STEPHY Publishers

Global Scientific Research in Environmental Science

Research Article

Assessment Risk of Water Supply in The Lower Colorado River Watershed

Juan M. Stella*

Tecnológico de Monterrey, Monterrey, México

Abstract

This research endeavors to quantify the risk to the future water security of the Mexicali Valley. This risk is specifically assessed under the projected scenario of potential discharge restrictions from the Colorado River, mandated by the enforcement dynamics of the 1944 USA-Mexico Water Treaty. To facilitate this analysis, a Water Resource Management (WRM) model was developed for the study area, utilizing the Water Evaluation and Planning (WEAP) system software. This model represents the regional water balance, incorporating historical data on supply and demand to characterize the fulfillment of water requirements for diverse users within the Mexicali Valley. Furthermore, it accounts for the supply to geographically distant municipalities, specifically Tijuana, Playas de Rosarito, and Tecate, which receive water via the Colorado-Tijuana River Aqueduct transfer system. A historical water balance simulation spanning 56 years was conducted within the Mexicali Valley using available hydrological and consumption data. The subsequent comprehensive validation and review of the simulated water balance revealed a critical finding: potential future alterations or mismanagement of discharge deliveries from the Colorado River, stemming from the 1944 Treaty stipulations, may constitute a significant threat to the future provision of water, particularly for agricultural irrigation in the Mexicali Valley and for the municipal supply of Mexicali, Tijuana, Playas de Rosarito, and Tecate.

Keywords: WEAP, Colorado river, Baja california, Water resources modeling

Introduction

Many regions around the world are currently facing with several challenges in obtaining and managing water resources. The allocation of these water resources, their quality and policies for sustainable use are topical issues and potential sources of local and international conflicts.

The Rio Grande watershed is shared by Mexico and the United States of America, and water problems in the watershed are characterized by long periods of drought, increased demand for water and reduced efficiency. The origin of this deficit is not only in the Mexican side of the watershed, but the deliveries to Mexico are restricted by the USA-Mexico treaty of 1944 that governs the deliveries of water from the Colorado River to Mexico.[1] This treaty includes articles related with the Colorado, Tijuana and the Rio Grande Rivers and gives preference to domestics and municipal uses, agriculture, stock raising and, electric power for the joint use of the international waters.[2] USA guaranteed the annual delivery of the quantity of 1,500,000 acre-feet (1,850,234,000 cubic meters) a year including a monthly scheduled for the delivery, but if there is a surplus the amount can increases to 1,700,000 acre-feet (2,096,931,000 cubic meters) a year upon Mexico and USA agreement.[2]

In the event of extraordinary drought or serious accident to the irrigation system in the Unites States, the water allocated to Mexico will be reduced in the same proportion as consumptive uses in the United States are reduced.[2] The treaty includes the agreement to build diversion structures in Mexico and the Davies storage dam and diversion canal by USA to make possible the regulation at the boundary of the waters diverted to Mexico.[2] However the agreement did not mention the quality of water deliveries. Sometimes, Mexico was receiving heavily saline drainage from irrigated fields in USA and in 1961 the Wellton-Mohawk Irrigation District, along the lower Gila River in Arizona, discharged drainage water rich in salt into the Colorado River, immediately above Mexico's diversion canal, and essentially doubled the average annual salinity of the flow across the border.[3,4]

The hydrological simulation models oriented to water discharges are not sufficient to optimize or maximize the use of this resource[5] since these models generally can only simulate the volume and/or the quality of the discharges of a Water course or the capacity of an aquifer, but not its distribution.[5]

In the last 90 years since the birth of the Tennessee River Valley Authority[6] a more integrated approach to water resource development has been established with the use of simulation

Quick Response Code:

***Corresponding author:** Juan M Stella, Tecnológico de Monterrey, Monterrey, México

Received: 03 February 2021 **Published:** 20 February 2021

Citation: Juan M. Stella. Assessment Risk of Water Supply in The Lower Colorado River Watershed. *Glob Scient Res Env Sci*. 2021;1(2):1–13. DOI: 10.53902/GSRES.2021.01.SI0506

models that seek a balance between resources and demand with the subsequent introduction of Decision Support Systems (DSS) that places water supply projects in a new dimension in the search for a balance between supply and demand as well as the problems associated with water quality and the preservation of the ecosystems where these resources exist.[5]

Ben Salem[7] conducted a study related to water resource management using the WEAP model and an Eco-hydrological approach for the Ziz watershed in southeastern Morocco (Africa). This watershed depends to a large extent on oasis irrigation in three different geographic units. First, the High Atlas Mountains, second, the Errachidia watershed above the dam of Dakhil Hassan and third the former plantation of palm trees of Tafila downstream of the reservoir.[7] In 1970 the Hassan Dakhil Dam was put into operation in order to protect itself against flooding. The WEAP model was applied in the Ziz watershed to simulate and analyze several scenarios of water allocation and user behavior. There is now much evidence of degradation, pollution and overexploitation of water resources in that area as a result of inadequate groundwater management.[7] Also this study demonstrates that the sustainability of groundwater use can be achieved through ecological approaches. The eco-hydrological method used is based on an in-depth understanding of the complexity of large-scale ecosystem processes and provides new opportunities for the protection of water resources.[7]

Abrishamchi[8] carried out an investigation using WEAP to assess the effects of water and land resource development in the Upper Karkheh River Watershed (Iran), where Karkheh Reservoir supply the water to the municipality, industry and agriculture of the area. The component of the WEAP water resources model called soil moisture model was calibrated for a period of seven years from 1988 to 1994 and validated for a period of three years from 1995 to 1997.[8] The results showed the high capacity of the WEAP model for the analysis of scenarios and the management of water resources at watershed scale.[8]

For Bonzi[9] the need for integrated models to find sustainable water management solutions is not new, however, there is a need to create a bridge between scientific uncertainty and complexity and practical application, which is a particular challenge in situations of low availability of data, institutional capacity and political barriers such as the Jordan River watershed. For this study, Bonzi[9] used WEAP model as an integration tool within a highly complex environment from the international point of view, the Jordan River is share by Jordan and Israel. The conclusion is that WEAP model is well suited for transdisciplinary applications in integrated water and land management and this model supports decision-making on a sound scientific basis.[9]

Haddad[10] studied the applicability of WEAP as a tool for a Decision Support Systems (DSS) for water and water resources management. The DSS for the management of water resources under investigation consists of three components (1) stakeholder survey to identify key planning issues and issues necessary for a DSS to be operational (2) data collection, organization, storage, handling and management and visualization and; (3) the management of the water resources under several scenarios. The use of a DSS involves considering the quantity and quality of water, its cost, management, water trade and other aspects.[10] The DSS developed was tested in a case study of Tulkarem district water resources within the Palestinian territory. The district of Tulkarem is 5% of the total area, 7% of the population, 10% of the irrigated land, and 11% for the use of water in the West Bank of the Palestinian area. The results obtained demonstrate the feasibility of developing a DSS with the WEAP model as the basis of this system.[10]

This project, aims to study the risk of future water supply in the Mexicali valley due to the hydric stress in the lower Colorado River watershed by the enforcement of the water deliveries by 1944 USA-Mexico treaty and a climate change hypothesis between 2016 and 2050 that could decrease in 9 % of the flows in the Colorado River along with the increase in the frequency and duration of droughts.[11]

A model for the management of water resources in the lower Colorado River study area was developed using WEAP with surface and groundwater sources as inputs data. A water balance was represented with the historical supply and demand during 56 years, that satisfies the various users of the Mexicali valley such irrigated land, as well as the supply of water to the most remote cities such as Tijuana, Playas de Rosarito and Tecate, through transfers of water from the Colorado-Tijuana River aqueduct to reproduce the historical water stress under which the lower Colorado River watershed has been living.

