of the river below 9.2511 Kilometer cubic (km^3) during a period of any ten consecutive years while at the same time simultaneously developing state and federal water works projects by the United States Bureau of Reclamation to enable a wide spread irrigation in the lower states of

the Colorado River Basin. The projects include the constructions of Hoover Dam and Glenn Canyon Dam. But, such developments have not been without some serious challenges and constraints. To begin with, the water allocation decision among the upper and lower basin states was made on the basis of rainfall patterns observed on wetter years before the treaty's signing in 1922. Since then, the amount of available water has fallen short during dry periods and during normal years when shortfalls occur. Also, the compact did not include concern on Indian water rights, nor did it consist of any provisions to protect the environment (Colorado River Research Group 2014, 2016). The latter two had to be rectified later with new regulations.

(3) **The Boulder Canyon Project Act of 1928 (***Public Law No. 642*) was enacted for purposes that include: (a) ratifying the 1922 compact; (b) authorizing the construction of Hoover Dam and related irrigation facilities in the lower Basin; (c) distributing the lower basin's 9.25 km^3 per year of flow among the states of Arizona (to receive 3.454 km^3 or 37.3%), California (to get 5.43 km^3 or 58.7%) and Nevada (to have a mere 0.37 km^3 or 4%); and (d) authorizing and directing the Secretary of the Interior to function as the sole deciding officer in charge of management and use of the water in the lower Colorado River Basin**.**

(4) **The California Seven Party Agreement of 1931** is an accord to help settle a long-standing legal dispute among seven different California agricultural and municipal users of 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 claimants reach a consensus on the amounts of water each can have annually. Even though the agreement did not resolve all water allocation issues, the regulations set forth have been incorporated into and have become parts of all major California water apportionment contracts made since then.

(5) **The Mexican Water Treaty of 1944** is an agreement on the use of the waters of the Colorado, Tijuana and the Rio Grande rivers. This agreement allocates 1.85 km^3 of the Colorado River's annual flow to Mexico. The amount, however, is not a part of the 18.5.km^3 per year of water divided between the Upper and Lower basin states of the United States. The treaty also sets aside an additional 1.36 km^3/year of water for the lower basin states 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 half of the annual Colorado River flow of 9.25 km^3 per year among the Upper Basin states of Colorado (with 4.76 km^3 or 51.47%), New Mexico (with 1.04 km^3 or 11.20%), Utah (with 2.11 km^3 or 22.8%), and Wyoming (with 1.283 km^3 or 13.86%). Arizona, also receives an

additional 0.0617 km^3 (or 0.67%) annually for its portion that geographically lies within the Upper Colorado Basin (U.S. Bureau of Reclamation 1948).

(7) **The Colorado River Storage Project Act of 1956 (***43 USC 620***)** is the legal basis for the decision that authorized the comprehensive Upper Basin-wide water resource developments that include the construction of Glen Canyon, Flaming Gorge, Navajo and Curecanti dams. The purpose for the decision was to regulate the river and store water for domestic supply, irrigation, hydropower generation, recreation and other uses.

(8) **The Arizona v. California U.S. Supreme Court Decision of 1963** settled a 25-year-old conflict between Arizona and California. The dispute arose due to Arizona's desire to build the Central Arizona Project (CAP) to get its full portion of the Colorado River water. In opposition to this idea, California argued that the water from the Gila River, a Colorado River tributary, which Arizona uses should constituted as its portion of the Colorado River water. Besides, since California had already developed a historical use of some of Arizona's share, the doctrine of prior appropriation should preclude Arizona from developing the project. The case was thrown out by the Supreme Court, which ruled that the lower basin states have the right to appropriate and use tributary flows before the tributaries co-mingle with the Colorado River. This means the doctrine of prior appropriation does not apply to water apportionments previously made in the lower basin (MacDonnell 2003). The decision was followed by a Supreme Court **Supplemental Decree** in 1979**,** which perfected the rights set forth by the Colorado River Compact and the Boulder Canyon Project Act. Those rights are entitlements essentially established under states' laws, and have priority over any 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 Arizona's CAP. The law stipulated that divergence of water by the CAP during periods of water shortage be subordinate to California's apportionment. It also directed the Secretary of the Interior to prepare, in consultation with the Colorado River Basin states, long-range operating guidelines for the entire Colorado River reservoirs system.

(10) **The Criteria for the Coordinated Long-Range Operation of Colorado River Reservoirs of 1970 (***Public Law 90-537 as amended on March 21, 2005***)** was enacted to permit a coordinated operation of upper and lower basin reservoirs and set conditions for the releases of water from Lake Powell and Lake Mead. The conditions for the releases are historic stream flow levels, knowledge of upper basin storage depletion amounts, probable water supply availability and the assurance of non-impairment of upper basin consumptive use.

(11) **Minute 242 of the U.S.-Mexico International Boundary and Water Commission of 1973** requires the U.S. to reduce the salinity of the Colorado River water delivered to Mexico at Morelos Dam. The minute declares that only limited groundwater can be withdrawn from both sides of the U.S. - Mexico border and requires each nation to consult the other on any future groundwater development. For a number of reasons, one of them being a rift between states and the federal government on the authority to control water rights, the agreement still remains difficult to apply (Mumme 2010).

(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 promulgated to ensure the compliance of the United States' obligations to Mexico made under Minute No. 242. The major features of the Act include construction of a brine discharge canal and a desalination plant for the treatment and conveyance of the discharge from Wellton Mohawk Irrigation and Drainage District (*Title I of the Act*). Accordingly, the United States is expected to deliver water to Mexico that have an average salinity of 115 plus or minus 30 parts per million (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 for twelve 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 to protect it from any adverse impacts while at the same time improving the conditions 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 consistency with the other "Laws of the River" that govern the allocation, appropriation, development, and exportation of the Colorado River Basin waters.

