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Santa Barbara

Assessing Water Demand for Agriculture in the Mexicali Valley Aquifer
Delta of the Colorado River using Remote Sensing and GIS

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Geography

by

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ABSTRACT

The Colorado River basin has been the subject of numerous studies covering a wide range of issues. Nevertheless, some areas require further analysis, such as the lowest part of the Colorado River basin, where lies the Mexicali Valley of Baja California, Mexico. The purpose of my thesis is to estimate the amount of water used in this valley and assess whether there is water deficit that could degrade the valley's aquifer.

Due to the difficulty of obtaining official data about water usage, this author estimated the annual farming water using Remote Sensing and Landsat imagery and the NDVI index, classified and determined the area of each main crop group in the Mexicali Valley. These areas were multiplied by the average water use by crop for the 2017-2018 water year. The Mexicali aquifer supplies drinking water for cities, communities and industries. I calculated this water use according to the population size and from Mexican specifications for water supply and added to the farming use to calculate the total water use in Mexicali Valley. The results of this independent method were compared with official (that is, from the Mexican government) data to determine, relevant differences and important coincidences. The most important difference concerns the estimate of the amount of water recharged to the aquifer considered in the formulation of a valley-wide water balance. The major coincidence

was the existence of a critical water deficit and the associated groundwater depletion, which threatens negative effects to the aquifer such as land subsidence, risk of pollution, seawater intrusion, and water insecurity.

Compounding the water deficit in the Mexicali Valley is the long drought in the Colorado River basin and the proposed reductions in water allocation for all the States in this watershed. Climate change models are predicting less water for the Colorado basin, which could bring even stronger water restrictions in the short term. The State (Baja California) and Federal water authorities in Mexico must develop a drought contingency plan to cope with the worsening water scarcity in the Mexicali Valley. This would require unprecedented and unpopular law enforcement, yet it would help avert a major water crisis in the California-Mexico border region.

The Mexicali Valley aquifer case demonstrates the fragility of relying on intensive groundwater exploitation for crop production in arid regions. Food production and food security must consider the sustainability of this type of irrigation systems in similar geographical settings. We must use groundwater strategically since it is a renewable yet exhaustible resource.

KEY WORDS: Mexicali Valley aquifer, Colorado River delta, Irrigation District Mexicali Valley, Landsat-NDVI crop classification, Water Deficit in the Colorado River Watershed, Water Insecurity in US-Mexico western border region.

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Introduction

The Colorado River has long been the fountain of fresh water for the Southwestern US. It is said to be the most controlled river in the world. However, it is also a source of competition and greed for securing its water resources. The conflict between water stakeholders and water authorities has continued for more than one hundred years and will continue. As the Colorado River crosses its delta in Mexico, and to its eventual outlet in the Gulf of California, it also meets the water needs of farming in the Mexicali Valley.

The purpose of this project is to assess the critical situation of the Mexicali Valley aquifer, which is on the Mexican side of the Colorado River, and supplies drinking water for the border cities, rural communities, industry, and fresh agricultural produce. As the surface water from the Colorado is reducing, increased pumping of water from the Mexicali Valley aquifer is threatening this water source.

Water availability in the Mexicali Valley is a function of the dynamic geology and hydrology of the Colorado River delta and the history of water allocation and water rights. Chapter one deals with the natural history of the region, chapter two with the human and economic development. Water depletion risk features natural environment and

human history components. The evolution and confluence of both components have created an environmental hazard, the depletion of the aquifer. To avert this ecological disaster, it is necessary to understand the problem and changes over time about the perception of water availability and the policies for water use and allocation. A new culture in the use of water and environmental protection is required to control and avoid the overexploitation of the aquifer and to stop its pernicious effects.

The first problem that stands out is that the Colorado River watershed is shared by the US and Mexico, being one of the more than one hundred international watersheds worldwide. Its water allocation problems are similar to many other regions of the world: the Nile River, Jordan River, Danube River, Mekong River, Congo River, etc., yet it is unique as each river, set of communities, and relationships can be. The Colorado River was the first major river in the world completely controlled through a series of large dams. Most of them built before the evolution of the notion of environmental protection. Such dams dramatically changed the ecology of the river, and its interaction with the sea where it used to discharge its water. The extensive wetlands and estuaries that were part of the river life changed forever when the water was diverted for farming and drinking water.

When Hoover Dam, close to Las Vegas, NE was finished in 1936, the flows of the river became managed according to the needs of the US

Southwestern region. The economic benefits and business opportunities were so beneficial that they eclipsed the environmental transformation and damage of the delta region. While many regions enjoyed the benefits of this transformation, the delta suffered a large ecological cost. After Hoover Dam, the Bureau of Reclamation built more hydrological infrastructure to expand the benefits of controlling the river to several States. The control and beneficial use of the water brought life and development to otherwise inhospitable areas and allowing the settlement of new cities and enterprises. The decision to control the river was a milestone in the development of the southwestern US. The delta was part of this national project. The Imperial Valley in Southern California became an important irrigation district in the nation. The Mexicali Valley became the largest cotton producer farming area in the world.

After the Mexican Revolution the government assigned land and water rights to the landless farmers in the Mexicali Valley, creating an unrealistic expectation of unlimited progress. Mexican farmers thought that they would have all the water from the Colorado River for themselves without sharing with American farmers. On the other side of the border, US residents thought this water was for them and they did not wish to share it. This through was rooted on the 19th century manifest destiny doctrine or belief that the expansion of the US throughout the American continents was both justified and inevitable. These perceptions

created conflict of interest between Mexico and the US. An important aspect was that each country believed they have the rights to the water. Both countries allocated water freely to their constituents. The US government allocated all the available water to the seven states in the Colorado basin, while the Mexican government gave the water to the communal farming settlements called "ejidos." The problematic situation started with this excessive allocation of the Colorado River water.

Years later, in 1944, there was an International agreement, which established that Mexico would receive 10% of the average annual flow of the River. Mexican farmers were disappointed, as they had expected a larger allocation. The Mexican government allocated the total water of this agreement only to farmers. The border's cities did not receive any allocation. The Mexican government moved to solve this careless allocation and allowed the cities to withdraw water from the Mexicali aquifer. Cities started to install wells for drinking water. Farmers asked groundwater rights to complement the surface water from the Colorado River. Initially the total extraction was small with just a few wells. Over time the number of wells and extraction increased rapidly; therefore, the aquifer started to decline.

After WWII, the enthusiasm for economic development was unlimited in the southwestern region. New investments and public infrastructure made the Colorado basin one of the most rapidly growing regions in the

world. Population, cities, economic activities, farming, industries, and services grew spectacularly. Major coastal cities, like San Francisco, Los Angeles, and San Diego built aqueducts for fresh water supplies. Northern California received water from the Sierra Nevada, and Southern California from the Colorado River and Owens Valley. In just a few decades, the watersheds felt the impacts of the intense extraction. Clever water users moved to secure the water as a strategic asset. Many negotiations and requests were made. Soon the multiple users found that water was scarce, and they engaged in long and continuous legal and administrative struggles for securing water and water rights.

The fights were so common that the US Federal government had to mediate through the Department of the Interior to solve a regional conflict and asked the US Congress to solve the international water allocation. Negotiations were intense and many times unsatisfactory for all parties. Still the final decisions belonged to the national governments of each country. Local and regional users had to lobby or endure the decision of their respective governments.

In the 1990s, social and economic development in the Southwestern region of the US and the neighboring Mexican side made the demand for fresh water surpass the supply possibilities. Groundwater extractions covered water deficits in the Mexicali Valley, making this the preferred option. Many more users asked for groundwater rights until the excessive

mining of the aquifer led to numerous problems. These included groundwater storage decline, higher energy costs, subsidence, and water quality problems. Legislation limited groundwater extraction, but it has been difficult to enforce. Not all States, nor all users wanted to limit their water use or invest in new water saving technologies. The water deficit in the region persists and it is accumulating.

Lower precipitation than the estimated average has been recorded in the last twenty years in the Colorado basin, a sign of a possible longer-term drought. The seven Western States in the watershed must adapt to this situation. The record drought in California from 2012 to 2020 has stressed even more the water deficit and the persistence of unsustainable groundwater extraction. Everyone looks for a series of plentiful-precipitation years that could replenish the reservoirs and allow for less groundwater extraction. Unfortunately, the precipitation prediction models for the Southwest are pessimistic and predict even more shortages in the following years. Each State must reduce its consumption, follow the declared Drought Contingency Plan, and generate a local action plan to reduce consumption to a sustainable level.

The Baja California State in Mexico has not created an action plan for reducing water consumption. They continue pumping groundwater and over exploiting the Mexicali aquifer, which is in a major risk of salinization, due to sea water intrusion in the southern part of the aquifer,

or brackish water extraction due to the special geology of the aquifer and delta region. Once the aquifer is polluted with salt, it could take decades to return to a freshwater reservoir, if ever possible, since water will remain in shortage, and other users will claim their water rights.

Upon resolving the key issues of water allocation and excessive wells, the water authority in Mexico decided to limit groundwater extraction. This regulation opened a speculative reaction of the stakeholders who asked for additional water rights when they did not use it or need it at that moment. The NAFTA (North America Free Trade Agreement) moved industries to the border area-opening job opportunities, migration made the cities grow rapidly. Industry and urban development at the border region required more water and CONAGUA authorized new wells, farmers asked for more water rights for extend the irrigation systems to produce fresh vegetables for the American market and implement packing and food industries. Tijuana grew rapidly yet its local resources were insufficient. The border cities asked for an aqueduct from the Colorado River. The sum of these factors has brought a major freshwater deficit to the region, the only available water source was the Mexicali aquifer, and its wells are depleting the aquifer. Once scarcity was obvious, greed and competition increased between the water right holders.

Water users know that the Mexicali Valley aquifer is in overdraft, and that it is due to intensive over-extraction. Farming is the major water

user by far and it is necessary to quantify the areas and water consumption of each crop to estimate the volume of water used in a farming annual cycle. Farmers do not want to disclose their total water consumption. It was necessary for this author to estimate the water use in an indirect way. Through satellite imagery, remote sensing techniques, and geographic information systems it was possible to determine the total surface area of each crop in the Mexicali Valley, the areas and crop types were used to estimate actual water use in irrigation. Regarding the urban areas, a time series of satellite imagery shows how the borders cities have grown in the last three decades, and industry has established itself in the region. Fortunately, the State government has population and economic data that were used to estimate total domestic and industrial water consumption. Chapter three and four deal with methods used to determine the water quantities and compare these results with official Mexican government data. There are interesting differences and important coincidences, which are analyzed in chapter five. A series of conclusions and recommendation are contributed to this work. Further research is envisioned. Among the references cited it is possible to find scientific works and useful data to continue this research, and to focus in new relevant projects that would assist in understanding and solving the complex web of human, social, and environment interactions being played in the Mexicali Valley.