Methods

Study site

The State of Baja California is located in the northwest of the Mexican Republic Figure 1 and remains in the interior of the geographical quadrangle given by the coordinates following: 28° 00' 00 "at 32° 43' 00" north latitude and from 117 ° 07' 00" North to 112 ° 48' 00" West longitude of the Greenwich Meridian.[12] Limit to the north with the States of California and Arizona in the United States of North America (USA) with an approximate extension of 253 km; to the east limits with the state of Sonora and to the Gulf of California with a coastline of 688.8 km; to the south limits the state of Baja California Sur and the west the Pacific Ocean, with a coastline of 716.9 km. The state of Baja California has an area of 71,576.26 km^2.[12]

According to the 11th Population and Housing Census, 1990, the rate of annual average growth of the state in the period 1980 to 1990 presents a rate of 3.6%, this means that the total population will double in twenty years.[12] In the state of Baja California, the phenomenon of urbanization, started to rise since 1990 census in which 1,513,478 inhabitants, were considered as urban population that represent 91.1 % against 8.9 % as rural.[12] In addition, there is the migratory phenomenon that defines current demographic situation in the state of Baja California, 47 % of the total population residing come from other locations in the Mexico.[12] Within the entity, residence percentages of the immigrant population are notorious in the four municipalities that make up the state; Tijuana owns the highest percentage with 56 %, while Mexicali has the lowest percentage with 36.7 %.[12]

Topographic elevations in the State of Baja California include the level from the sea to those with more than 1,000 and 3,000 meters above sea level.[12]

The State of Baja California due to its physiographic features and clima gives rise to a varied flora, of which the chaparral community stands out for its distribution; sarco-crasicaule scrub, cardonal, rosetofilo bushes desert and subinerme thicket, sarcocaule scrub and coastal rosetofilo scrub.[12]

The use of land for urban and agricultural purposes has caused the deforestation of some places, such is the case of the small valleys of the Pacific, or the case of the extensive valley of Mexicali where the flora native has disappeared completely, leading to large areas for agriculture.[12]

The State of Baja California, in its northern portion and central, the isotherms of lower value that it is 8° and 6°C; in the higher elevations of the mountainous system that forms this province, also you have the presence of the 22°C isotherm, for the southeast portion of the state, being the highest value.[12]

The Mexicali Valley Irrigation District is an arid region that receives less than 101.6 milimeters of precipitation annually.[13] Precipitation occurs irregularly in the state; rainfall records average annually higher values in the central and northern zones; and ascending from the coast to the mountains, are the precipitations monthly maximums between the months of December to March and the period of least rainfall presents from May to July.[12] In the northwest part of this province, precipitation annual total goes from 200 to 400 mm, while for the center portion varies from 100 mm in coastline up to 600 mm, in areas of higher height of the sierra San Pedro Mártir. In the southern portion, precipitation is 100 to 200 mm.[12] For the Desert Discontinuity of San Sebastian Vizcaíno and Sierra La Giganta, annual total precipitation has a range of values

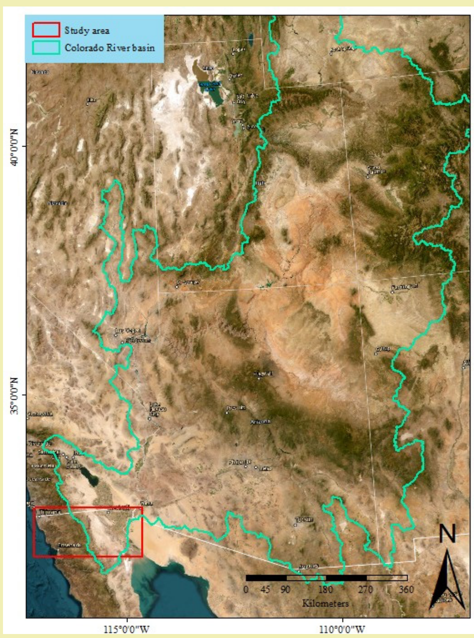

Figure 1: Study area of the lower Colorado river, Mexicali and Baja California

The average annual evaporation oscillates between 1,248.9 and 2,795.41 mm from the mountain to the coast. In the coastal strip of the Gulf of California the average annual evaporation of 2,278.35 mm, while than for the central and southern portion of the Pacific coast it has 1,387.63 mm. For the northwest portion, in the municipality area of Tijuana the average evaporation is 1,498.035 mm and south and southeast of Tecate the average precipitation is 2,008.7967 mm.[12]

The Río Colorado watershed has a total surface area of 634,000 km^2, occupies eight states of USA and in Mexico the states of Baja California and Sonora, with an area of 7,085.125 km^2, of which 5,052,625 km^2 belong to the state of Baja California.[12] The runoff is little significant and tend to flow into the Gulf of California, however according to the treaty on International Waters between Mexico and the United State,[2] USA assigns to Mexico a guaranteed volume of 1,850 million m^3 per year (mcm) under normal conditions, of which 1,677.6 mcm correspond to Baja California, through the Morelos diversion dam, susceptible to increase to 2,096 mcm.[2] When there are surpluses or reduce in time of drought, in equal proportion the consumption in U.S.[2] Table 1 summarize the level conditions in the Lake Mead for water delivery from the USA side of the border to Mexico.[2]

Table 1: Water delivery to Mexico in function of Lake Mead water level conditions (US-Mexico 1944 Treaty, 1946)

Lake mead elevation	Mexico annual increase
At or above 1,145 feet msl and below 1,170 feet msl	40,000 acre-feet (49 mcm)
At or above 1,170 feet msl and below 1,200 feet msl	55,000 acre-feet (68 mcm)
At or above 1,200 feet msl and flood control releases are not required	80,000 acre-feet (99 mcm)
When flood control releases are required, regardless of the elevation	200,000 acre-feet (247 mcm)

The most outstanding hydrographic feature is the Colorado River, which has its origin in the center of the state of Wyoming, in addition to, Utah, Arizona, Nevada and California, all located in the United States of America. This current serves as International between the two countries in a 20 km section, at the end of which the general collector, It has a distance of 185 km in Mexican territory, and its flow brings 1,850 mcm/year, which are exploited by the Irrigation District #14[14] and for domestic and industrial use.[12]

The Irrigation District # 14 belong to the municipalities of Mexicali (State of Baja California) with 181,318 ha, and San Luis Río Colorado (State of Sonora) with 26,647 ha makes a total of 207,965 ha with the right to irrigation. The district is divided into 6 irrigation units, in which the main crops are: alfalfa, wheat, vegetables, cotton, barley and ryegrass.[12]

The irrigated surface has presented variations with an upward trend until 1984, this was the year with the greatest area sown for Baja California with 202,965 ha, due to the availability of surplus volumes, which led to the sowing of surfaces without the right to irrigation, the surplus volume was 2,741.6 million m^3, with an efficiency of 78 %, from that year the surface has been decreasing until reaching the current one of 170,577 ha, with a volume used of 2,319.5 million m^3, with efficiency of 82.9 %.[12]

The Irrigation District # 14 currently operates actively only at the 83 % of the irrigation capacity due to the problems of lack for the conservation and maintenance of the current infrastructure that needs complementary works for the rehabilitation of some structures, with drainage and measurement problems among others.[12] Also, the 2010 earthquake destroyed 600 km of canals and drainage ditches.[15]

In the state of Baja California, the phenomenon of urbanization is presented in the 1990 census in which 1,513,478 inhabitants, were considered as urban population, figure that comes to represent 91.1 % against the 8.9 % that constitutes the rural population.[12] As for the spatial distribution, it is observed that the rural population group has been irregularly dispersed in 1,877 localities, while the urban population tends to concentrate in only 33 localities.[12] There is also the migratory phenomenon that defines the current demographic situation in the state of Baja California, where 47 % of the total population residing in the State, most of them in Tijuana and Mexicali, comes from other entities in the country.[12]