(14) **The Arizona Water Settlement Act of 2004** (*Public Law 108-451*) was authorized by President George W. Bush. The legislation provides some adjustments to the allocation of the CAP water and the settlement of the litigation between the United States and the Central Arizona Water Conservancy District concerning repayment for the CAP. The Act includes the Gila River Indian Community Water Rights Settlement and the Southern Arizona Water Rights Settlement Acts of 1982. It also provides funding for the Gila River Indian Community and the Tohono O'odham Nation's rehabilitation and expansion of their water infrastructures to meet the needs of their respective reservations.

(15) **The Water Rights Settlement between the State of New Mexico and the Navajo Nation** was signed on April 19, 2005 to resolve the Navajo Nation's claim to the use of the San Juan River Basin water in northwestern New Mexico. The

intention of the settlement was to adjudicate the Navajo Nation’s water rights and to provide associated water development projects for the benefit of the Tribe, and in exchange for a release of claims to water that can 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 that solves current problems but also prepare ahead of time for future droughts or surpluses rather than waiting to respond to future disruptive litigations. The decision implements new and interim operational guidelines that meet the challenges of current drought in the basin, and the low-water conditions that would be created 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, operation and maintenance, and water allocation, there are many laws and regulations related to power generation and its sale and distribution, adjudication of Indian water rights, and water quality control. These laws consist of 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 unhindered with little or no human interference. In its natural state, the Colorado River, especially during the pioneer and Euro-American settlement periods of the West, was viewed as a "natural menace"' that affected human movement instead of an asset. Even then, the River had many invaluable ecological and environmental values as it flowed unimpeded to the Gulf of California, 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 2407 m^3/s while the highest flood in record was 5946.5 m^3/s. The river also had temperatures that fluctuated between 0.2 to 28°C, salinity that ranged from 200 to 1300 ppm and sediment inputs into the Grand Canyon that reached up to 57 billion kilograms per year, 20% of which coming from the Paria and the Little Colorado rivers (Topping et al. 2000; Grams et al. 2015; George et al. 2016).

It has taken only less than 100 years and the above "Laws of the River" for the Colorado River to become physically and commercially developed. In the process, the River has been dammed, desilted, and diverted to irrigate crops, produce hydropower, provide sites for recreation and serve as a source of water to nearby and distant cities, towns and other communities (U.S. Bureau of Reclamation, Lower Colorado Region 2016). 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 distributed (four in Colorado, five along the border between Arizona and California, two between Arizona and Nevada and one in Arizona) along the 2352 kilometer distance of the River. The capacities of the reservoirs in the main stem range from 0.023 km^3 to 35.7 km^3 with the total capacity of all the reservoirs being 72 km^3. In addition, there are 20 other dams in tributary streams (13 of them in Colorado, five in Utah and one each in New Mexico and Wyoming). These dams have reservoirs with capacities that range from 0.068 km^3 to 4.67 km^3 and a total capacity of 12.12 km^3 in the upper basin. The lower basin has 11 dams along tributary streams (10 of them in Arizona and one in Utah) with reservoir capacities that range from 0.063 km^3 to 3.59 km^3, and a total capacity of 11.34 km^3. Most of the reservoir capacities listed are the original design capacities and do not account for any sedimentation and other aggradation and degradation that may have occurred since construction and operation of the reservoirs (Colorado River Research Group 2014).

The dams were built in an era that can be referred to as the Age of Impoundment during the fifty years ending in the 1970s. In that period close to 35,000 dams were constructed around the world, to obstruct, store and divert the natural flow of rivers. The two biggest dams at the time, Hoover Dam and Glen Canyon Dam were built in the Colorado River. The larger of the two, Hoover Dam, is the first major project in the Colorado River. It was built during the Great Depression and completed in 1935. The dam stands more than 213.4 meters tall, has a reservoir capacity of 35.7 km^3 and stretches for a distance of about a hundred sixty kilometers upstream. With these characteristics, 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 completed in 1963 and when it is full, the reservoir, which is called Lake Powell, stretches for a distance of more than 322 kilometers upstream. In terms of physical size, Glen Canyon Dam is still one of the largest dams in the United States. It rises 216.4 meters over the bedrock and 194.5 meters above the original river bed. The original capacity of Lake Powell is second to Lake Mead and could hold 32.34 km^3 when it started operating. Altogether, there are more than 93 reservoirs in the upper and lower basin states that control the Colorado River Basin. The total costs of constructing the dams and the reservoirs and associated water supply infrastructures are $4.7 billion and $4.125 billion, respectively (Colorado River Commission of Nevada 2006). These expenses do not include the costs for non-federal dams, which contribute significantly to the basin's water impoundment. Collectively, all the dams in the Colorado River basin can hold four to five times the river's annual flow amount, and as a whole it is used to generate hydroelectricity and provide water for irrigation and municipal water supply for use in the U.S. Southwest and the Mexican side of the region (Schuster 1987; Cohen et al. 2001; Colorado River Research Group 2014; Miller et al. 2016).

The Benefits of Damming the River

The Laws of the River described above are designed to help manage the Colorado River and its tributaries efficiently, sustainably and equitably to meet multiple demands. For thousands of years, communities in many areas around the world have dammed rivers to store water for irrigation, to provide domestic water supply and to generate hydropower 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 at first in response to the slow migration of people westward in the nineteenth century. With rapid population movement to the area since then, the Colorado River has become exhaustively dammed to become the lifeblood of the fast-paced economic growth in the Southwest; and the benefits have been remarkable.