Chapter 1

Natural History of the Delta of the Colorado River

The Colorado River Watershed

The Colorado River watershed is in the southwestern part of the US. The Colorado River has a length of 1,450 mi (2,330 km) and the basin encompasses 248,000 sq. mi (640,000 km²) of southwestern US, and 22,000 km² in Northwest Mexico. Ninety-five percent of the watershed is in the US and five percent is in Mexico, the Mexicali Valley. Fig. 1

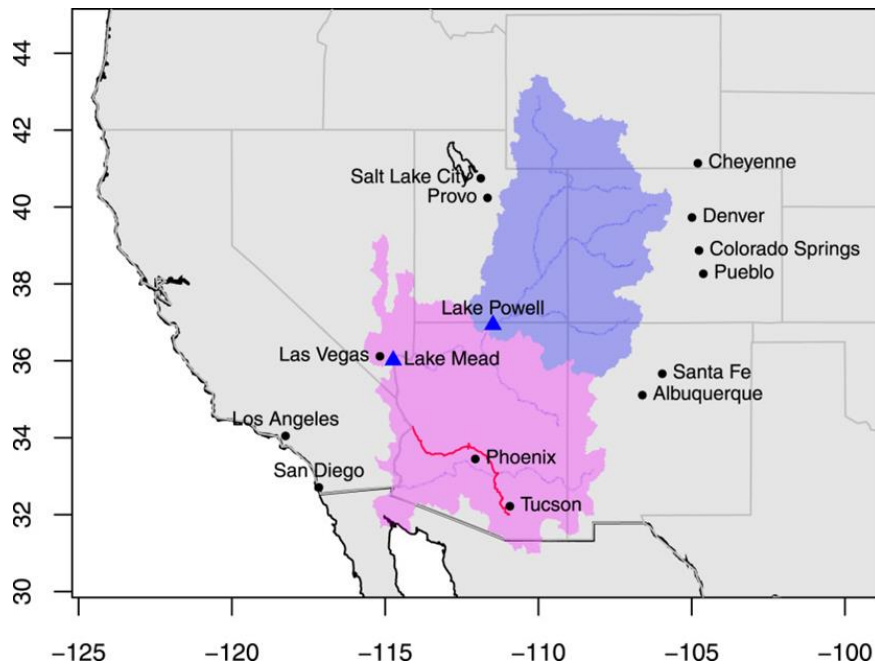


Fig. 1 The Colorado River watershed location in the Western USA.

The watershed has evolved through different geological eras. It is part of the North American Plateau and lies west of the Rocky Mountains that were subjected to the Pleistocene glaciations (Fig. 2.)



Fig. 2 Headwaters Colorado River. Western side Rocky Mountains.

The basin central part is the Colorado Plateau, which emerged after being submerged under vast ancient oceans, the Western Interior Seaway (Archibald, 1996). The river drained large amounts of water during the melting of glaciers and ice dams breaking apart, with episodes of large torrents that formed the deep canyons of the region. The walls and strata of the Grand Canyon recorded this amazing natural history of the Colorado River watershed. Close to the borderline between Utah and Arizona is Lee's Ferry Point on the river. This point is the division between the Upper Basin and the Lower Basin. Fig. 3



Fig. 1 Colorado River Watershed. Ref. US DOI, Bureau of Reclamation.

Hydrology of the Colorado River

The headwaters of the river are in the Rocky Mountains in Wyoming, Colorado, Utah, and New Mexico. This region receives most of its precipitation as snowfall during the winter. In the spring, snowmelt generates the runoff that accumulates from different tributaries along the upper basin. Fig. 4.



Fig. 2 The Upper section of the Colorado River.

This part of the river has a steeper slope and higher energy than in downstream reaches. It has over 25 major tributaries, being the largest ones the Green River from Utah, Gunnison River from Colorado, and the San Juan River from Utah.

Before the dams and reservoirs were built the river's, flow averaged 15 million of acre per year (MAFY). In fig. 5 it is possible to observe the great annual variability of the flow volume. These records over 100 years

long are complemented with climate correlation variables such as lake sediment deposits, tree-ring widths, and coral bands. Tree rings have been studied extensively in the Rocky Mountain and northern Utah (Gray, et al, 2004). Scientists have reconstructed the history of drought in the southwestern US, determining that since 1226 A.D. nine droughts of 15 to 20 years have occurred in the Colorado River watershed. The last part of the graph shows the initial stages of the present drought in the Colorado Basin, which started in 2000 and continues through 2020 with minor interruption in 2018, Fig. 5

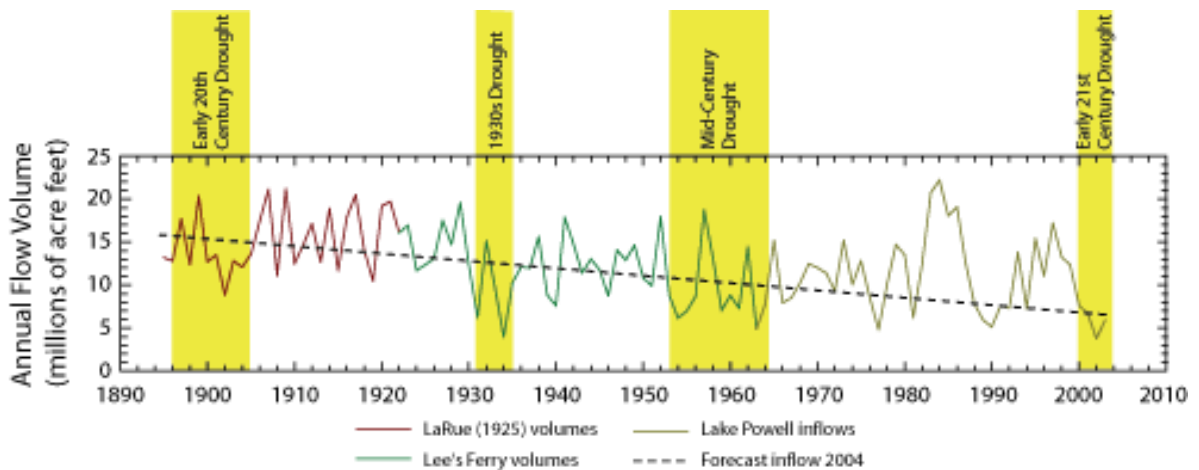


Fig. 2 Annual Colorado River Flows at Lee's Ferry (1895-2004) USGS.

Most of the central part of the Colorado basin is a dry region, with scarce precipitation. The tributaries add to the river flow that enters the large deserted areas including the Grand Canyon of the Colorado. Fig 6.



Fig. 3 The Grand Canyon of the Colorado River in Arizona

It was about 5 million years ago when the Colorado River established its present course into the Gulf of California (Prisciantelli, 2002). The sediments of the Grand Canyon were deposited on the delta when the river discharged to the sea. Major tectonic process created the Gulf (Young, Spamer, 2001) between the Pacific and North American tectonic plates. A combination of divergent and transform plate boundary motion is opening the Gulf of California, causing the Baja Peninsula to separate from the rest of Mexico and moving northwest with the rest of Southern California Coast along the San Andreas Fault, which connects with the

East Pacific Rise, generating a Mid-Ocean Ridge under the Gulf of California, Fig. 7.

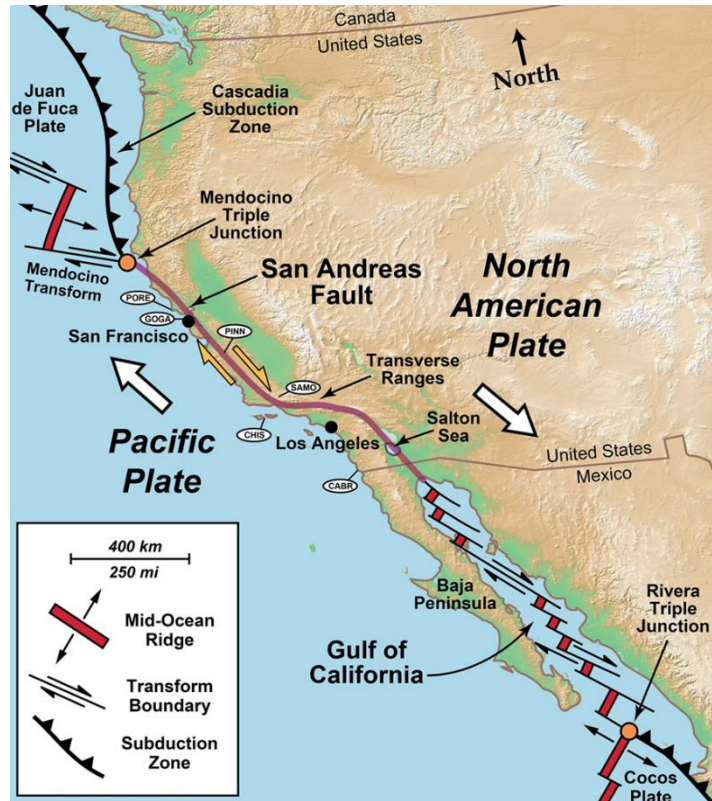


Fig.7 Pacific and North American Plates, Gulf of California, San Andreas Fault.

The lower section off the river in the delta region had frequent course changes caused by seasonal flow variations. Beyond Yuma, AZ, at the confluence with the intermittent Gila River, which carries runoff from western Arizona, the Colorado River enters its delta, which is a large alluvial fan where the river's course varied periodically. By reviewing the natural history of the delta, it is possible to understand this critical condition. The Mexicali Valley is the lowest part of the Colorado River

basin, it is a large alluvial plain formed by the sediments of the Colorado River as it flowed into the Gulf of California.

The Mexicali Valley

The Mexicali Valley encompasses the lower reach of the Colorado River as it reaches the Gulf of California. The valley is at 32° 30' North and 115° West, in Mexican territory. The events and actions in the upper basin influence the delta. The Imperial Valley in Southern California, and the Mexicali Valley in Baja California are the north and south parts of the Delta formed during two million years of Pleistocene glacial ages and sedimentary deposition (Alles, 2011). Both valleys have the same geological history and salinization risk. They are the result of two major geologic processes: the collision of the Pacific and North American Tectonic Plates, and fluvial deposition by the Colorado River. The interaction of both processes renders the Delta's geology complex. Fig. 8.



Fig. 4 Delta region, Mexicali Valley, Gulf of California. NASA. May 2011.