The highest density of vegetation is represented through the pine forests and táscate, distributed in the San Pedro Mártir and Juárez mountain ranges located in the portion central state, at heights greater than 1,200 meters and by chaparral, developed on the slopes of the hills above the level of the characteristic thickets of these arid and semi-arid zones are also found interspersed with pine forests; in the state it is found from sea level to 1,400 meters of altitude.[12]

Figure 2: Colorado River Delta (Photo taken by the author: May 9, 2017)

The most abundant rainfall occurs in the months of December and January, with 36 %, of the total annual precipitation, these precipitations are due to fresh winds that they blow from the southwest from the ocean to the front peninsular, are winds moderately loaded with humidity, so that they do not generally produce strong rains. The average annual rainfall varies gradually 60.3 mm in the municipality of Mexicali in the San Felipe station, during the period 1948-1991 a 645.9 mm in the El Hongo station, municipality of Tecate during the period 1978-1990 in the Mexicali valley area, in the lower Colorado River watershed.[12]

Environmental protection zones in the Colorado River Delta and the Sonora Desert include the Xerophilous Scrublands, Chaparral Pine-Encino Forest, coastal dune vegetation, marine ecosystem, and estuary. These areas have been heavily impacted by the USA-Mexico 1944 Water Treaty for the lack of water for environmental purposes from the Colorado River, as shown in Figure 2.[12]

Sources of water supply

The Colorado River delta is in the western edge of the Sonoran Desert and covers 169,000 ha, at the common border of the Mexican states of Baja California and Sonora, surrounded by the driest biomes of the ecoregion.[16] Flow regulation and water diversion for irrigation have considerably affected the exchange of surface water between the Colorado River and its floodplains.[17] However, the way in which both have impacted groundwater–surface water interactions is not completely understood.[18]

Surface water

Daily discharges contributed by the Colorado River to Mexico in the location known as Lindero Norte and Lindero Sur Figure 3 on the Mexican side of the border and units of discharge measurements USGS # 09522000 and USGS # 09529300 Wellton-Mohawk main outlet drain both in the State of Arizona[19] in the USA side of the border and, above the Morelos Dam located in the northeastern of the State of Baja California in the Mexican side of the border.

Daily discharges contributed by the Colorado River to Mexico in the location known as Lindero Norte Figure 4 on the Mexican side of the border and unit of measure USGS # 09522000 Rio Colorado, above the Morelos Dam, in the State of Arizona American side, since January 1, 1950.[19] The gage measured a maximum of 1,110 m^3/s in August 19, 1983 and a minimum of 16.1 m^3/s in September 29, 1970.

Daily discharges contributed by the Colorado River in the location known as Lindero Sur Figure 5 on the Mexican side of the border and as the unit of measurement USGS # 09529300 Wellton-Mohawk main outlet drain in Yuma in the State of Arizona on the American side since October 1, 1966 with a maximum of 9.51 m^3/s in December 18, 1969 and 0.0 m^3/s in many opportunities.

Figure 6 shows the total discharges contributed by the Colorado River, taking together the discharges incurred by the entry points Lindero Sur and Lindero Norte, the flows agreed in the USA-Mexico 1944 Water Treaty and the difference between the agreed flows and the delivered flows.[19]

The total accumulated flows delivered in the Colorado River by the United States of America from January 1, 1950 to May 21, 2017 was 90,779,157 mcm and the total of the accumulated flows agreed by the USA-Mexico 1944 Water Treaty on the same dates should have been 45,795,538 mcm, therefore the American part has delivered more than twice the agreed flows. That means, that on average the United States has delivered 3,709 mcm /year against the 1,850 mcm/year agreed in the USA-Mexico 1944 Water Treaty. Otherwise, in 24,613 days of water deliveries from January 1, 1950 to May 21, 2017 the American part delivery water over the agreement for 14,712 days, almost 60% of the time.

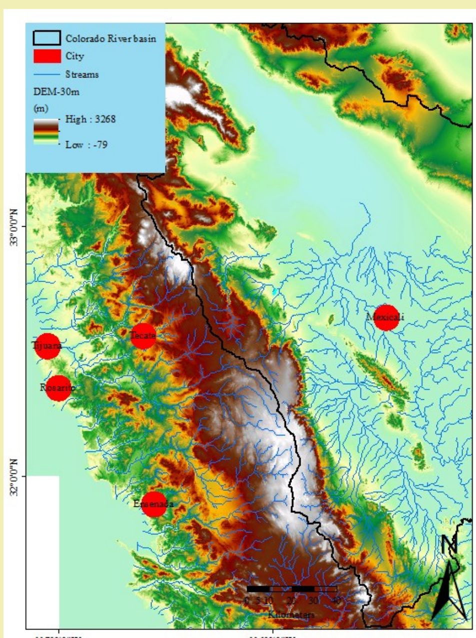

Figure 3: Streams and Cities of the study area

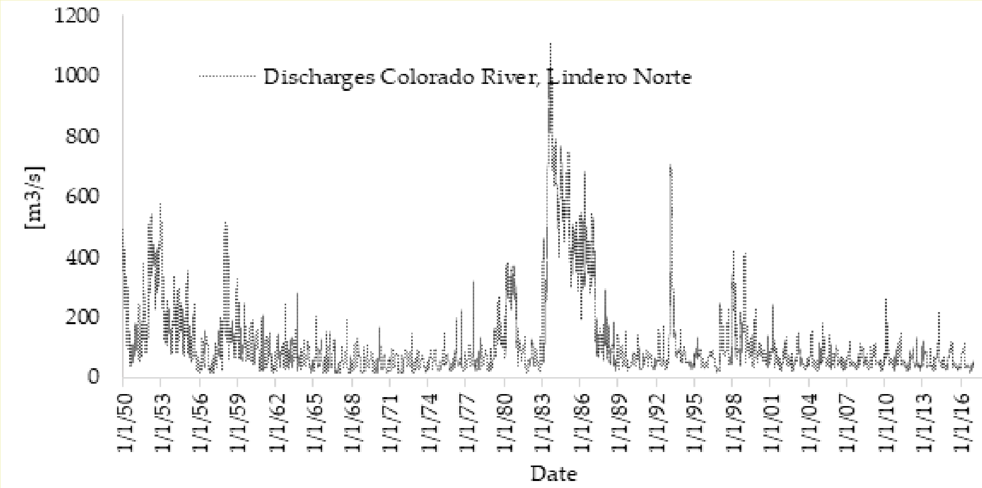

Figure 4: Daily discharges of the Colorado River in Lindero Norte unit of measure USGS # 09522000, from 1950 to 2016 (USGS, 2017)