The beneficial outcome of building dams may vary depending on whether they are in reference to their effects upstream or downstream from the dam. Most upstream benefits may come in the form of storing water for various uses, aesthetics and providing recreational opportunities (Mehta et al. 2012). The reservoirs behind the dams in the Colorado River have been used for boating, fishing and other water sports. For example, the Glen Canyon National Recreation Area, mainly consisting of Lake Powell hosts more than three million visitors every year, many of them on houseboats and other pleasure crafts. Altogether, the various recreational activities alone fueled a $26 billion economy to support a quarter of a million sustainable recreation-related jobs in Arizona, California, Colorado, Nevada, New Mexico, Utah, Wyoming, and across the border in Mexico. Other upstream benefits are in the form of providing water supply to irrigate expansive farmlands in the arid and semi-arid areas of the southwest, and to provide drinking water supply to the growing population in 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 also serve as valuable habitat for many species of fish, other aquatic wildlife, and numerous riparian flora and fauna though most of them are exotic that have invaded the area and replaced native species following the lake formation. Another major benefit of dams is their contribution to the amount of water that seep into the underlying groundwater aquifers in the area (Mehta et al. 2012).

The vast spaces under and on the sides of reservoirs are suitable and convenient areas for both groundwater recharge and discharge that affect the amount of water stored in the reservoirs. This is so because there is an intimate interaction between the groundwater in the aquifer under reservoirs and the surface water stored above. Such relationships usually make dams effective structures for increasing stored groundwater during wet periods. Such stored water can then be pumped to augment water supply during times of water shortage and droughts. Conversely, the reservoirs behind dams and the streams below them can benefit from groundwater discharges that come in the form of springs from mostly shallow aquifers beneath surrounding watersheds. This is baseflow, the source for about 56% of the stream flow in the upper basin and 86% of the flow during low-flow conditions in the lower basin of the Colorado River (Castle et al. 2014; Scanlon et al. 2015; Miller et al. 2014, 2016). This indicates the importance of having adequate knowledge and understanding of the quantitative relationships between groundwater and surface water in the Colorado River Basin. This would allow for water resources mangers and policy makers to adopt conjunctive water resources management to meet current and future water resource demands in the Basin (Castle et al. 2014; Miller et al. 2016).

A very important point to note in this paper is that the dams in the Colorado River Basin are built to provide critically needed downstream goods and services. Some dams are built to contain excess flow to protect downstream communities, agricultural farms and other installations from damaging floods. Others like the Glen Canyon Dam were partly built to store water and /or regulate erratic flow and guarantee water availability for downstream users. Also, the stored water behind the dams generates more than 4200 megawatt of hydroelectricity that serves about 15 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 store water that irrigates over 20,000 km^2 of mostly arid agricultural land, and provides water for residential, commercial and industrial uses (Colorado River Commission of Nevada 2006; U.S. Bureau of Reclamation 2012; Miller et al. 2014, 2016). For example, the Central Arizona Project supplies needed irrigation water for the vast agricultural areas and drinking water to the growing metropolitan areas of Phoenix and Tucson and many other communities in the valley. Another structure in the Basin, the All-American Canal provides water for the Imperial Valley of southern California, a productive agricultural region converted from a desert wasteland. Without the water from the Colorado River, huge swaths of arid and semi-arid land would not have been converted into highly productive farmland that produce a variety of rich agricultural crops in the lower Colorado River Basin.

The Drawbacks of Damming the River

With the damming and expanded use of the Colorado River, there are profound changes that have occurred in the Basin. Many large fertile agricultural areas, invaluable cultural remains, areas of natural beauty, wildlife habitat and valuable environmental treasures along and away from the river are inundated and covered by lakes that backup for hundreds of kilometers upstream from the dams. Aquatic and terrestrial habitats are altered to the extent that many native plant and aquatic animal species have become endangered and even extinct due to either submergence under water or changes in habitat characteristics due to water shortage (Glenn et al. 1996; Colorado Foundation for Water Education 2016). These are happening because recent and new societal demands for water and energy seem to go on a collision course with vested legal rights and past commitments (Colorado River Research Group 2016). This has become more serious with time when the rapid population growth (both through internal growth and immigration), and the mammoth economic forces operating in the area are converging to competitively exploit the scarce water available in the Colorado River Basin. Such a scramble for these resources has significant quantitative and qualitative implications, which are described in some detail below.

Effects on the amount of stream flow

The damming of the Colorado River and the extensive diversion of its water for irrigation and domestic water supply have prevented the river water from reaching the coastal lowlands in the delta for many months of the year and sometimes for the entire year. This condition has seriously detrimental effects on downstream ecosystem conditions and the very survival of communities like the Cocopah Indians and other lower basin water users that depend on the Colorado River. This type of problem is by no means unique to the Colorado River Basin as the effect of the Kpong Dam in Ghana demonstrated (Owusu et al. 2017). To deal with such problems in the Colorado River Basin, the first ten laws and regulations under the "Laws of the River" which are exclusively related to the quantitative control and distribution of the Colorado River are issued for implementation. These laws 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 to irrigate downstream farmlands to provide reliable water supply for Arizona and southern California and to control the flow of the Colorado River. As a result of the significant retention of water in the reservoirs, or lakes behind dams such as Glen Canyon Dam, there have been considerable reductions in the regular and peak flows downstream (Colorado Foundation for Water Education 2016). This is demonstrated in Figure 2 where pre- (1921-1963) and post- (1964-2015) Glen Canyon Dam average monthly flow rates at Lee Ferry are compared. The graph shows a difference of 850 m^3/s (that is a 60% decrease) between the pre-dam (1416 m^3/s) and the post-dam (566 m^3/s)

peak flows. It should be noted that the post-dam flows do include the six individual releases of experimental high flows (EHFs) ranging from 1048 to124 m^3/s in size that lasted for 24 to 168 hours in duration.