The Tectonic Process

Along the West Coast of the US the Pacific Plate has subducted under the North American Plate. The Central Coast and the Peninsula of California form part of the Pacific Tectonic Plate, which is moving to the North West along the San Andreas and San Jacinto faults (Cohen & Henges-jeck, 2001). These dynamic fault systems cross the Colorado delta region, and they connect to the larger Eastern Pacific Rise, which separates the Peninsula from the North American Plate¹. (Fig 9).

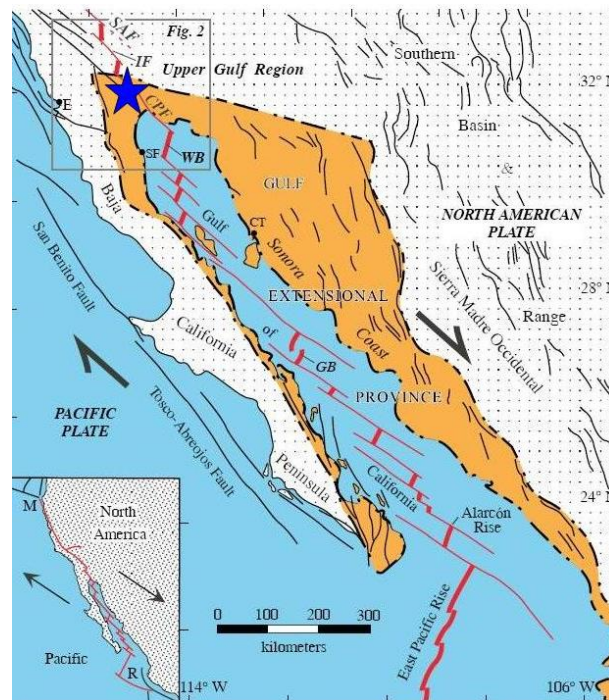


Fig. 5 San Andreas Fault, Eastern Pacific Rise, Gulf of California, Bol. Soc. Geol. Mex v.61 n.1, 2009).

¹ Atwater, Tanya, 1981, Propagating rifts in seafloor spreading patterns. Nature, v. 290, p. 185 186. UCSB Department of Geology Emeritus Professor.

The region is geologically active with spreading centers and transform faults under the delta. The magma ejections formed basaltic ranges along the fault systems. When water from the aquifer reaches the magmatic fields water vapor rises to the surface heating and reacting with the sediments from the river, in a continuous tug of war. Fig. 10.

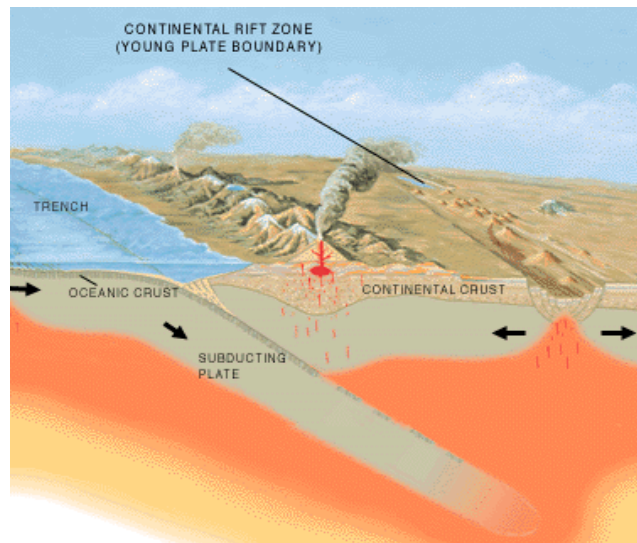


Fig. 6 Subduction of Pacific Plate, spreading center, and rift zone.

Tectonic processes are the strongest movements on the lithosphere that create and destroy continental boundaries. They cause most of the major earthquakes and volcanic activity. Fig. 11. The West Coast of the US is one of the most geologic active regions in the world and it is the northeastern part of the Ring of Fire of the Pacific Ocean Plate. The delta is at the intersection of powerful geologic and hydrologic processes that still active and transform the region.

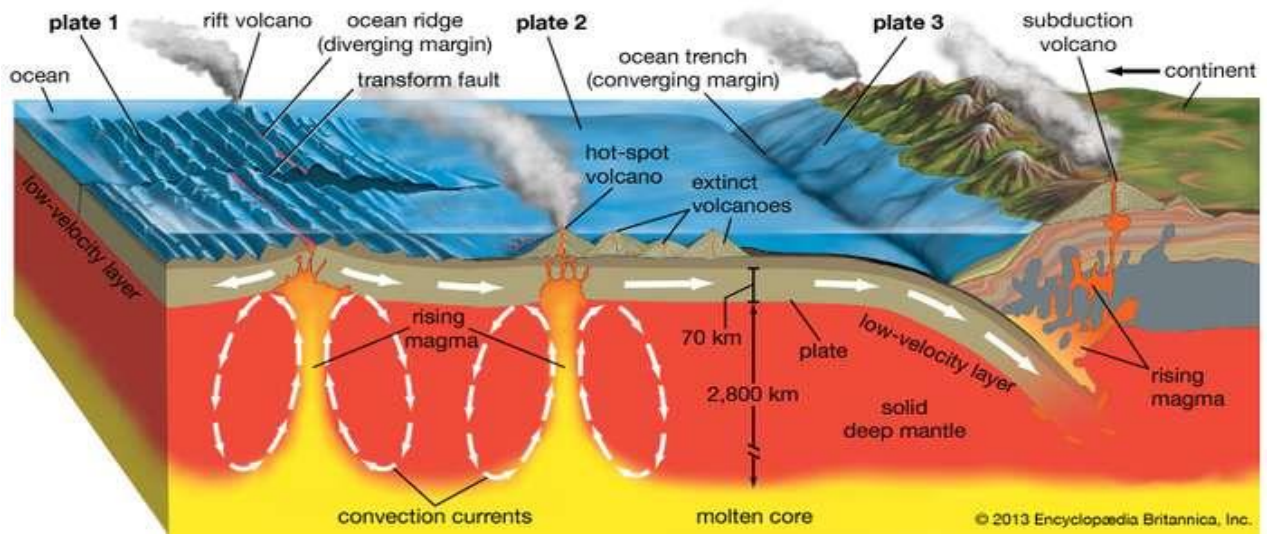


Fig. 3 Subduction zone and volcanic activity. Encyclopedic Britannic.

Colorado River Delta

River processes are continuous. The deposit of sediments carried by the Colorado river slowly built its delta, which covered and hid the tectonic features until the geologic stress reaches a breaking point releasing an enormous amount of energy, in the earth crust (Argone National Laboratory, 2013). Tectonic events reshape the region along the fault zones, generating volcanism, earthquakes, the emergence of new ranges, and geothermal processes. The Colorado River flows to the Gulf of California that separates the Peninsula from the continental plate. The sediments of the river filled the rift that continued to open along the major East Pacific Rise. The Salton Trough is an active continental graven, defined by the San Jacinto and San Andreas Faults, part of an oceanic spreading

system into which fluvial processes discharged thick sediments on top of the tectonic faults, forming alluvial fans and dynamic wetlands. Fig. 12.



Fig. 12 Alluvial Fan and Delta at The mouth of the river.

The sediments transported by the river built the delta as a natural earthen dam across the northern part of the Gulf of California, separating the Salton Trough from the Sea of Cortez (Imperial Irrigation, 2017).

The delta formed a wedge along the Salton Trough. The northern tip of this tectonic wedge ends near Palm Springs, California. The southern part reaches the Gulf of California. Large geothermal fields are located in the transform faults rifts in Imperial Valley, and the Cerro Prieto field in Mexicali. Delta sediments influence the mineralization in the rift. The combination of tectonic activity, magmatic heat, fluvial sediments, and saline lakes is a unique environment for metalliferous hydrothermal brines. The sediments of the Colorado filled the ridge leaving to the north side an

isolated marine lake, ancient Lake Cahuilla, ranging from the junction of the Colorado and Gila rivers to Indio, California (Alles, 2011).

Salton Trough and Lake Cahuilla

This ancient lake used to be in a low area. Its bottom was 85.3 m below sea level. At present, Salton Sea water level is 69.2 m below sea level. The elevation of the Colorado River at its junction with the Gila River was about 36.6 m above sea level implying a 106 m elevation difference along the river's course, a steep gradient. The Colorado River flushed sediments, refilling Lake Cahuilla for about two decades until the lake reached a critical level and started flowing to the Sea of Cortez, redirecting the river path to the south (Fig.13). The lake underwent desiccation, and after a few decades, the Salton Trough became a desert. The dissolved salts stayed on the dry bed of the desiccated lake, until a new flood dissolve them again. These salts have been in the region since the sea transgressions (Olmsted, Loeltz, & Irelan, 1973). Being under sea level, they cannot be drained by gravity flows. The river sediments cover some of the salt lenses. Floods came and fresh water infiltrated the soil layers dissolving and dispersing salt through the whole water body (Fig. 14). The Colorado River filled the ancient Lake Cahuilla many times during its geologic life. High evaporation rates dried the lake, when the river changed its path leaving behind the marine salt. The water

evaporated repeatedly. The river sediments refilled the breaches causing again a separation between the Lake and the Gulf of California. This process left a salt path in the layers of the delta. Geothermal activity brings salts to the surface.



Fig. 7 Salton Trough, Lake Cahuilla, and Delta regions.

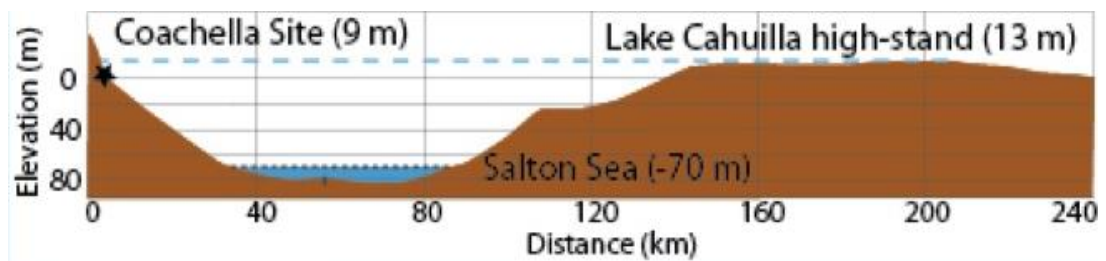


Fig. 8 North-South Profile of the Salton Sea (-70 m). Source UCSD.

Groundwater pumping along the path of the ancient Lake also has revealed high salinity². In April 2011, there was a major earthquake in the Mexicali Valley. Sand liquefaction and brine ejection were present along the fault provoked by the earthquake. Salt deposit were present after the ejected water desiccated. (Fig. 15).