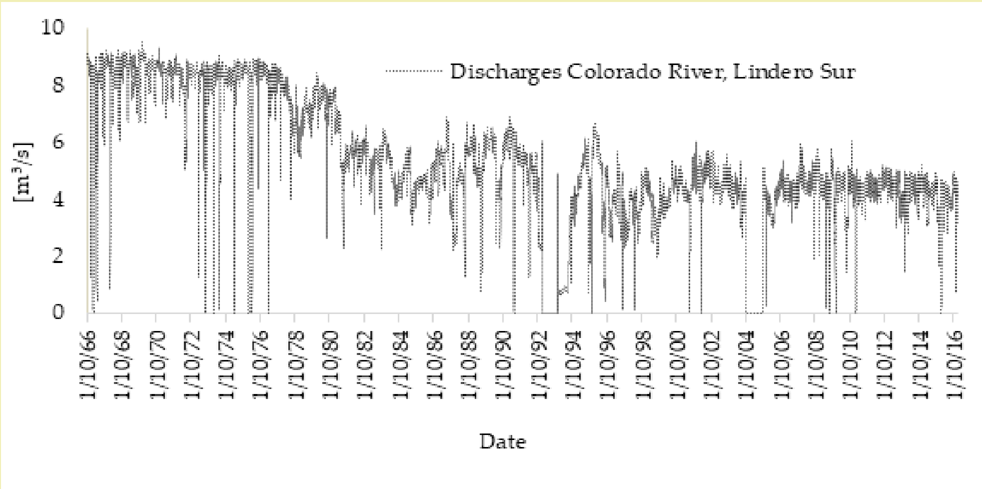

Figure 5: Daily discharges in the Colorado River in Lindero Sur unit of measurement USG # 09529300 Wellton-Mohawk from 1966 to 2016 (USGS, 2017)

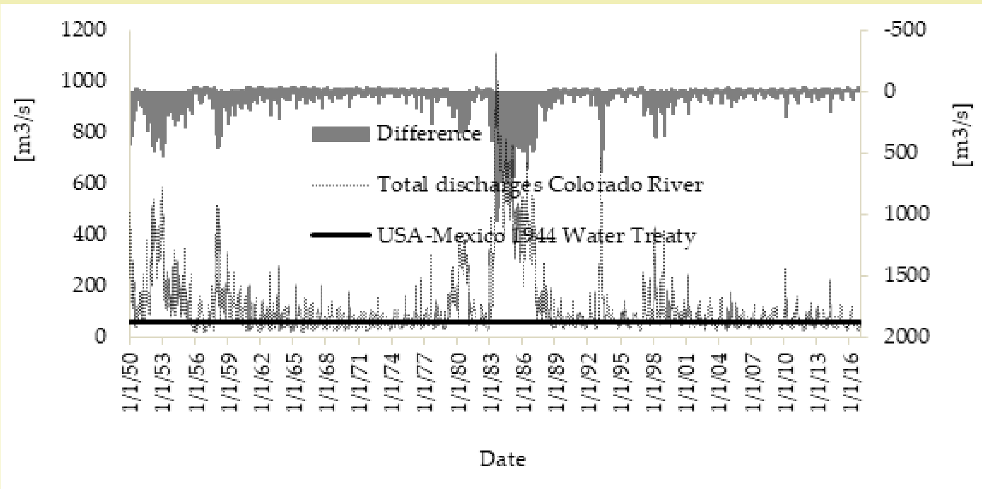

Figure 6: Total daily discharges from the Colorado River, USA-Mexico 1944 Water Treaty and the differences between them from 1950 to 2016 (USGS, 2017)

recharge due to irrigation and losses in the water potable net is 0.33 for irrigation and 0.25 in the distribution net which give a recharge of 197.3 mcm /year.

The annual recharge is estimated in the order of 520.5 mcm/year, that represents 28% of the total. The volume of groundwater extraction is estimated to be of 602 mcm/year, of which 588 mcm/year correspond to agricultural use, 13 mcm/year for urban public use and 1 mcm/year for domestic use, but the total volume groundwater in concession by the Registro Público de Derechos de Agua (REPDA) is 892.9 mcm/year that means a deficit of 372 mcm/year and, there is not more groundwater available for concession.[20]

Summarizing Table 2 shows the yearly offer of water surface from the Colorado River by the USA-Mexico 1944 Water Treaty, groundwater by recharge and the total water supply by millions of cubic meters by year, cubic meters by second and percentage of the total, 72 % of the potential water supply to the region belongs to the Colorado River and 28 % by groundwater.

Table 2: Potential offer of water surface from the Colorado River, groundwater and Total water supply

Source	mcm/year	m^3/s	%
Colorado River	1,850	59	72
Groundwater	520.5	21	28
Total	2,370.50	70	100

Groundwater levels

Lesser[21] conducted a study related with groundwater levels due to the construction of the 42 km long canal in southern California (USA) near the border with Mexico in 1939. Lesser[21] applied a numerical groundwater flow model to determine the hydrodynamic effects of the Canal on the Mexicali Valley aquifer from 1957 to 2012 and monitoring 88 wells in the area of interest. Lesser[21] found that the Canal seepage have generated infiltration, inducing groundwater to flow into the Mexicali Valley aquifer which raised groundwater levels in the Mexicali Valley. From 1939 to 1972, field evidences and the model approach suggest that seepage from the Canal resulted in the rise of groundwater levels to 14 m in the northern Mexicali Valley aquifer and in the Canal area, creating a groundwater dome producing benefit effects on the agriculture in Mexicali Valley, in the southern portion of the study area, groundwater levels did not show any change in the same period.[21]

From 2008 when USA completed the lining of the Canal to reduce infiltration to 2011, started a gradual process of drawdown in groundwater levels in its vicinity, groundwater dropped 4.0 m near the border with drawdowns of up to 5.8 m have been observed, that means a 1.3 m drawdown per year.[21] The potentiometric dome formed due to infiltration from the Canal gradually started to disappear in 2009. The higher simulated water levels in the south of the modelled area that is highly sensitive to pumping extraction rates were 20 masl 1957, decreased to 17 masl in 1984 and to 13 masl from 2008 and onwards.[21]

These results support the idea that the lining of the Canal will produce a drawdown on the aquifer to groundwater levels like those that existed prior to the infiltrations produced Canal seepage and that may affect the existing ecosystem.[21]

Ramírez Hernández[17] conducted research on groundwater seepage from irrigation canals, irrigation returns, and river discharge in the Mexicali Valley. Flows were identified and the water level and its influence on riparian vegetation was analyzed. Ramírez Hernández[17] used existing data on groundwater levels that was collected from regional piezometers on both sides of the border every five years from 1980 to 2005. Regional flow direction from NE to SW was observed in all years.[17] A groundwater depression cone in the southwest part of the border was identified from 1980 to 1995. A general rise of groundwater levels was observed from 2000 to 2005 on both sides of the border, but during the same time period, a depression cone formed along the border between Arizona and Sonora, in the Mesa Arenosa area on the Mexican side of the border.[18] Ramírez Hernández[17] found a strong correlation between flow discharge (up to 60.49 mcm from November 2009 to April 2010) and groundwater elevation (average elevation changes of 1.62 mcm January 22, 2010).

Losses

Losses by evapotranspiration increase in the north and center of the lower Colorado River watershed, with a surface area around 1,519.1 km^2, where the level of saturated soil is at deep lowers than 10 meters, the average yearly evaporation is 2,316 mm that means 11.0 mcm/year.[20] Other groundwater losses due to the flow with southwest direction of the area of study, are 2.5 mcm/year.[20]

The change in groundwater storage, with a coefficient of storage S = 0.3, and due to the granulometry of the aquifer is -95.0 mcm/year.[20]

Water supply distribution

Morelos dam in the Colorado River in the USA-Mexico border and 1.6 km downstream Lindero Norte, was built in 1950 to divert water from the Colorado River to the city of Mexicali and irrigation, is run by the International Boundary and Water Commission (IBWC) between USA and Mexico.[22] Table 3 shows the maximum flow, elevation, diversion and number of gates of the Morelos Dam.