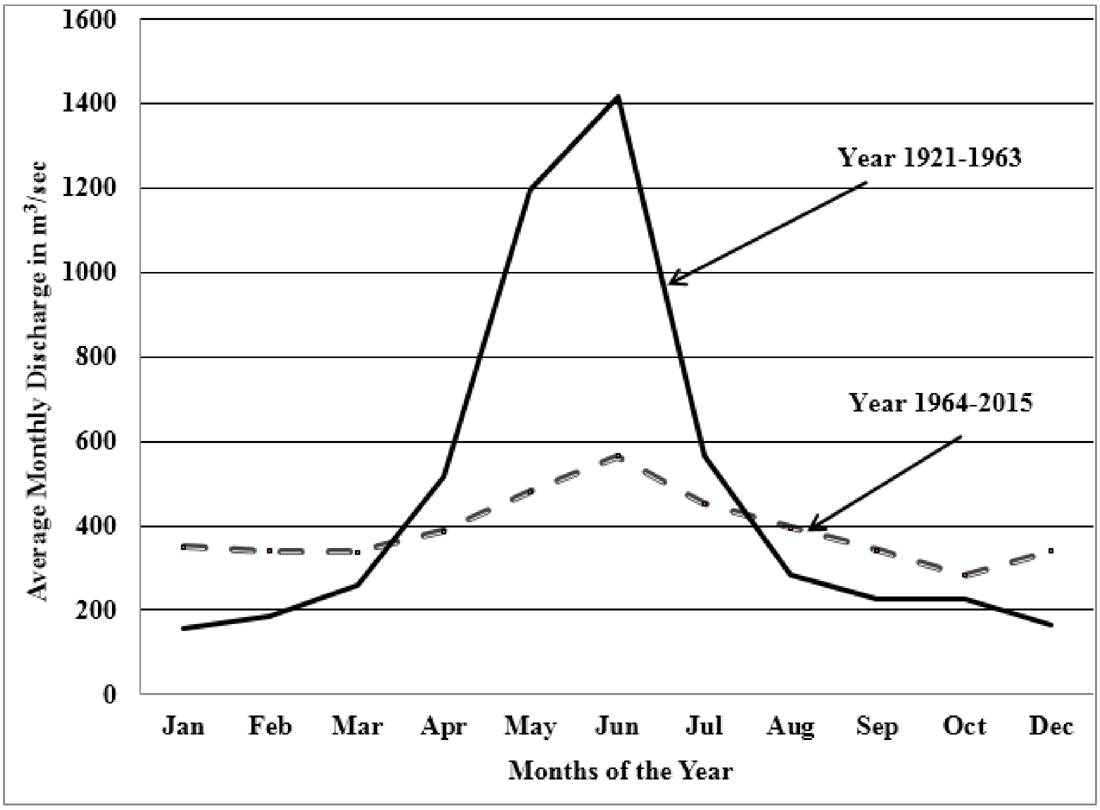

Figure 2. Comparison of Pre-Dam and Post-Dam monthly average flows of the Colorado River at Lee Ferry, Arizona.

The quantitative impacts of damming the Colorado River and the post-dam state of its downstream flow are more visible in the delta area where stream flows drastically decrease and at times disappear for months (April, June, July and August in particular) during the warm season and at times for the entire year (Lavín and Sánchez 1999; Lustgarten 2016). This is demonstrated, respectively, in Figure 3, which shows the monthly average amounts of flows for the post dam period of 1964 - 2015 and Figure 4, which shows the monthly flow magnitudes for a single year (2015) at Kilometers 27 and 38 south of the international boundary with Mexico and north of the delta (Albert Flores, personal communication, December 20, 2016). The closer the river gets to its mouth the drier it becomes. This is because most of the stream flow is consumed upstream in the lower Colorado River basin in the U.S.A. and the Mexicali farms in Mexico before it reaches the delta (Colorado Foundation for Water

Education.2016). Note that the 1964-2015 monthly average flow in Figure 3 is substantial (with some decreases due to lower snowmelt on the headwaters in February) in the upper gaging station at Kilometer 27 while decreasing drastically in the lower gaging station at Kilometer 38. In contrast, Figure 4 shows a complete absence of flow at both gaging stations in February, and July through December, and throughout the year in the lower gage at Kilometer 38. This lack of water in the delta is the cause for the near disappearance of the Cocopah Indians from their ancestral land. The tribe's present status is summarized by Onesimo Gonzales, a village chief of the Cocopah Indians, when he said in 2001 "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 of the delta area when he travelled 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).