Fig. 9 Salton Sea salinization problems.

In summary, the Colorado River increased its delta with sediments, and the Cahuilla Lake refilled with fresh water when the river changed course towards the Coachella Valley. The river water filled the lake for many years until it reached a critical level and then started to flow into the Sea of Cortez again, triggering the drying of the lake (Tompson et al., 2008). The ancient salt deposits in the Cahuilla basin dissolved in the fresh

² California Government. (2007). California Department of Water Resources. Retrieved September 9, 2017, from <http://www.water.ca.gov/saltonsea/documents/history.cfm>

water and made the evaporating lake saltier, and hostile environment to support life. Some species migrated to environments that are more benign; others adapted to these harsh conditions until survival became impossible.

This summarizes the Pleistocene and Holocene geologic history in the delta of the Colorado River. It is possible to observe the history in the walls of canyons and crevices in the region. This is an indication of the existence of salty water in the strata of the aquifer, especially along the natural channel formed by the lake along its desiccation pathway, Fig. 16.



Fig. 16 Ancient Lake Cahuilla desiccation path and salinity.

Hydrogeology of the Delta

The Colorado River changed its course within its the delta many times, sometimes flowing to the north, at others to the south, creating and abandoning its channels. During the glacial periods, the sea levels were lower, and the continental glaciers tied up vast amount of water. During the interglacial periods, the ice melted, and larger amounts of water and sediments washed to the sea. The sea level rose, covering part of the delta deposits with salty water. These dynamic processes formed the delta. The multilayered aquifers of the delta have a high probability of containing salty layers (Moncada-Aguilar, Ramírez-Hernández, Quintero-Núñez, & Avendaño-Reyes, 2010).

The compressible nature of some saturated sediments allows for subsidence in the delta. The local ranges run parallel to the fault systems, which allows extrusion of magmatic material, with basaltic and rhyolite characteristics. A very active fault system crosses the Mexicali Valley is the "Sierra de Cocopah", a volcanic uplift with hot springs at its base, which are an important source of thermal energy along the Salton Trough. There are many geothermal power plants in the delta on both sides of the international border. Volcanic activity moves sulfur salts into the aquifer, which are a major concern due to their corrosive potential in the geothermal plants (Miranda-Herrera, 2015).

The stratigraphy of the aquifer is made of Quaternary alluvial and deltaic deposits. It is unconfined, with a minimum saturation thickness of 500m. The Imperial and Mexicali valleys are a single heterogeneous aquifer with strata of variable interspersed gravels, sands, silts, and clays. Clay layers are more common in the western and southern sides of the aquifer, which can cause localized aquifer confinement³ (Alles, 2011)

The precipitation in the delta area is very low (50 to 200 mm/year), most of the water of this region comes along the Colorado River, 1,850 Mm³ /yr. Potential evapotranspiration is very high, about 2,000 mm/yr due to the region's hot and dry climate. The area would be a desert without the water input from the river, which flows from northeast to southwest, with a gentle slope along the delta (Cohen, Henges-Jeck, & Castillo-Moreno, 2001). The aquifer features gravel, sand, silt and clays strata, and some cobbles-gravel-sand veins that mark the ancient alluvial channels of the river. This geology makes a good aquifer. There are some layers of shale, and volcanic ashes. All of these soils are a good combination for agricultural purposes. The presence of salty layers to the southwest of the valley is a limitation to farming. This is the remnant of the ancient Lake Cahuilla (Dainier, 2005).

³ CICESE. (2005). *Pozos Mesa Arenosa SLRC*.

Ecology of the Delta

The Colorado delta is one of the largest desert estuaries in the world. Its abundance is shared by birds and other terrestrial species, both plant and animals. The marked seasonality of the river made this region a unique and active ecosystem. The river and sediments used to reach the Sea of Cortez generating a rich coastal aquatic environment. In deeper waters the submarine tectonic rift generates geothermal flows that promote a great diversity of marine environments, Fig. 17.

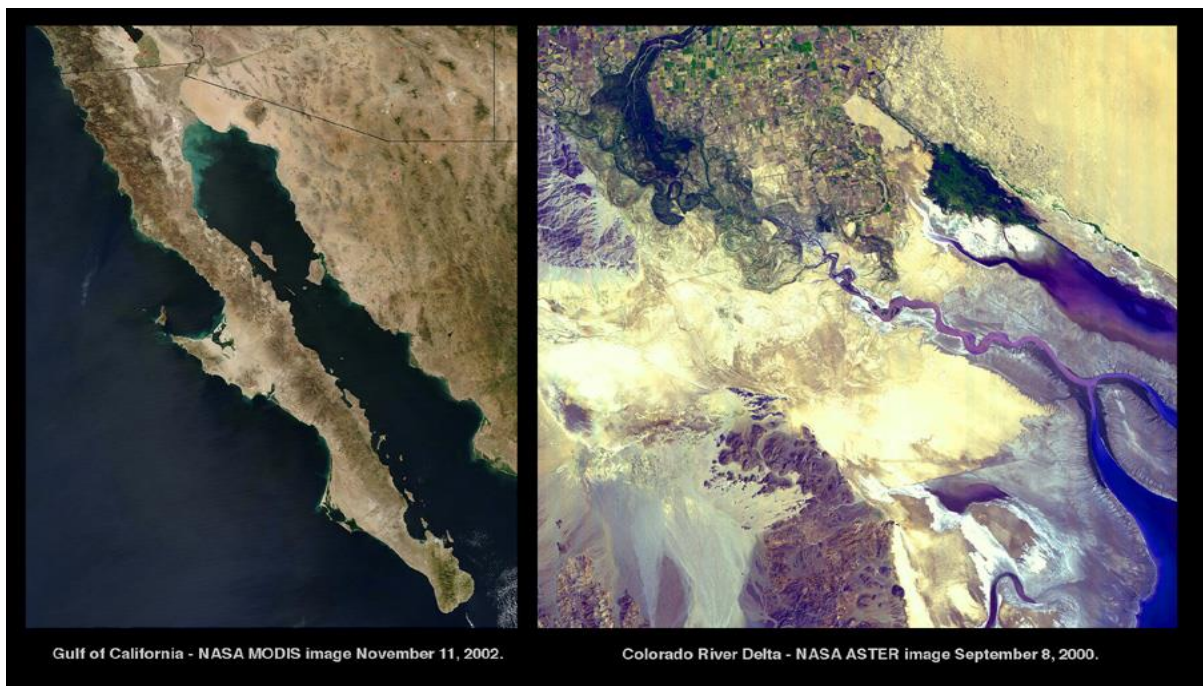


Fig. 10 Satellite images of the Delta region. Sediments in the Sea of Cortez.

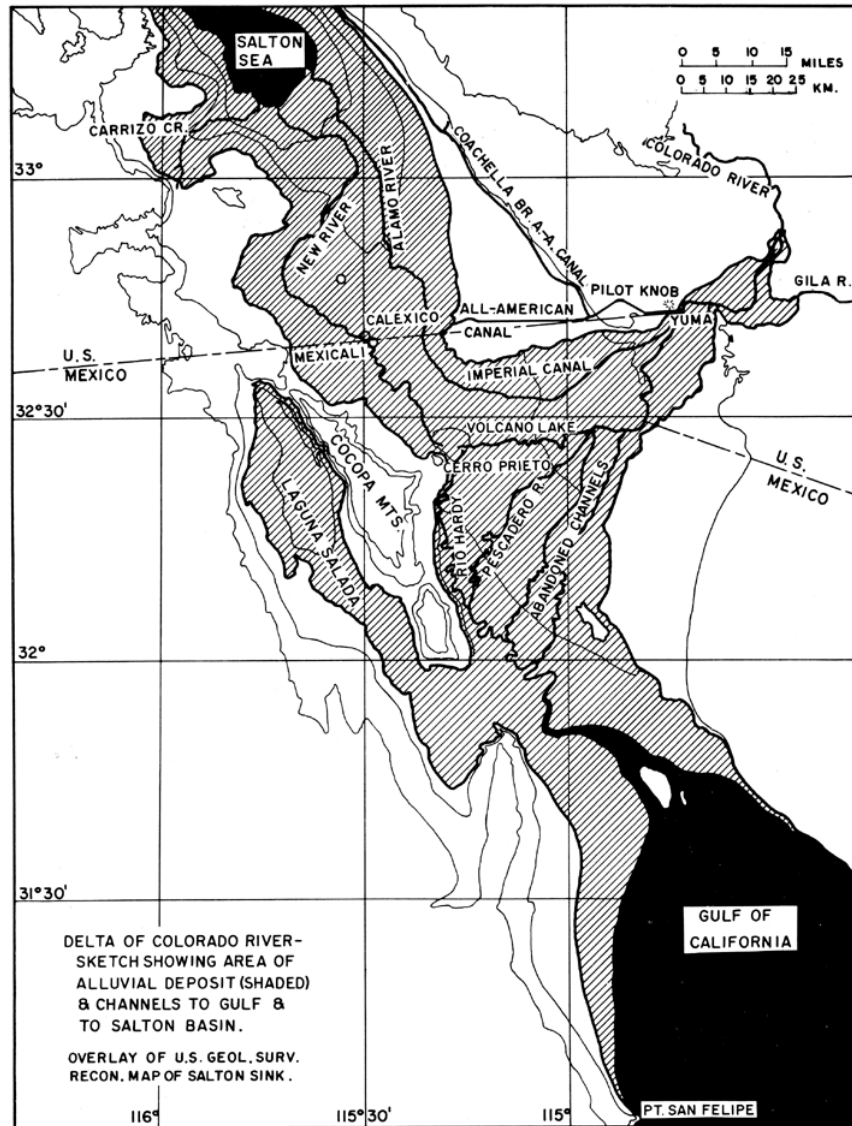


FIGURE 1. Delta of the Colorado River. Based on U. S. Geol. Surv. Map of Salton Sink, 1908.

Fig. 11 The Delta in 1908, before Hoover Dam construction in 1936.

The sediments of the Colorado River formed the delta, and an active marine ecosystem. After construction of Hoover Dam this region harboring wetlands changed dramatically. The dry delta has currently a vastly different appearance and functions differently. The high tides of the Gulf

move upstream a long distance, leaving salt on the coast, and causing sediment erosion when receding, Fig.19



Fig. 12 Sediment erosion in the delta. The wetlands vanished.