Table 3: Maximum flow, elevation and, diversion from Morelos Dam (IBWC, 2014)

Maximum flow [m^3/s]	Elevation m.a.sl.	Diversion [m^3/s]	Gates [#]
9,900	42.1	228	20

The main hydraulic structure to supply water from Morelos Dam to the cities of Mexicali, Tecate, Tijuana-Rosarito and Ensenada is the water pumped by the aqueduct Rio Colorado-Tijuana Aqueduct (ARCT). Figure 7 shows the water pumped by the ARCT from 1982 to 2015 to this cities, null data for some years are nonexistent data.[23]

Figure 8 shows, the water expenditures by the Irrigation District # 14 in the Mexicali Valley[24] from 1997 to 2016 and from 1960 to 1996 were calculated using irrigated area and the amount of water used in 1960s, 1984 and 1994.[12]

Table 4 shows, the yearly supply of surface water from the Colorado River and groundwater sources, by 2015, in millions of cubic meters by year, cubic meters by seconds and percentage of the total.[23,24]

Also, has to be taken in consideration minute 319,[25] an initiative taken after the damage caused by the 2010 El Mayor-Cucapah earthquake in Mexicali. Minute 319 of the U.S.-Mexico Water Treaty of 1944 is an agreement for a pulse flow of approximately 130 million cubic meters (105,392 acre-feet) that was released to the riparian corridor of the Colorado River Delta from Morelos Dam at the U.S.-Mexico border. The water was delivered over an eight-week period that began on March 23 of 2014 and ended on May 18 of 2014. Peak flows were released early in this period to simulate a spring flood. Some pulse flow water was released to the riparian corridor via Mexicali Valley irrigation canals.[25] Base flow volumes totaling 65 mcm (52,696 acre-feet) are also being delivered to new and pre-existing restoration areas during the term of Minute 319 through December 31, 2017.[25] This base flow will be considered the minimum necessary flow for environmental proposes. The most important achievement may be in setting a precedent in which resource allocations are made, at least in part, for the benefit of the environment.[25]

Table 4: Offer of water surface from the Colorado River, groundwater and Total water supplied

Location	mcm/year	m^3/s	%
DR 14	2,320	73.6	85.6
Mexicali	244	7.8	9
Tecate	6	0.2	0.2
Tijuana	120	3.8	4.4
Ensenada	6	0.2	0.2
Others	12	0.4	0.4
Total	2,708	86	100
Environmental	65	2.06	2.3

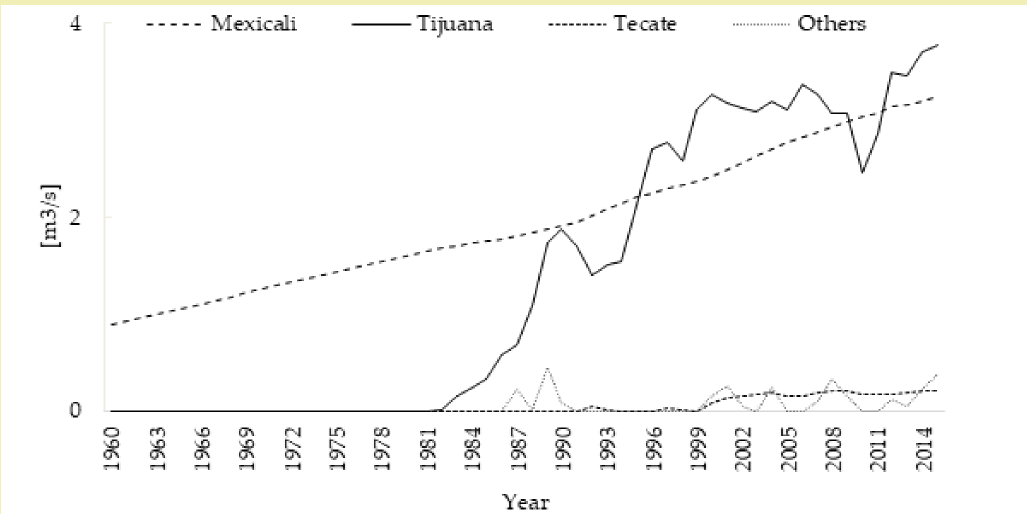

Figure 7: Water pumped by the aqueduct ARCT to the cities of Tecate, Tijuana-Rosarito y Ensenada, from 1982 to 2015

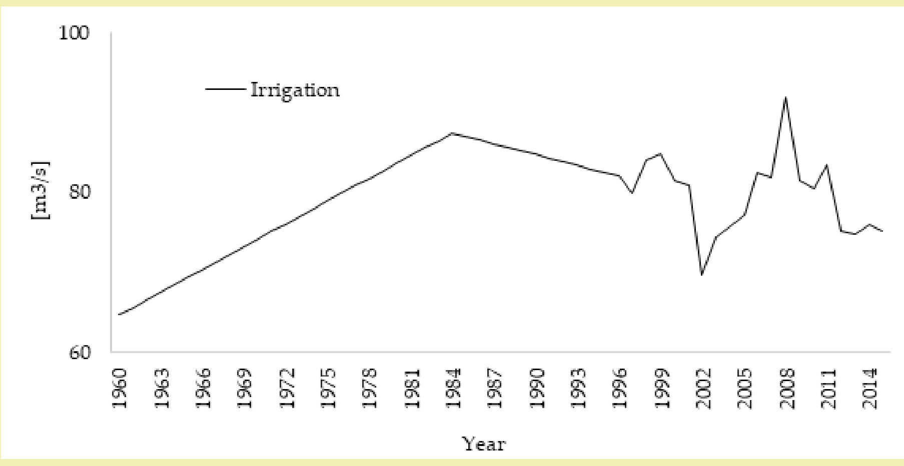

Figure 8: Offer of water for irrigation in Mexicali Valley, from 1960 to 2016

WEAP model

The WEAP (Water Evaluation, Assessment and Planning) model aims to incorporate these values into a practical tool for water planning and management was developed by the Stockholm Environment Institute (SEI), this model operates on the basic principle of water balance accounting. The user represents the system in terms of its diverse sources (rivers, groundwater and reservoirs), withdrawals, water demands and ecosystem requirements.[26]

WEAP model has a long history of development and use in water resource planning.[27] WEAP was first applied to a study on the Aral Sea in 1992, but that version of WEAP had several limitations, including an allocation scheme that treated rivers independently.

The WEAP model has two main functions:[28]

i. Simulation of natural hydrological processes (evapotranspiration, runoff and infiltration) for assessing the availability of water within a watershed
ii. Simulation of anthropogenic activities superimposed on the natural system to influence water

WEAP model has an integrated approach to simulate the water resources system of an area and places demand (patterns of water use, equipment efficiency, reuse, prices, hydropower demand and allocation) on an equal basis with supply (flow, groundwater, reservoirs and water transfers). Thus, it is possible to examine alternative water development and management strategies.[5]

WEAP has been described as a complete, simple and easy-to-use model, and tries to help instead of replacing the expert modeler[29] and as a database. WEAP provides a system to maintain information on demand and the water supply. As a forecasting tool, WEAP simulates the demand, supply, flows and storage of water, and the generation, treatment and discharge of pollution. As a tool for policy analysis, WEAP evaluates a full range of water management and development options and considers the multiple and competitive uses of water systems.[5]

Applying the principle of water balance accounting, WEAP is applicable to urban and agricultural systems, simple sub-accounts or in complex river systems. WEAP can monitor sectoral demand analysis, water conservation, allocation priorities and water rights, groundwater simulation with MODFLOW groundwater model, hydroelectric power generation and other energy demands, pollution monitoring, ecosystem requirements, and cost analysis.[5]

The model represents the system in terms of its various sources of requirements and supply, e.g., rivers, streams, groundwater, reservoirs; the extraction, transport and wastewater treatment facilities ... etc. The requirements of ecosystems, water demands and the generation of pollution. The data structure and the level of detail can easily be customized to meet the requirements of an analysis and reflect constraints imposed by the constrained data.[5]

The WEAP application generally includes the following steps.