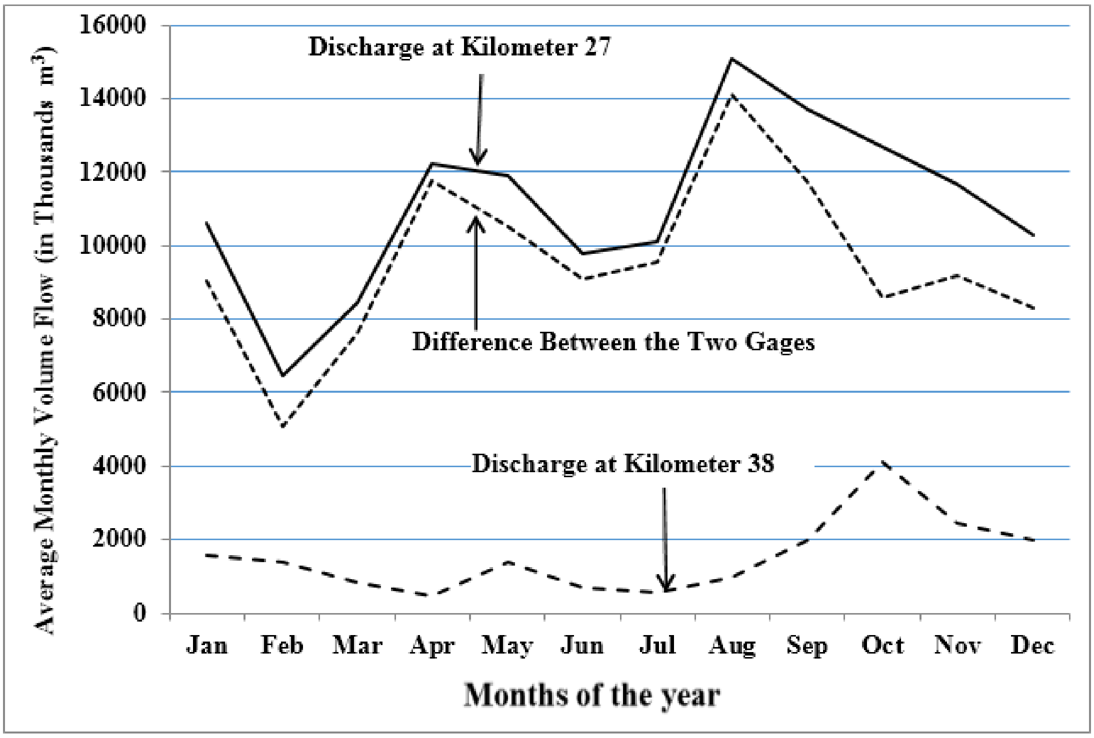

Figure 3. Average monthly discharge for the post-dam years of 1964 -2015 of the Colorado River at Kilometers 27 and 38 south of the U.S.A - Mexico border.

The ecosystem of the lower Colorado River Basin has been steadily declining from the time of Leopold's observation when it was green and lashes to the time of Gonzales' lament on its ecological demise. Now, the Colorado River delta is a wetland

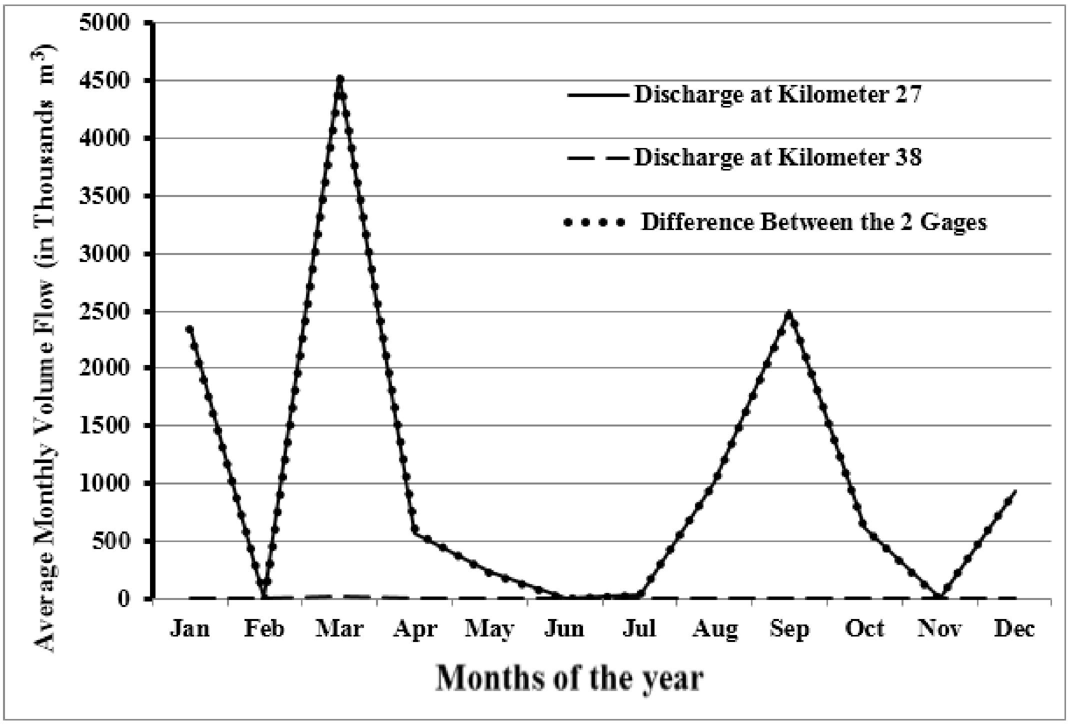

Figure 4. Monthly discharge for the year 2015 of the Colorado River at Kilometers 27 and 38 south of the U.S.A - Mexico border.

remnant that has become the subject of growing scientific and political concerns. Such observations have led to a continuing research on the ecology and restoration of the Colorado River delta with special emphasizes to finding natural and anthropogenic sources of water to sustain the delta habitats (Glenn et al. 1996, 1999; Morrison et al. 1996; Pitt et al. 2000; Lowry 2003; Medellin-Azure et al. 2007; Colorado Foundation for Water Education 2016). In this light, vulnerability analysts are racing to determine the amount of quality water that would be needed to maintain the ecological integrity of the Lower Colorado River to support healthy ecosystems at a time of widening imbalance between supply and demand for water (Sheer et al.1992; Glenn et al. 1999; Colorado Foundation for Water Education 2016).