The Climate of Mexicali Valley

The Mexicali Valley has a Mediterranean desert climate, very dry and hot during the summer. The annual average temperature is 22.9 °C, with lows in winter of 3 °C, and maximum during summer of 52 °C. Rain is the only type of precipitation. It falls during the winter with annual average of 70 mm/yr. (2.79 in). Minimum precipitation on record is 56 mm/yr. (2009), and a maximum of 145.8 mm/yr. (6 in, 1992). Occasionally, it may rain in the summer due to tropical storms forming over the Pacific Ocean that move northerly through the Gulf of California. Evaporation varies from 304

to 380 mm/year, much higher than precipitation. Potential evaporation is much higher, yet there is not open water to evaporate. Winter is warm. Atmospheric humidity is usually very low except during the "Gulf surges," when maritime tropical air mass from the Gulf of California moves northward, usually in connection with the summer monsoon or the passage of a tropical storm from the south. On average winters freezes are fewer than 1 every 5 years, and about 120 days per year the temperature reaches or exceeds 38 °C (Smerdon et al., 2007).

Natural Risks

Earthquakes are a constant threat in the Mexicali Valley region. The latest major earthquake was in April 2011 (7.2 Richter scale), and it aligned with the San Jacinto Fault, very close to the Cocopah Sierra. Sand liquefaction and fluid extrusion that accompany earthquakes brought to the surface minerals and saline waters.

The Sierra de Cocopah and the Sentinel Mount are of recent volcanic origin, with igneous rocks found on the western side of the aquifer. These volcanic ranges have separated the "Laguna Salada" (Salty Lake) from the rest of the Mexicali Valley. The ranges harbor an active fault system that could cause tectonic displacement at any time (Moncada-Aguilar et al., 2010).

Interruption of the aqueduct service to Tijuana and the coastal cities due to a major earthquake is a considerable risk. There is a contingency plan to repair the aqueduct in case of earthquake damage.

Heat waves are a common thread during the hot summers, when diurnal temperatures reach 45 °C. Small farming communities and poor neighborhoods in Mexicali and San Luis Rio Colorado are vulnerable. There is an alert system and first responder team. Before the hot season, there is a public awareness campaign released.

Flash flows are frequent in the desert. Usually the soil is dry and hard and has low storage capacity. A flash flood can destroy homes, crops, infrastructure, and endanger population.

Small tornadoes in the dry desert may destroy specific areas. They are difficult to predict and are capable of disrupting traffic and cause accidents. They pollute the environment and can propagate fire.

In the coast, tidal erosion is strong and it is eating the coast continuously. The north extreme in the Gulf of California has high tides of 30 feet, which move faster along the dry channel of the Colorado River. This fast tidal it is dangerous for uninformed tourist and visitors. The erosive action of the tidal currents is changing the ecology of the coastal area. Sediment and salt concentration is different to what use to be before the Hoover Dam. There are some endemic marine coast species

that are in risk of extinction due to habitat lost. Fishermen and ecologists struggle to find a balance point between the survival needs of families and the required conditions for survival of endangered species.

Most of these risks affect disproportionately the poor, making their living conditions harder. It is difficult to protect impoverished families in the rural areas of the desert. Most of them migrate to the border cities, looking for jobs and opportunities to cross the border and enter the US. Many of the migrants are hired as temporary farm workers in California and Arizona. Their mobility hinders tracking them and providing assistance. The cycle of poverty increases with increases risk of natural disasters.

Chapter 2

Human History in the Delta and the Colorado River

The Mexicali Valley Location

Many people and activities share the water from the Colorado River, in a complex legal and administrative system. To understand the struggles and find feasible solutions it is necessary to know the history of the region and its specific environmental conditions. It is difficult to analyze only one sub-basin of a larger watershed because all of them are interconnected. The Mexicali Valley in Mexico is located in the lowest reach of the Colorado River, across the border with the US. Fig. 20



Fig. 20 Location of the Mexicali Valley Aquifer.

Native Americans in the Southwest

America was the last continent populated by humans. Most of its regions had extensive natural resources that allow human settlement and the creation of functional societies. The American southwest is a region with diverse natural resources; yet the natural provision of fresh water is typical of that found in arid and semi-arid regions in most places. . Native American groups inhabited the region and traded actively. Tribes inhabited the riparian valleys and the delta in the lower part of the Colorado River. This condition prevailed in the American Southwest until about 1800, when pioneers of different nationalities came to the region (Johnson, 2013). Fig. 21

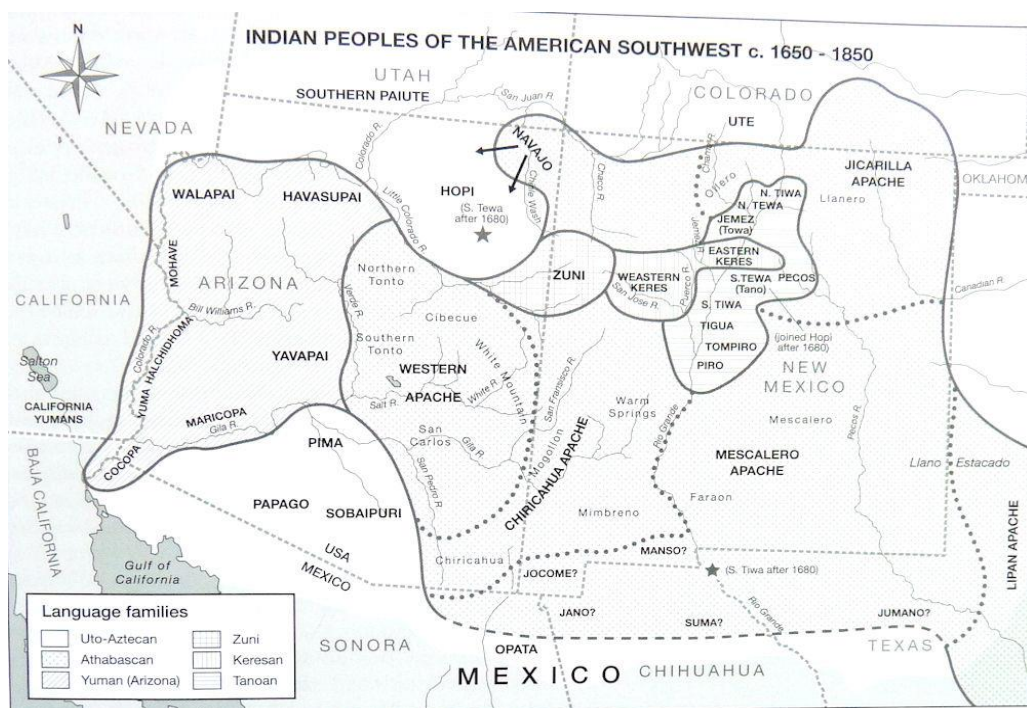


Fig. 13 Southwestern Native American Tribes. Johnson, 2013.

European Colonization of the American Southwest

Spaniard soldiers and priests were the first European pioneers in the American Southwest. Spain attempted to expand its colonial territory from Mexico by extending north into Alta California through a series of expeditions and establishing Christian missions and towns to convert the Native Americans, and at the same time claiming the occupied territory for the Kingdom of Spain. Many other European powers wanted colonies in America, and they sent other expeditions. The struggles, disagreements, and wars between the European powers extended from Europe to America. The strongest army would keep the territory. The American southwest was up for grabs.

During the Spanish occupation from the 16th through the 18th Centuries, the region was mostly unknown to the colonizers, and it was very difficult to settle. The environment was unique, and communication with the local tribes difficult. Pioneers introduced agriculture; but water and fertile soil were limited resources in the region. Survival was the priority. Spaniards and Mexicans first, US citizens and other immigrants later colonized the region. The Colorado River basin is a natural mosaic of physiographic regions, ecosystems, and cultural differences. In 1821, Mexico became independent from Spain. Mexico and local descendants of 18th century colonizers claimed the American southwest. The region was

appropriated in 1848 by the US following the Mexican American War. Over the last two hundred years the territorial claim of part of the Colorado River basin shifted from Spain, to Mexico in 1821, and to the US in 1848, which modified political boundaries, land tenure policies, and economic activities, all struggling for water (Potter, 1997)

Farming Development in the Delta. The Imperial Valley

The second half of the ninetieth Century brought to the region a great flux of immigrants. Many of them immigrated lured by the desire of quick enrichment during the Gold Rush in California and the southwest. Once the gold rush waned, farming and ranching became important economic activities. The US Congress encouraged colonization of the Colorado River territory (Potter, 1997). In the last decades of the 1800's a large number of pioneers settled in the US West. They introduced improved agricultural technology in the delta region (Brown, 2001). Successful agriculture was a difficult endeavor due to the inclement climate and the variability of river flows. Sometimes water was plentiful sometimes it was scarce. In 1869, the American naturalist John Wesley Powell led the first recorded expedition along the Colorado River. He reported to the US Congress the water scarcity of the region in an 1879 report on the arid lands of the United States that exerted enormous influence in guiding federal water

policy in the American West well into the 20th century (Powell, John Welsey, 1879).

At the end of the nineteenth Century land developers invited farmers to settle in the delta of the Colorado, and attempts were made to tame the river and irrigate the land (District, 2017). The fertile soil and weather of the Imperial and Mexicali valleys were favorable for irrigated farming. The irrigation district was diverting water from the river when in 1905 a flood overtopped the riverbanks and directed the river course towards the north for three years, flooding Mexicali and the Imperial Valley. This accident formed the Salton Sea. Fig. 22



Fig. 22 Colorado River floods 1905-1907. Salton Sea. Imperial Valley, CA.

Many pioneers evacuated the zone; all their property and belongings were abandoned under the Salton Sea water. The Federal government relocated farmers who operated in the Imperial Valley and intervened to return the river to its previous course discharging to the Gulf of California. This event prompted the Federal government's intervention seeking to engineer the Colorado River and extract beneficial use of its water. Funds were an issue, and the project to control the river had to wait for thirty years (Alles, 2011).

After a few decades, the Salton Sea became saltier. Many factors contributed to the salinization of the Salton Sea, but one that went little noticed was the existence of salt deposits at the bottom of the Salton Sea. Water salinization is a problem in the Colorado River Delta because of the convoluted geology of the region. The early pioneers who settled the delta, as well as the Mexican authorities, were unaware of the salinization risk.

The southwestern states received land and water rights from the Federal government, and the states allocated these water rights to their users. The management of the river followed the prior appropriation principle: first in time, first in right (Reisner, 1986). A well-known legal doctrine that worked well in humid areas such as the eastern coast of the US. Pioneers delimited the borders of the new states and worked with

unwavering determination. However, the erratic hydrologic regime of the Colorado River complicated the allocation of water in a just and fair manner. Struggles for water were intense, and soon they became very complex; often the Federal government had to mediate between the parties.