- It establishes the time frame, the spatial limits, the system components and the configuration of the problem
- The actual demand for water, pollutant loads, resources and supplies for the system. Alternative assemblies of future assumptions are based on policies, costs, technological development, and other factors affecting demand, pollution, supply, and hydrology. These scenarios are built on alternative sets of assumptions or policies
- Finally, scenarios are evaluated with respect to water sufficiency, costs and benefits, compatibility with environmental objectives and sensitivity to uncertainty in key variables

WEAP model application

During this study and the application of the WEAP water balance model, the following steps were followed:

- The current conditions of exploitation of groundwater and of the Colorado River were detailed and the works of storage, conduction and distribution: dams, canals, drains, etc., detailing the volumes of water used and their distribution by applications
- A digitized hydrological map was drawn up on an appropriate scale, illustrating the location of the considered climatological and hydrometric stations, the hydrographic network, the main rivers and surface water utilization
- A digitized hydrological map was drawn up on an appropriate scale, illustrating the location of demand from irrigation and urban systems
- The necessary scenarios were created to simulate historical supply and demand under the hypothesis of climate change and border conflict

A WEAP model was created to simulate the historical water balance of the Baja California region between 1960 and 2016, with a supply and demand scheme Figure 9 which includes the supply of surface water represented by the government's United States by the USA-Mexico 1944 Water Treaty from 1960 to 2016 through the Colorado River in Lindero Norte and Lindero Sur on the Mexican side of the border and groundwater represented in the model by an annual recharge of 520.5 mcm/year. The demand was represented by the cities of Mexicali, Tecate, Tijuana-Rosarito and Ensenada, as well as the irrigation zones in the lower Colorado River region.

The supply of water for the cities of Mexicali, Tecate, Tijuana-Rosarito and Ensenada are represented by the water pumped by the Rio Colorado-Tijuana Aqueduct (ARCT), from 1982 to 2015.

Results and Discussion

Under the hypotheses described above WEAP model was developed and run, Figure 10 shows the monthly average of the surface water and groundwater supply for irrigation and the cities of Mexicali, Ensenada, Tecate and Tijuana-Rosarito from 1960 to 2016. A maximum of surface water and groundwater offerd from the Mexicali Valley happens in August with 1,503 mcm/year and a minimum in Febraury with 27.4 mcm/year.

Figure 11 shows the average percentage by month of surface water and groundwater offered from the Mexicali Valley for irrigation and the cities of Mexicali, Ensenada, Tecate and Tijuana-Rosarito from 1960 to 2016. From April to September mor than 93% of surface water and groundwater offered from the Mexicali Valley goes to irrigation and from January to March and from October to November almost 65 % of the water goes to Tijuana.

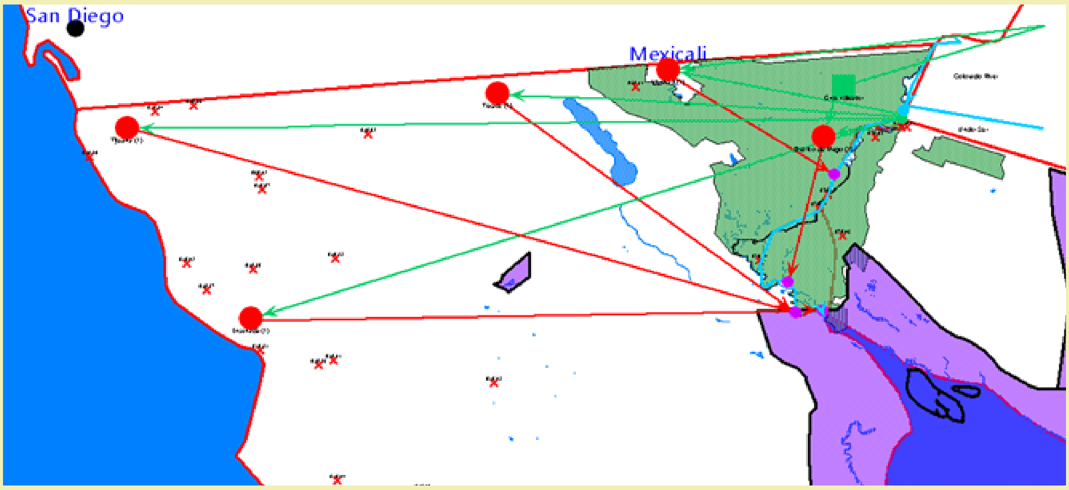

Figure 9: Scheme of the WEAP model with water demand and offer, cities (red points), supply (green lines), water excess (red lines), Morelos Dam (green box), irrigation lands (green), environmental protected lands (scarlett)

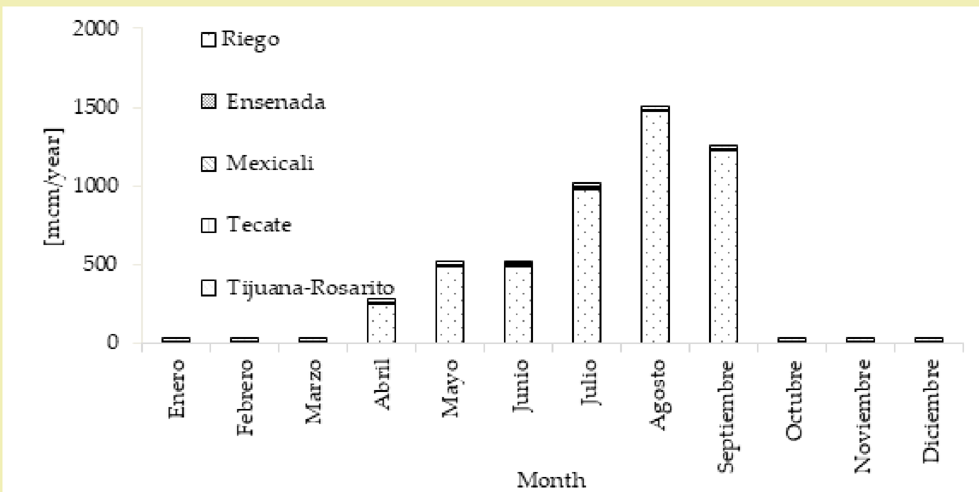

Figure 10: Monthly surface and groundwater offer for the cities and irrigation, from 1960 to 2016

In summary, Figure 12 shows, the Total Consume of water for irrigation used in the Mexicali Valley, and the cities of Tecate, Tijuana-Rosarito and Ensenada from 1960 to 2017 with a maximum of 3,202 mcm/year in 2008. Total Consume of water for irrigation used in the Mexicali Valley, and the cities of Tecate, Tijuana-Rosarito and Ensenada from 1960 to 2017 plus losses in the system and the environmental flow. The surface water supply that should be obtained by the 1944 USA-Mexico Water Treaty (1,850 mcm/year) plus the groundwater with maximum extraction limit equal to the recharge (520.5 mcm/year) minus the losses in the system (425.8 mcm/year).

Figure 13 shows, Total water consume plus losses plus environmental flow, Water offer from the Colorado River plus groundwater recharge and, Observed inflows from the Colorado River.

There is a gap between the Total water consumed by the region (water consumed plus losses plus environmental flow) and the inflows (observed water delivery by USA authorities), only in 12 years of 57 the water delivered was greater than the Total water consumed by the region.