Figure 5 shows the steady increase in the average demand for water in the Colorado River Basin. With the rapid development of the Southwest, the demand (consumption) for water had surpassed the average supply briefly in the late 1990s and continuously since early in the 2000s (Colorado River Research Group 2014). This milestone seems to have passed mostly unnoticed, while proving to be incredibly salient, as it increases vulnerability for drought. This makes the Colorado River to be operating at a dangerously water deficit for which it is rightfully referred to as the nation’s Most Endangered River by a leading river conservation organization, the

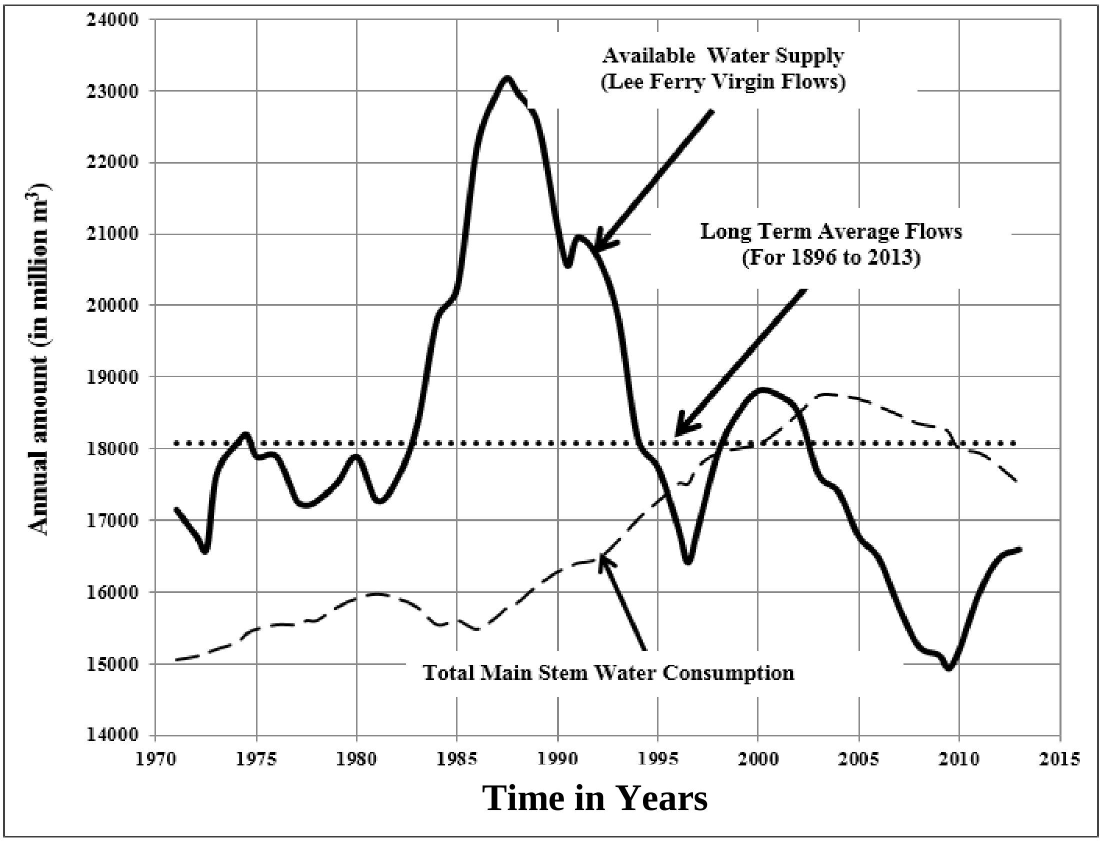

Figure 5. Average water Supplies versus Demands on the Colorado River Main stem (10-year averages) (mostly based on Colorado River Research Group 2014)

American Rivers (Cohen et al. 2001; Colorado Foundation for Water Education 2016). The bottom line is that more water is currently being taken out along the river's arid path than is obtained from annual rain and snow melt on its headwaters and from groundwater discharge along its downstream flow path. This means the overall demand for Colorado River water exceeds the supply and if the Colorado River were a business it would be considered operating “in the red” (Wildman and Forde, 2012; Colorado River Research Group 2014). Unfortunately, the problem is more seriously exasperated with the on-going climate change in the southwest. According to a recent study by Udall and Ovepeck (2017), the annual average flow of the Colorado River between the years 2000 and 2014 shrank by 19% compared with the average for the years 1906 to 1999. According to these researchers, most of the loss is due to an unprecedented rise in temperature of 0.9^0C over the years 1906 - 1999 average.

Effects on downstream sediment accumulation

Other important quantitative and qualitative impacts of damming the Colorado River are 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. Reduced supply and transport of sediment have been observed as factors responsible for the degradation of the post-dam Grand Canyon ecosystem. Sediments provide both nutrients and substrate for growing plants; serve as habitat for fish and wildlife, and form beach for recreational use by visitors into the Canyon. The construction of Glen Canyon Dam has brought major changes to the ecosystem of the Colorado River downstream of the dam. One of them happens due to the trapping behind the Dam all the sediment and nutrients that come from the 279,300 km^2 watershed area above the Dam (Ingebretsen 1998; Grams et al. 2015). Prior to the dam construction, there were distinctly high and low flow periods that coincided with seasonal and annual climate variations. Low flow periods accumulate sediment in alluvial plains via erosional and aeolian depositional processes (George et al. 2016; Maffly 2017), and thus minimizing long-term erosion of sandbars in the Canyon. High flow periods usually coincide with monsoonal rains and spring snow melts. The floods spread the stored sediment along the river channel and surrounding floodplains to build sandbars. Dam controlled flow patterns and the sediment entrapment behind the dam have altered the natural processes that created the Grand Canyon through long period of erosional processes (Ingebretsen 1998; Topping et al. 2000; Grams et al. 2015). Sediment deficiency 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 (Melis 2011). So far six HFEs have been conducted with some success in achieving long-term desirable restorative effects throughout the Canyon, while also resulting in localized aggradation in some areas and degradation in others (Lane 2014; Grams et al. 2015). The only certainty 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.