The rogue nature of the river was an obstacle to benefiting from its flows. It was impossible to predict when the river would have a major flood; many times, the river flooded farmlands and towns. Most of the precipitation falls as snow during the winter months in the upper reaches on the western side of the Rocky Mountains. During spring snowmelt flows towards the lower reaches. Before construction of hydraulic infrastructure, floods caused extensive damage to farms and small cities along the river. After the intense spring runoffs, water became scarce for the summer and fall. Farmers and towns along the riverbanks suffered from lack of water, or an excess of it. Farmers wished to regulate the river floods, but these were too large to tame without federal support (Farr, 1918).

The Colorado River Compact 1922

The US Congress approved the Colorado River Compact in 1922 to resolve the water conflicts, avoid disasters, and promote the development of the Southwest (States, 1922). The hydrologists of the Department of

Interior (DOI) estimated the average annual river flow as 15 Million of Acre Feet (MAFY) at Lee’s Ferry location. The US government allocated the Colorado River water between the upper river states, with fifty percent of the water, or 7.5 MAFY, for Wyoming, Utah, Colorado, and New Mexico; the other fifty percent (7.5 MAFY) went to the lower river states: Nevada, Arizona, and California. Mexico asked the US Congress for water allocation and received 1.5 MAFY, which was 10% of the original flow measured at Lee’s Ferry.

Table 1. Colorado River Water Allocation (States, 1922). 1 Mm³ = 10⁶ m³

User	Allocation (MAFY)	Allocation (Mm ³)	Share (%)
Wyoming	1.06	1,307	6.4
Colorado	3.88	4,786	23.5
Utah	1.72	2,122	10.4
New Mexico	0.84	1,036	5.1
Upper Basin	7.5	9,251	45.5
Nevada	0.3	370	1.8
California	4.4	5,427	26.7
Arizona	2.8	3,454	17.0
Lower Basin	7.5	9,251	45.5
Total USA	15.0	18,502	91.0
Mexico	1.5	1,850	9.0
Grand Total	16.5	20,352	100

The states would in turn distribute their allocations within their territories according to their water laws; otherwise, they could lose their water rights. The Imperial Valley Irrigation District received large water rights and support for establishing a successful farming operation (Farr, Elms, 1918). Soon the water conflicts returned. The upper basin states claimed that California was taking too large a volume of water.

Most of the states needed hydraulic infrastructure to use the water, which was expensive. The US Congress approved a plan to irrigate and to protect the lower part of the Colorado River watershed; the Bureau of Reclamation (BOR), the Army Corps of Engineers (ACE), and the Bureau of Land Management (BLM) were in charge of developing that plan (Udall & Overpeck, 2017).

The BOR built dams to produce electricity (hydropower). The ACE built control dams to avoid flood risks. The BLM coordinated the development of irrigation districts. The western states received a large federal investment. In this context, the Colorado River represented a special challenge, since it caused major disasters. The DOI, developed an ambitious plan, and decided to dam the Colorado River. They looked for a site where to build the dam; after many proposals, the engineers chose Boulder Canyon to build Hoover Dam. It was a major project which

required a series of special agreements to fund and built the dam (Department of Interior, 2017b).

Controlling the River. Hoover Dam

The DOI built Hoover Dam, close to Las Vegas, Nevada. A major dam built in the middle of the desert during the Great Depression (1933-1936) was a significant accomplishment. For the first time in its history the Colorado River was under control. Hoover Dam became a symbol of American ingenuity and engineering capacity. Hence, the Colorado River began generating hydropower, irrigation water, drinking water, and recreation benefits, and environmental improvements. The economic development of the Southwest was spearheaded with great momentum (DOI, 2012).

Nevertheless, due to its location, Hoover Dam benefited mainly two of the lower basin states, i.e., Nevada and California. For the upper basin states (UT, WY, CO, NM) where most of the precipitation falls it was difficult to gain from their water (Department of Interior, 2017a). The upper states encompass mountainous regions and cultivation is relatively challenging. They needed to engineer a large and expensive hydrologic infrastructure. On the other hand, after Hoover Dam initiated operations in 1936 California farmers enjoyed the works of hydraulic infrastructure. The Imperial Valley in southern California already had a well-organized

Imperial Irrigation District (IID) (Farr, Elms, 1918). California farmers received the largest water allocation, 3.3 MAFY, and used it extensively. The other states and Mexico did not have the same opportunity when Hoover Dam began operation. The stakeholders in other states were afraid of losing their water rights if they did not establish a beneficial use for them.

Ecological Transformation of the Delta

The flow regime of the Colorado River changed dramatically following Hoover Dam operations in 1936. Lake Mead receives and holds water and sediments from the river. Without the natural flows and sediment load the ecology of the estuary changed radically. Many plants and animals perished, and other species emigrated from the estuary region. New species flourished in the new environmental conditions. The loss of freshwater flows to the delta reduced it to about five percent of its original extent. This was one of the fastest and most pronounced environmental changes in the world. The Delta has become a desert without the flow of the Colorado River (Kerig, 2001).

At the same time across the border, Mexico was recovering from the Mexican Revolution (District, 2011). In the late 1930's, the Mexican government was allocating land for cooperative farming in the Mexicali

Valley on the delta of the Colorado River. The US objected this socialist system and the struggles for the land and water that it engendered (Ejido, La, & Del, 2016). Before agricultural development and the construction of the Hoover Dam in 1936 the Mexicali Valley was a desert delta-riparian system, with about 115 km of riparian environments, close to 7,800 km² of estuaries and wetlands defined by the irregular flows of the Colorado River, and thriving with aquatic life.

The hydrologic infrastructure transformed the natural ecologic balance of the delta into a successful farming region. The ecological cost was very high, and many native species, both terrestrial and marine were adversely impacted some are at risk of extinction. The Delta used to be a strategic point on the Bird Pacific Flyway (California Government, 2007). Now it is just five percent of what it was less than a century ago. For a while, the Salton Sea became an excellent habitat for birds and other species that migrated there. The creation of a lake in the northern part of the delta had happened many times in the past, recall the ancient Lake Cahuilla, when the river changed its flow-path towards the north (Tompson et al., 2008). However, this time the Salton Sea has become saltier and polluted with farming chemicals and waste, making it harder for the species to survive and thrive in the degraded environment. There are no longer estuarine zones in the delta.

The river carried sediments from the upper reaches to the delta. The construction of dams and reservoirs along the river reduced the sediments in the Colorado River. The dams and lakes in the watershed trap them. During high tides in the delta the seawater flows upstream along the river into the flat delta, carrying back sediments, and leaving salt residues (DOI, 2012). Changes have occurred in the Gulf of California, also, where the salinity and sediment content has changed. This loss of sediments has modified the environment of the delta and coastal marine ecosystems. It stopped the accretion of the delta, now the strong tidal currents are eroding the estuary, Fig. 23 (Government,2010).



Fig. 14 Satellite image of the Salton Sea, Delta, Imperial, Mexicali Valleys.

Farming Development. The 1944 International Treaty

In 1936, the BOR closed the gates of Hoover Dam to fill Lake Mead. This meant many farmers and cities could not use their total water allocation. Population was small. Therefore, the surplus was stored in the reservoirs and released later according to energy production and irrigation programs (Department of Interior, 2017a).

Short after Hoover Dam dedication WWII began. Funds were scarce; the US suspended most water projects because of its participation in the Second World War after December 1941. The West Coast received many strategic projects and formed alliances with Mexico. The Imperial and Mexicali valleys became strategic wheat and cotton producer regions. The energy and irrigation from Colorado River supported the requirements of the war. In 1944 Mexico and the US signed an International Treaty that guaranteed for Mexico ten percent of the average water flow of the Colorado River (1.5 MAFY) (Series, The, States, & America, 1945).

After WWII, the Federal government constructed more dams to generate electricity. A rapid economic expansion came to the US Southwest*. Many people moved to the region that was receiving increased capital investment. Dam and infrastructure construction returned to the southwest (Bureau of Reclamation, 2008).

The upper river states and Arizona asked for infrastructure that would allow them to benefit from their Colorado River water allocation. The Bureau of Reclamation built the Colorado River Storage Project, a system of six dams on the Colorado and major tributaries, a complete water-control system. The two largest dam-reservoirs are Hoover Dam-Lake Mead (1936) in the lower part, and Glen Canyon Dam-Lake Powell (1966) in the upper part of the basin. They have a storage capacity of 32 and 30 million-acre feet, respectively, about two times each one more than the average annual discharge of the river. Filling these dams took many years, and this was possible since the water demand was smaller than those of the 1970s (Bureau of Reclamation, 2008).

Each state took advantage of diverting their water to irrigation districts and cities inside and outside the Colorado River watershed. The dam-reservoirs system controls the water to avoid floods and to produce hydropower. Water releases irrigate farmlands, supply urban water districts, protect the environment, and generate recreational uses. Water brought great benefits to the Southwest that became one of the most productive regions in the world. By the second half of last Century the delta had developed an intense agriculture thanks to fresh water of the Colorado River (Robison & Kennedy, 2012).

Although fresh water is scarce in the region, especially in the southern part of the watershed, water diversion is so large that the river's flow vanishes before reaching the Sea of Cortez in Baja California. Farmers, cities, and industries use all the available water in the river, which is causing important ecological changes, and is creating new ecosystems in the benefited areas. Thirsty users satisfy growing demand by pumping groundwater, which is a temporary solution since most of the regional aquifers are over drafted, and the overdraft is stressing the old and new ecosystems (Smerdon, et al 2007).

The Mexicali Valley has developed an irrigation district that outgrew the irrigation capacity of the river. To complement for irrigation water the Mexican government has allowed the use of groundwater. In the last four decades, the groundwater extraction has incremented to the point of causing decay in the phreatic levels and water quality. At the same time, the socioeconomic development in the border region between California and Mexico has increased the demand for fresh water and the stress caused by droughts (Samaniego López, 2008).

Water Problems in the Mexicali Valley

Most of the water that enters the Mexicali Valley is through the Colorado River allocation. Evapotranspiration from plants and crops is

large, and it is the larger factor in water consumption. The Delta is one of the sunniest places in the world, conditions that are highly favorable for winter vegetables.