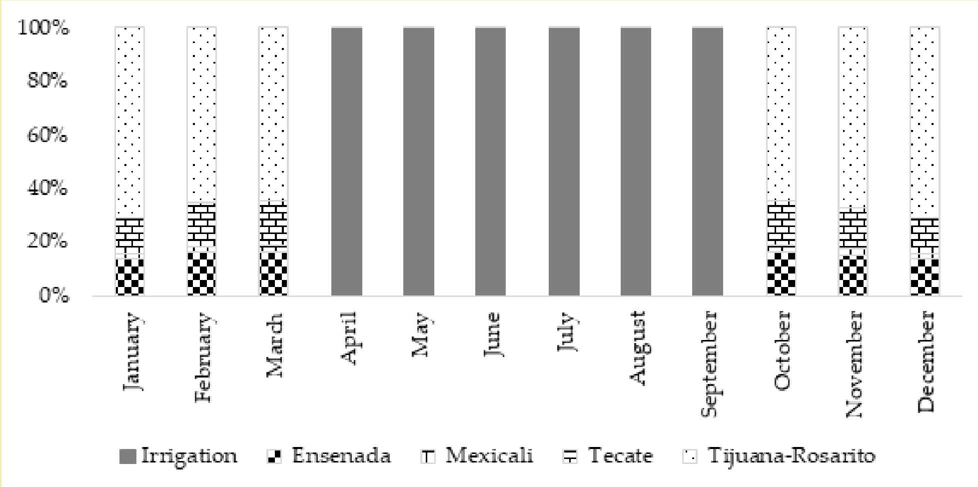

Figure 11: Monthly supply of surface and groundwater in the Mexicali valley between 1960 and 2016 for irrigation and the cities of Ensenada, Mexicali, Tijuana-Rosarito and Tecate

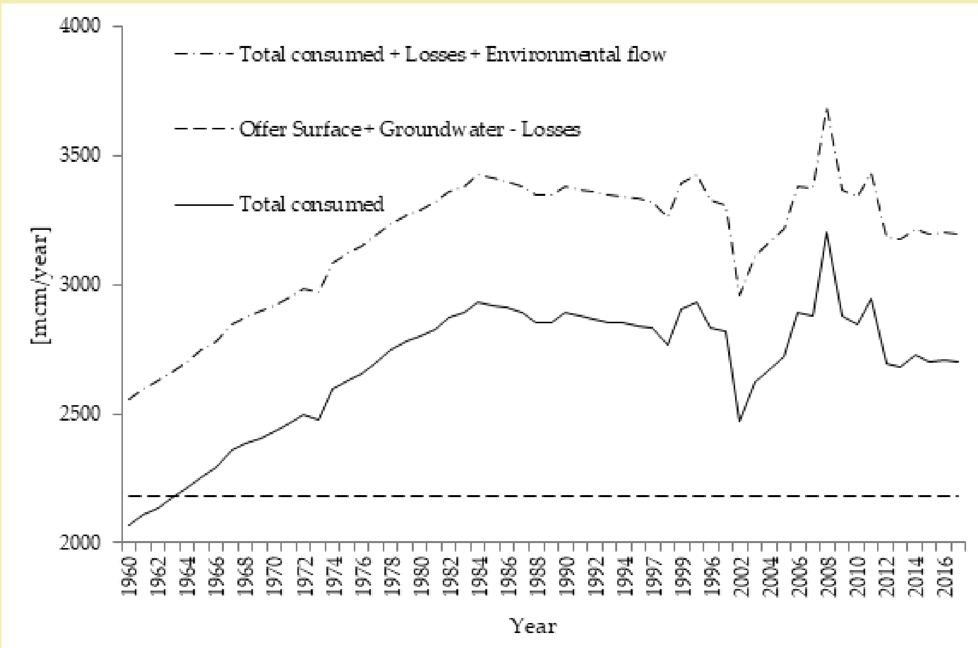

Figure 12: Total Consume of water for irrigation and the cities of Mexicali, Tecate, Tijuana-Rosarito y Ensenada, offer of Water from the Colorado River plus groundwater with losses and Total consume plus losses and environmental flow

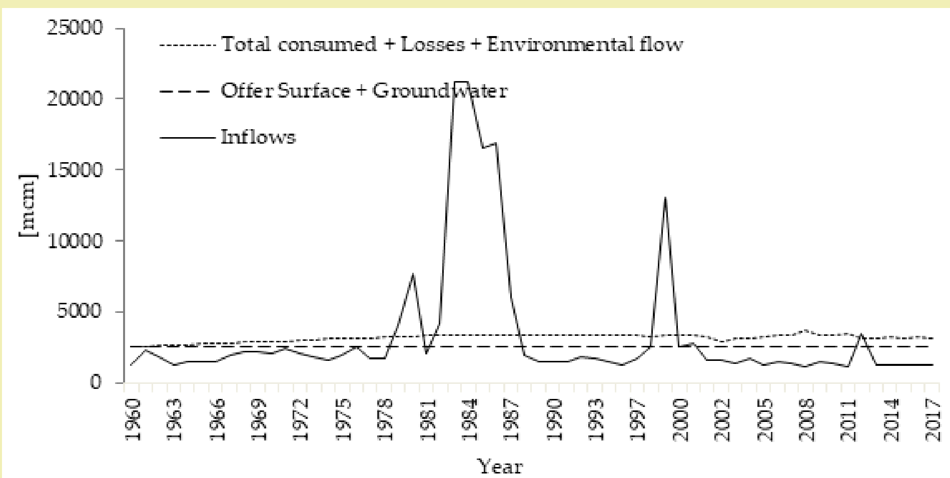

Figure 13: Total water consume plus losses plus environmental flow, Water offer from the Colorado River plus groundwater recharge and, Observed inflows from the Colorado River

If the surface water by the 1944 USA-Mexico Water Treaty plus the groundwater recharge is taking in consideration only in 10 years of 57 the water delivery by USA authorities was greater than the deliveries upon agree and the groundwater recharge. But if the total amount of water is taking in consideration during the period, Total observed inflows were 197,110 mcm, Total water consumed by the region 184,234 mcm and surface water by the 1944 USA-Mexico Water Treaty plus the groundwater recharge 151,194 mcm from 1960 to 2017.

Conclusions

The Water Evaluation and Planning (WEAP) model effectively characterizes the extraction, allocation, and long-term evolution of surface and groundwater resources in the Mexicali Valley. Model results indicate that over the past 56 years the region has approached conditions consistent with a potential water-shortage scenario. The findings show that water availability in the lower Colorado River watershed is likely to become increasingly vulnerable to future droughts under projected climate-change conditions. Nonetheless, adaptive management strategies could substantially mitigate adverse impacts. Model outputs also demonstrate a significant increase in vulnerability for irrigation, municipal supply, and treaty-mandated deliveries, intensifying competition for water resources on both sides of the U.S.–Mexico border.

The WEAP platform proved to be a valuable decision-support tool, offering satisfactory performance and user-friendly operation. When informed by accurate and comprehensive datasets, WEAP can support water-resources management for the lower Colorado River watershed through scenario evaluation and system-wide impact analysis. Beyond the scope of this study, the model can incorporate additional components such as hydropower and water-supply costs, groundwater–surface-water interactions, and water-quality dynamics. Effective management based on such analyses is essential to prevent further groundwater depletion and to promote sustainable development in the Mexicali Valley.

The implementation of WEAP in the lower Colorado River watershed demonstrated its utility for scientific water-resources management, which is critical for sustainable socio-economic development. Specifically, the model was used to simulate and assess historical water-allocation patterns in irrigation districts and urban centers in northwestern Mexico. WEAP's capacity to represent diverse water-use systems and evaluate future scenarios—particularly those involving water shortages, economic impacts, and climate-change projections—provides planners with a robust analytical framework for Baja California.

Water-balance simulations highlight that the future water-supply security of Mexicali, Tecate, and Tijuana is strongly influenced by irrigation demand. Although groundwater availability is declining rapidly, surface-water users dependent on rivers and reservoirs are also expected to experience future deficits. Rapid population growth along the U.S.–Mexico border is intensifying competition for water between agricultural and urban sectors.