Another effect of damming a river is downstream sediment deposition, which affects the fertility and use of riparian areas and floodplains. For example, the delta at the mouth of the Colorado River has been drastically changed by deposition of sediments from periodic flooding. This has reduced the size of the Colorado River delta from some 12,577 to 971 square kilometers (Glenn et al. 1999; Medellin-Azure et al. 2007; Galindo-Bect et al. 2013).

Effects on downstream water quality

In addition to their having adequate amount of quality water supply, the economic and social well-being of major cities and rural communities in the Colorado River Basin are inextricably linked to 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 socio-economic development that ensued. There are many qualitative and quantitative factors that influence the health of a river. The factors may be physical, chemical and biological in nature. The post-dam downstream changes in the Colorado River are manifested in the form of low stream flows and changes in chemical content and sediment accumulation. There are also observed changes in the water temperature especially immediately below the dam. The water temperature regime there is typically altered by the dam and is largely determined by the depth in the reservoir from which the released water is pulled out. Deeper water is typically colder. Also the river water temperature downstream from Glen Canyon Dam varies with release time and the distance from the Dam. Generally, temperatures are warmer in warmer months and colder in colder months. It is also determined that post-dam temperatures are colder than pre-dam, but there is a much lower fluctuation in post-dam temperatures than those before the construction of the dam (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 aquatic organisms such as fish and mussel populations. This happens because many organisms have evolved with a specific temperature regime and are not suited to adapt to rapidly changing temperatures.

One other important qualitative downstream impact of damming the Colorado River has to do with chemical-related changes to water quality. For the purpose of this paper, the chemical quality in the Colorado River Basin may be expressed in terms of salinity (U.S. Bureau of Reclamation 2005, 2013). 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 expressed in a river as either in terms of concentration (mass per unit volume) or in terms of load (mass per unit time), or in parts per million. The numerical threshold Standards for salinity in the Colorado River, which increase with distance downstream, range from 723 ppm at Hoover Dam to 879 ppm at Imperial Dam near the Mexico border (Morford 2015). The sources for the 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, weathering of saline rock and surface runoff, which together amount to 47% of the River water salinity. The main anthropogenic salinity sources are irrigation, reservoir evaporation, and mining and industry, which contribute 37%, 12%, and 4% of the total salinity load in the Colorado River water, respectively (U.S. Bureau of Reclamation, 2005, 2013). Altogether, the Colorado River transports between 6.35 and 8.165 billion kilograms of salt annually to the Gulf of California depending on climate 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 735.5 grams of salt per cubic meter (g/m^3) of water (U.S. Bureau of Reclamation, 2013). As a result, the Bureau of Reclamation estimates that salinity contributes more than $306 million dollars a year to the economic damage of the Colorado River Basin, with roughly half of it coming from 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 1180 million kilograms of salts from entering the Colorado River (U.S. Bureau of Reclamation, 2005, 2013). The primary prevention methods used 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 salt discharge such as by pumping from different depths in large dams. As shown in Figure 6, the long term effect on the salinity of Glen Canyon Dam is positive. In spite of a slight fluctuation from year to year, there is a significant decrease in the amount of salinity and its periodic fluctuations with time in the Colorado River below the Dam since the dam was put into operation in 1964 (U.S. Bureau of Reclamation 2013). The main reason behind the decrease in salinity may be settlement of most of the sediment coming from upland watersheds in the bottom of the reservoir behind the dam. This decreases the amount of salt in the water passing through the dam in the Colorado River within the Grand Canyon.

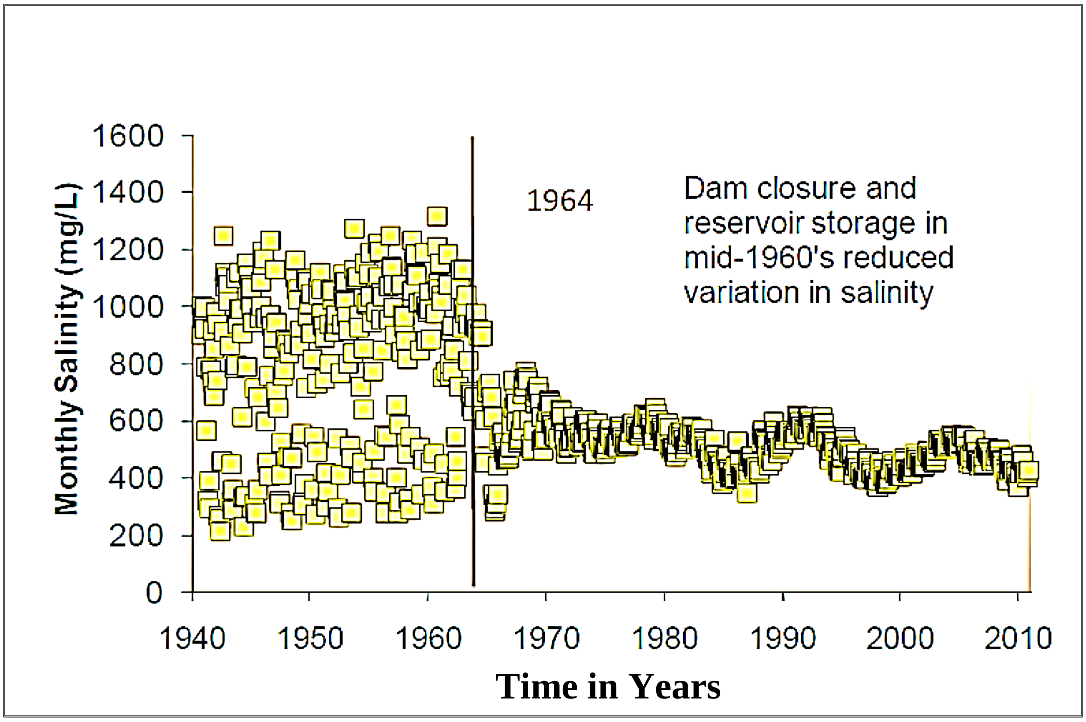

Figure 6: Effects of Glen Canyon Dam on Colorado River Salinity at Lee Ferry (Bureau of Reclamation 2013)