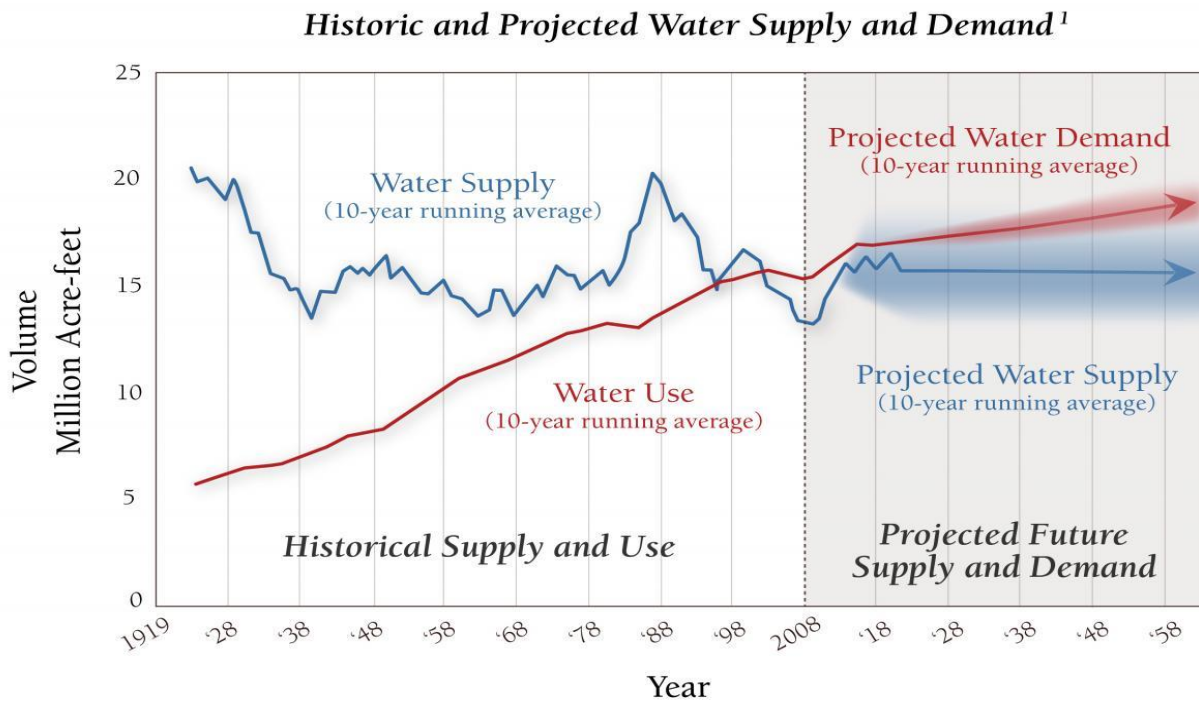
The US delivers the allocated water to Mexico heightening disputes over Colorado River north of the Mexico-US border. One of the most well-known cases is Arizona vs. California, which have engaged in legal battles about their water rights. Over time, when more areas developed in each State, the overall water demand increased and exceeded the average supply. In 1983, an especially El Nino wet year, all the reservoirs were filled, and water overflowed Hoover Dam (Department of Interior, 2017a). That year the Colorado River flowed to the Gulf of California. Many stakeholders became convinced that a rainy year could refill the reservoirs.

After 1983, lower precipitation levels produced smaller flow levels and a lower supply volume in the Colorado system. In the following dryer years, reservoirs released storage water to satisfy the growing demand. Most of the States developed aqueducts to use the water, mostly outside the river watershed. Among the water recipients, irrigation districts and drinking water for urban areas are the most common. Water from the Colorado River reached far away regions. San Diego, CA and Phoenix, AZ, are among the cities that receive water (Walsh, 2013).

During the 1990's the water deficit was relatively small for the reservoirs sizes. Hydrologists and stakeholders had the conviction that one or two wetter years would fill up the reservoirs again. That had happened in the past, and they thought it could happen again. However, increasing development in each state started to use their water up to the limit of their respective allocations. Eventually, the demand reached the average annual capacity of the Colorado River; stakeholders were using all the available water in the river. The following dry years generated water deficits, and the reservoirs covered these deficits. Despite small storage recoveries, the general trend was lower reservoir levels each year (Committee on the Scientific Bases of Colorado River Basin Water Management, 2007)

Since 2000, the deficit has grown in the whole Colorado River watershed(Swenson & Famiglietti, 2014) Year after year, the reservoirs have supplied the water allocations, lowering the storage levels (Fig. 24). Frequently the BOR, which operates the main system and delivers the water in block, must transfer water from one reservoir to another to meet water allocations. In order to deliver and receive water from the reservoirs each State prepares an annual water budget up to the limit of their respective allocation, specifying monthly and weekly deliveries, indicating the location and the time for the delivery. The BOR

accumulates all requirements and prepares a master plan that covers all of them in the best possible way. The major consumer of water is irrigation, yet the reservoirs are multifunctional; they supply drinking water, environmental, industrial, and recreational uses. It is a great challenge to balance all these demands for water (State of the Rockies Project 2011-2012 Research Team, 2012).



¹U.S. Department of the Interior. Bureau of Reclamation. "Reclamation Managing Water in the West: Colorado River Basin Water Supply and Demand Study." (Executive Summary). Dec 2012

Fig. 24 Colorado River Runoff. Water supply and water demand (in red).

Water demand surpassed the capacity of the Colorado River generating a water deficit. Reservoirs first and aquifers later helped to cover the deficits. Levels of the larger reservoirs were falling constantly.

Smaller reservoirs fill and empty each year, that is their regulatory mission. Yet lakes Powel and Mead, on the other hand, have a long-term storage mission, due to their large capacity. Subsequently, the storage in the latter two lakes has been in long-term decline. When water reached critical levels the BOR conducted strategic water transfers to keep operations extant. Volumes for energy production and irrigation must be coordinated carefully (DOI, 2012) . Additionally, drought conditions in the watershed complicated the situation.

The dams in the Colorado watershed grant the water masters a very efficient control of the river, allowing the BOR to execute timely and accurately water diversions for different beneficial uses. The recent water shortages are due to increased demand plus lower than average annual rainfall in the watershed for the last 20 years (2000 through 2020), but not to operational problems. Water shortages affect the entire watershed. Each State used different strategies to overcome this critical situation. For example, Las Vegas, drinking water penstocks at Lake Mead were critically close to no-flow levels (Department of Interior, 2017a). Las Vegas Valley Water District built a lower level gate to supply its customers. At the same time, Arizona, a state with water reserves in several reservoirs, moved water among them strategically to support its water supply. Initially, these transfers looked like normal operations

(DOI, BOR, 2017). In fact, they became more common. Each year there were fewer options, nevertheless the public believed that heavy rains would restock the reservoirs. It was unfathomable that the largest water reservoirs in the country could be close to depletion. For many years the water levels declined, meanwhile users hoped for wet years. The demand for water increased paired to population and economic development. In year 2000, the BOR estimated the demand equaled the total average capacity of the Colorado River. Once passed the balance point between supply and demand of water the reservoirs delivered complementary water. Soon the deficits accumulated.

Since the late 1990s the flow of the river that crosses the border to Mexico has been used for irrigation and drinking water purposes. South of the borderline, the lower reach of the Colorado River is completely dry. The river used to discharge in the Sea of Cortez, but not anymore, since farmers, cities, ranchers, and industries divert this water. In the Mexicali Valley demand grew faster than supply since the number of farmers grew quickly (Cohen et al., 2001).

Negotiations in the Colorado River Allocations

Each State claimed its water rights, calling for the piece of law that best fit their local interests. During the 2010's no one state conceded to

receive less water, fearing to lose part of its water rights. The over-allocations that established the 1922 River Compact made all the states and Mexico to struggle for water. All the States and Mexico asked for their total volume. After technical revisions on the records kept by the BOR and USGS, it became clear that the average annual flow of the river is less than the 16.5 MAFY allocated see Table 1. This allocation was unsustainable (Bureau of Reclamation, 2012).

Disagreements were common due to strong political positions. It required hard work and political skills to bring the parts together in search for a solution. The situation became more complex because of population growth, fast economic development, more than one nation share the watershed, growing water demand for different uses, and a long and persistent drought in the watershed during the 2000's and 2010's decades (Robison & Kennedy, 2012).

The US Department of Interior summoned the States to major meetings. The International Borders and Waters Commission (IBWC) under the Department of Interior called their Mexican counterparts to review this situation. There were high-level meetings to convince Mexico about the lower levels of precipitation and to reduce the water allocation (State, 2017). There were important revisions to the 1944 International Treaty in interim agreements called Minutes. Especially Minutes 319 and

323, wherein both countries established a Drought Contingency Plan based on the Lake Mead level just before the annual allocation. These reduction would increase if the drought conditions and water deficit continue (International Boundary and Water Commission (IBWC), 2014).

Since the 1944, International Treaty Mexico obtains 1.5 MAFY. The BOR releases the water at Hoover Dam through the Colorado River system. It reaches Mexico at the borderline, at Morelos Dam in the Mexicali Valley. Nowadays this dam diverts all the allocated water to the Mexicali Valley's Irrigation District DR 014 through a series of irrigation canals. Fig.25. The river has been dry in parts of the Mexicali Valley for the last two decades (Government, 2010).

The region close to the US-Mexico border became one of the most dynamic in Mexico. Water from the Colorado River supplies drinking water to the coastal cities in Baja California, Tecate, Tijuana, and Rosarito (IMTA, CEABC, 2011).



Fig. 15 Morelos Dam, Mexicali Valley. Close to US-Mexico borderline.

The Year 2020 Status at the Mexicali Valley

The river has been dry in the Mexicali Valley for the last two decades, except for a relatively small Pulse Flow in 2014, meant to help the riparian environment and the Santa Clara Reserve in the Gulf of California (International Boundary and Water Commission (IBWC), 2014). This Pulse Flow was part of the Minute 319 of the IBWC. Most of this water recharged the Mexicali aquifer, showing the strong aquifer abatement. After the pulse flow, scientist from the international group did piezometric measures to define the aquifer recharge and the effect of this water in the environment. After the few weeks of the pulse flow, Morelos Dam was closed to divert all the water for irrigation.

The Irrigation District has water rights to divert all the surface water. Since the demand for water is larger than the possible water supply, users in the valley are pumping additional water from the aquifer, which also supplies drinking water for the cities, industry and communities in the border region (IMTA, CEABC, 2011).

With the use of well water pumps, it was possible to supply the demand for water. The aquifer yields groundwater but may be depleted if extraction remains at unsustainable rates. For a few decades farmers believed that it was possible to extract more water in the delta region with deeper wells and powerful pumps. Unfortunately, the Mexicali Valley aquifer, as many other aquifers in semiarid regions would have a shortened life and water quality issues if the over-exploitation continues (Zektser & Loaiciga, 1993).