The WEAP model was applied in the Mexicali Valley and in the cities of Tecate, Tijuana–Rosarito, and Ensenada to assess future water-supply risks in northern Baja California under the constraints imposed by the 1944 U.S.–Mexico Water Treaty. Daily discharge records (1950–2016) provided by U.S. authorities, along with aquifer-recharge estimates, were incorporated to identify potential system imbalances.

Over the more than 60 years of treaty implementation, the United States has delivered approximately 3,709 million cubic meters (mcm) per year—nearly double the 1,850 mcm/year specified in 1944. These surplus volumes supported the expansion of irrigated agriculture, which peaked at 202,965 hectares in 1984, as well as the urban and economic growth of Mexicali, Tijuana–Rosarito, Tecate, and Ensenada.

Groundwater recharge in the Mexicali and Sonora valleys is currently estimated at 520.5 mcm/year, while extraction exceeds 892 mcm/year, resulting in an annual deficit of more than 372 mcm. Simulated groundwater levels in the southern Mexicali Valley—an area highly sensitive to pumping—declined from 20 masl in 1957 to 17 masl in 1984 and to 13 masl by 2008. Strong positive correlations between river discharge and groundwater elevation, and strong negative correlations between pumping and groundwater elevation, indicate that any reduction in U.S. treaty deliveries, combined with sustained pumping, will further exacerbate groundwater decline.

Model results also confirm that overexploitation has already produced substantial environmental damage, including the collapse of the lower Colorado River Delta ecosystem, now largely desiccated. These impacts extend to drinking-water security for the northern Baja California cities and constrain agricultural productivity, exemplified by the underutilized vineyards of the Guadalupe Valley, operating at only 35% of their potential due to limited water supplies.

Although a simplified theoretical water balance—treaty deliveries (1,850 mcm/year) plus groundwater recharge (520.5 mcm/year)—might suggest sufficient supply, this assumption fails to account for:

1. Distribution losses within Mexico's canal and pipe networks immediately downstream of the border

2. Potential treaty-delivery reductions under climate-change scenarios (2016–2050), including a projected 9% decrease in Colorado River flows and increased drought frequency/duration

3. Continued groundwater depletion due to persistent over extraction

Considering these factors, northern Baja California faces an annual water-supply deficit exceeding 372 mcm, with significant socio-economic implications. Addressing this deficit requires the development of medium-term alternative water-management strategies, including reallocation of irrigation rights, reduction of conveyance losses, and recognition that regional water resources are finite.

Acknowledgements

The author acknowledges the assistance and thanks the anonymous reviewers of the journal for their contributions, which enriched this document.

Funding

This Research Article received no external funding.

Conflict of Interest

Author declares that there is no conflict of interest.

References

1. Ingol Blanco E, McKinney DC. Analysis of Scenarios to adapt to climate change in USA-Mexico Pacts in the Rio Conchos Watershed. *In World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability.* 2011:pp.1357-1364.
2. US-Mexico 1944 Treaty. *Treaty between The United States of America and Mexico.* 1946. Signed at Washington, February 3, 1944 and Protocol signed at Washington November 14, 1944. Treaty Series 994. United States Government Printing Office, Washington. 1944.
3. Worster D. *Rivers of empire: water, aridity, and the growth of the American West.* New York, New York: Pantheon Books. 1985;153:240.
4. Goldsmith E, Hildyard. *The Social and Environmental Effects of Large Dams.* Wadebridge Ecological Centre, Camelford, Cornwall.1984:pp.134-163.
5. *Water evaluation and planning system (WEAP) user's guide*. 2015.
6. *Tennessee Valley Authority (TVA)*. 2017.
7. Ben Salem AA, Messouli M, Yacoubi khebiza M. Developing an Oasis-Based Water Management Tool: Ecohydrologic Approach and Weap Software for a Large Arid Catchment in Morocco. *Int J Water Resour Arid Environ.* 2011;1:387-396.
8. Abrishamchi A, Alizadeh H, Tajrishy M, et al. Water Resources Management Scenario Analysis in Karkheh River Watershed, Iran, Using WEAP Model. *Hydrological Science and Technology*. 2007;23(1/4):1.
9. Bonzi C, Hoff H, Stork J, et al. *November. WEAP for IWRM in the Jordan River Region. Bridging between scientific complexity and application.* In Proceedings of the Integrated Water Resources Management Conference. 2010;24-25.
10. Haddad M, Jayousi A, Hantash SA. March. *Applicability of WEAP as water management decision support system tool on localized area of watershed scales: Tulkarem district in Palestine as case study*. In 11th International Water Technology Conference, IWTC. 2007;11.
11. Prairie JR, Jerla C. *December. Colorado River Watershed Water Supply and Demand Study.* Paper presented at the AGU Fall Meeting Abstracts. 2012;1:1362.
12. Instituto Nacional de Estadísticas, Geografía e Informática (INEGI). *Estudio Hidrológico del Estado de Baja California.* México City: INEGI. 1995:pp.206.
13. Brun LA, Abdulsamad, C Geurtsen, et al. *Agricultural Value Chains in the Mexicali Valley of Mexico.* Center of Globalization, Governance and Competitiveness, Duke University. 2010.
14. Distrito de Riego # 14 (DR14). 2017b.
15. Schuster E, Colby. Farm and ecological resilience to water supply variability. *Journal of Contemporary Water Research and Education.* 2013;151:70-83.
16. Hinojosa Huerta O, Briggs M, Carrillo Guerrero Y, et al. Community Based Restoration of Desert Wetlands: The Case of the Colorado River Delta. *USDA Forest Service General Technical Report PSW-GTR-191*. 2005:pp.637-645.
17. Ramírez Hernández JO, Hinojosa Huerta M, Peregrina Llanes A. et al. Groundwater responses to controlled water releases in the Limitrophe Region of the Colorado River: Implications for management and restoration. *Ecol Eng*. 2013;59:93-103.
18. Hinojosa Huerta OPL, Nagler Y, Carrillo Guerrero, et al. Effects of drought on birds and riparian vegetation in the Colorado River delta, Mexico. *Ecol Eng*. 2013;59:104-110.
19. *United States Geological Service (USGS).* 2017.
20. Comisión Nacional del Agua (CONAGUA). *Actualización de la disponibilidad media anual de agua en el acuífero Valle de Mexicali (0210) Estado de Baja California*. Publicada en el Diario Oficial de la Federación, 20 de abril. 2015a.
21. Lesser LE, Mahlknecht J, López Pérez M. Long-term hydrodynamic effects of the All-American Canal lining in an arid transboundary multilayer aquifer: Mexicali Valley in north-western Mexico. *Environmental Earth Sciences*. 2019;78:504.
22. International Boundary and Water Commission (IBWC). 2014.
23. Comisión Estatal del Agua de Baja California (CEABC). *Informacion a Diciembre 2016.* Operacion del Acueducto Rio Colorado-Tijuana. 2017.
24. Comisión Nacional del Agua (CONAGUA). *Estadísticas Agrícolas de los Distritos de Riego Año Agrícola* 2013-20. 2015b.
25. *International Boundary and Water Commission United States and Mexico (IBWC)*. Minute # 319. Coronado, California. 2012.
26. Stockholm Environment Institute (SEI). *WEAP: Water Evaluation and Planning system, user guide, Boston*. MA: Stockholm Environment Institute. 2007.
27. Raskin P, Hansen E, Zhu Z. Simulation of water supply and demand in the Aral Sea. *Region 17*. 1992;(2):55-67.
28. Sieber J, Huber Lee A, Raskin P. WEAP: Water Evaluation and Planning System User Guide (for WEAP 21). *Stockholm Environmental Institute-Boston, and Tellus Institute, User Guide for WEAP 21, Boston, MA*. 2007.
29. University of Kassel. *ECOBAS project: meta-database for existing mathematical models in ecology*. 2002.