With the construction of the dams, the Colorado River has gone through various critical changes that have affected the biota in the River. Prior to damming the River, water rushed through canyons at various amounts and speeds continuously changing all aspects of stream dynamics. High velocity flowing water scoured canyon walls cleansing debris along its paths, removing sediments containing harmful trace minerals that when accumulated become toxic to the ecosystem (Ingebretsen 1998; Grams et al. 2015), while at the same time changing the depth and the carrying capacity of the canyons. During the pre-dam period, extreme fluctuations in the flow of the Colorado River provided good habitat for various fish such as carp, catfish, razorback and bluehead suckers, humpback and bonytail chub, speckled dace and the Colorado squawfish, most of which are endangered today (USBR and USDOI 1996; Colorado River Research Group 2016). With the construction of the dams, however, the qualities of water and aquatic habitat in the Colorado River became significantly reduced. For example, the changing pre-dam natural water temperature range of 0^{o}C to 26.67^{o}C has become relatively constant at 7.78^{o}C following the construction of the dam (USBR and USDOI 1996; Colorado River Research Group 2016). Likewise, the river water below Glen Canyon Dam has become practically devoid of nutrients as most of the chemicals remained bound to the sediments in the bottom of the reservoir behind the dam (Lin 2011). Also, otherwise harmless, trace metals and various salts, such as selenium, arsenic, and mercury, when trapped in the stationary sediments behind a dam can accumulate and become harmful and even lethal. Such chemicals may become incorporated into the floating planktons and zooplanktons in the river, and eventually get distributed throughout the food web to have significantly damaging effects on the flora and fauna thriving in the River. Also the effect of damming on water quality and flow characteristics may stimulate the introduction and propagation of exotic species including various species of trout and other game fish, like striped, large and small mouth bass, black crappie, walleye, bluegill sunfish, and channel catfish (USBR and USDOI 1996). Such exotic species tend to outcompete the weakened, endemic native species which are often specialists whose specific niche easily becomes destroyed. Similar conditions have been leading to the threat and endangerment and even elimination of native fish species and other aquatic organisms in the Colorado River.

Elimination of flooding in the post-dam period at first led to proliferation of riparian vegetation downstream from Glen Canyon Dam. The absence of natural seasonal flooding at first had led to abundant and diverse vegetation growth on the sandbars and canyon walls in the Grand Canyon of the Colorado River (Marzolf 1999). Howeveer, as the years pass by the sandbars become eroded due to the absence of stream flow with enough strength and adequate amount of silt or sediment load to create new sandbars. This phenomenon decreased the health and vigor of the vegetation in the Canyon for a while until the high flow experiments (HFEs) started in 1996 (Lane 2014). As stated previously, there have been six HFEs released since

1996 to help maintain and restore downstream flood dependent resources without any significantly adverse effects on the physical infrastructure, the environment, the "Laws of the River" and the demands for water and energy. These artificial floods have been successful by providing the amount of flow and sediment concentration needed to rebuild sandbars, sustaining food and substrate for healthy riparian vegetation growth and improving habitat for wildlife and other riparian organisms in the Colorado River within the Grand Canyon (Melis 2011).

CONCLUSIONS AND RECOMMENDATIONS

Since early in the 1900s, the Colorado River Basin states have been very much concerned about the increasing demand for Colorado River water and its fair allocation among its claimants. These have become more serious with the increasing population growth, 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 than 15 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 and agreements in order to meet new challenges, address unmet demands and arrive at more fair and equitable distribution of the dwindling river water among the seven U.S. and two Mexican states. The problem of water shortage along the Colorado River has worsened since the 1990s when the demand for water has exceeded the supply (see Figure 5). As a result, except in years with unusually high precipitation and runoff, virtually the entire flow of the Colorado has been captured and used (see Figure 4, for example) before reaching the river’s mouth (Morrison et al. 1996; Owen 2015).

To deal with the increasingly unmet demand in the lower Colorado River basin, there needs to be changes in the way water is apportioned among claimants and to promote a more comprehensive management scheme that includes knowledge and inclusion of groundwater resources in the basin. This is especially true with the recurring drought and the prevalence of climate change in the Southwest (Christensen et al. 2004; Medellin-Azure et al. 2007; Castle et al. 2014), which have worsened the shortage and unavailability of water in the region. To ameliorate the problem, there needs to be a management scheme that includes, first, issuing new laws and regulations that lead to designing advanced, realistic, science-based and data-supported management of the River to allocate what is there rather than what ought to be. Second, since groundwater is heavily used in the basin and about 58% of the water in the river is groundwater base flow, water management should use conjunctive approach to incorporate the intimate interrelationship and interactions between groundwater and surface water in the basin. Third, given that the river water is used for multiple purposes such as irrigation, hydroelectric power generation, drinking water supply for a rapidly growing population, and for industrial, recreational and other uses, there needs to be a clear understanding, and concrete efforts to promote collaboration and partnership among all interested parties in determining the priorities for apportioning and use of water (Harrington 2017). Likewise, decisions must be made in a multi-objective, collaborative, holistic, sustainable, adaptive and evidence-based to avoid conflicts and resolve issues that arise in an amicable, fair and just manner (Tecle and Duckstein 2010; Basdekas 2014). Under such a situation, there is a good chance for groups even those sharply in conflict with each other to come together and reach a compromise solution and accept mutually beneficial and environmentally friendly and sustainable management of the water, related resources and the ecosystem in the Colorado River Basin.

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