All users, including ecologic, and economic interests want to secure their water and there were struggles among them. Therefore, water authorities, development planners, environmentalist groups, academics, and advocates started a series of formal and informal meetings to assess the situation. Called by the CONAGUA, these meetings have promoted a better understanding of the water conditions in the valley. A council that represents different group users meets regularly to analyze the situation; CONAGUA officials submit relevant data for the meetings and they work

an agenda of important issues. Information about the whole watershed is crucial for decision making (Smerdon et al, , 2007). Fortunately, the BOR web pages show the water levels, inflows, and outflows of strategic points in the watershed. It is possible to observe the reservoirs levels and the effect of extended drought. There are important historical data and operation records that allow to analyze the trend in the last decades and extrapolate them in probable scenarios. It is possible to compare real data against the climatic model outputs of the recent years, and choose the most appropriated model. However, a decade has passed without any preponderant recovery in the Mexicali aquifer. Drought conditions continue in the watershed. Nobody can predict when these conditions might change. Even with all the advances in technology precipitation prediction remains unreliable for mid to long terms (Committee on the Scientific Bases of Colorado River Basin Water Management, 2007).

Human and Environmental Risks in the Mexicali Valley

Some vulnerabilities are obvious: decline of groundwater levels, higher pumping costs, land subsidence, wetlands desiccation, and seawater intrusion in a coastal part of the aquifer. Salt can contaminate the groundwater in a sort term due to the strong aquifer overdraft by farmers, industries, and cities in the region. If this trend continues, the

economic and social consequences could be dramatic (Pricope, Lopez-Carr, Pardo, 2016).

Aquifer depletion and water shortage will generate more water conflicts among the water users. Some of these conflicts have caused already riots and social unrest. Sometimes the State government and CONAGUA agreed on new well permits to reduce the social and political pressure (CONAGUA, 2016). Unfortunately, this action increase the extraction and future water deficit. Soon the protests may return. This would create more social unrest and capital investments could slow down at the border region, including Tijuana and Rosarito, where drinking and municipal water is limited.

Mexicali Valley is a desert without the Colorado River water, experiencing heat waves during the summer months. Drinking water and municipal services are vital at those moments. Water districts have a critical responsibility. The Mexican Law establishes that water is a Federal matter. The government allocates the water to specific uses and users, yet water could be required for a high priority use (Spring, 2014). The Law establishes vital human consumption as the highest priority. Therefore, cities and rural communities would keep the minimum necessary supply for drinking water and their basic public services. Vital animal consumption, to avoid animal deaths, is second in priority. Third

priority belongs to urban uses to keep commercial and industrial activities (keep employment and economy); fourth are farming activities, and lastly, environmental protection. Always existing users have priority over newcomers, yet in reality economic power could make an important difference.

On the side of environmental risks water depletion in estuaries, wetlands, and riparian corridors is already causing major ecological losses in habitat for endemic and migratory animal species, loss of native plants, and invasion by exotic ones. There is a risk of salinization of the aquifer, due to seawater intrusion in its southern part. Sand liquefaction is a threat by earthquakes. The Sierra de Cocopah and the Sentinel Mount on the western side of the aquifer are of volcanic origin. These volcanic ranges harbor an active fault system (Argonne National Laboratory, 2013) the generates high temperature effluents. Geothermal plants use these effluents to generate electricity (Moncada-Aguilar et al., 2010), yet their salty brines contribute to the ecological problem in the area.

Land subsidence is an associated risk of water depletion that will cause disruption of vital service networks due to differential soil settlements. Sewage, drinking water, gas and other pipelines will suffer spills and leaking that could cause aquifer pollution, besides of structural damage to buildings, highways, canals, and bridges (Alles, 2011).

In the rural area, there is a risk of aquifer pollution due to lack of sewage treatment. This must be corrected to avoid risk of infections by polluted water or food. Along the US-Mexico border, many regions must deal with sewage treatment. The New River in the delta area was contaminated with urban sewage and farming tailings (Medina, 1996). The New River is in better condition following an novel social project (Peattie et al., 2014)

The aqueduct Rio Colorado- Tijuana crosses the San Andreas –San Jacinto Fault system. This could be a critical issue if a major earthquake occurs in the region. State Water Authority has a contingency plan in case of an emergency. It remains a major risk for the coastal cities in Baja California.

Chapter 3

Estimating Annual Surface of Major Crops in Mexicali Valley

Using Landsat Satellite Imagery

Plant Phenology

The cropping pattern of a region defines the areas occupied by crops and the areas' locations. One of the key tasks in the estimation of the amount of water used in irrigation is estimate the average volume used for each crop during its production or life cycle. This amount is a function of environmental conditions, for a specific crop, place, and time. Each phenological stage of the plant has an optimal moisture level, which is related to the plant environment, Fig. 26. The phenological stages of a typical crop are:

1. Germination: seeding, leaf initiation, emergence, and establishment.
2. Vegetative development: branching, juvenility, rosette, spikelet initiation.
3. Inflorescence development: budding, floral initiation, tillering, booting.
4. Inflorescence: Flowering, heading.
5. Reproductive stage: seed set, grain set.
6. Ripening grain filling, fruit development.

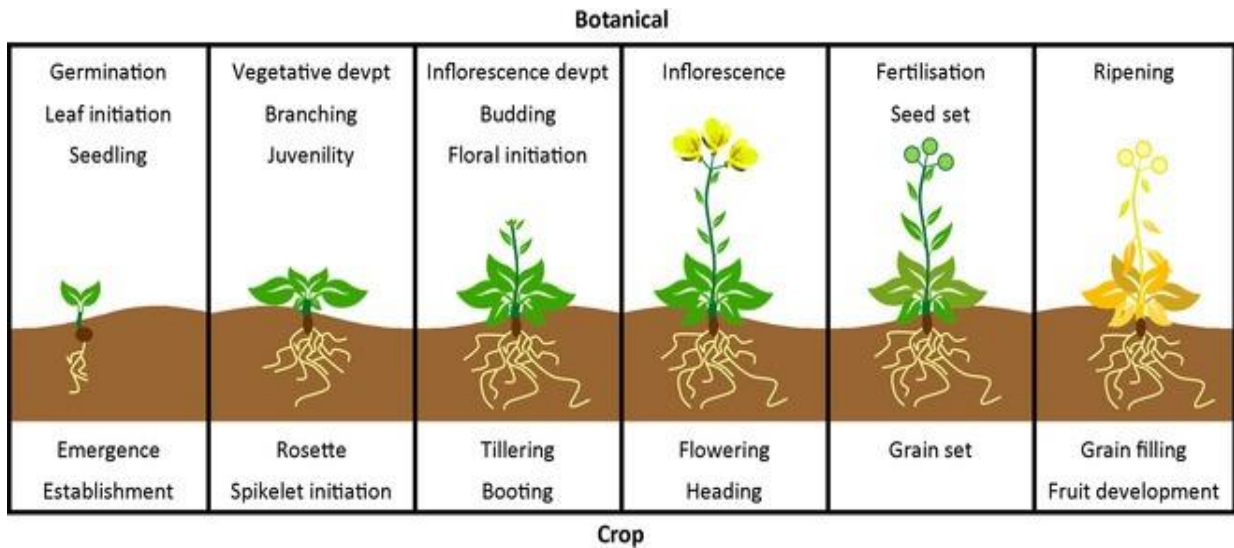


Fig. 16 Phenological stages of crop plants.

Summing the volumes of water used by a plant over time, multiplying the total of volume by the number of plants, and dividing the result by the cultivated area yields the crop water use per unit area, or specific water use by a crop. These results must be modified to account for the irrigation efficiency due to soil characteristics of the parcel, slope, aspect, terrain topography. Agricultural practices in each region have established the specific water uses of crops, adjusted for the specific weather in a season.

Mexicali Valley Irrigation District 014. Farmland

The Mexicali Valley irrigation district has an average allocation of 117 cm of water depth per hectare (area unit = 10^4 m^2), which is

modified according with the type of crop; such as wheat, cotton, alfalfa or other. Modules organize agricultural production in Mexicali Valley. There are 22 irrigation modules (module: a group of agricultural parcels managed collectively by their owners), each of which has an annual volume of water allocated to it. Parcels' owners decide in an annual planning meeting how many hectares of each crop will be planted and irrigated and which farmers will grow them in the planning year. The irrigation district accumulates the water requirements of the 22 modules and petitions the National Water Commission (CONAGUA) to approve the requested water. CONAGUA reviews the module's request and forwards its approved version to the International Water Commission (IBWC) and the Bureau of Reclamation (BOR). The BOR receives the water requirements of all US seven states, and evaluates the requests made by the delegates of other uses of water such as energy production utilities, city water districts, Native Americans, environmental, and recreational agencies. The BOR establishes the operational program for the coming year after evaluating all the water requests. The US Department of Interior informs all the parties of their approved allocations. The water for Mexico is transmitted to the IBWC, which in turns informs CONAGUA and the latter informs the Irrigation District about its water allocation. Up to 2019 Mexico has received its total allocation based on the International Treaty of 1944, which is 1.5 MAFY.

After all the needed authorizations the water flows from Hoover Dam through the lower Colorado River system to Morelos Dam, which delivers the water to the district irrigation canals, to the modules' irrigation ditches, and to the individual parcels. The irrigation water would cover the parcels to a certain depth. Farmers and water masters are present from start to finish of the irrigation operation.

This author visited Mexicali Valley and determined an irrigated area larger than that the allocated water from the Colorado River can cover during irrigation. This can be confirmed by comparing the satellite imagery of Imperial Valley with that of the Mexicali Valley, which cover similar areas. Yet the Imperial Valley has 3.3 MAFY allocated compared with the 1.5 MAFY for Mexicali Valley. This is a remarkable difference in water volume, even though both valleys have a similar climate and farm similar crops. The only alternative for additional water in Mexicali Valley is groundwater. Farmers must withdraw groundwater with wells and electric pumps. It was impossible to ascertain how much water was extracted from the aquifer by relying on well extraction records. In fact, even the number of existing and operating wells proved elusive to determination. The irrigation modules possess that information and treat it confidentially. Many wells do not have meters to determine how much water they extracted every season. Gathering the groundwater withdrawal data and

well data would require accessibility privileges and well-metering actions that call for improved institutional policies and transparency with respect to data access. Updating this information is a major task, even if the farmers allowed visits to the wells. Three types of wells operate in the Mexicali Valley: federal, private, and drinking water (Fig.2). The Irrigation District operates the federal wells, independent farmers and some industrial and commercial activities, including the geothermal energy plants, run private wells. The State (Baja California) government operates drinking water wells. For instance, the well battery that extracts water for Tijuana and other cities has sixty-seven wells. The National Water Commission and the state agricultural department data help to identify the wells and the water use, but information is not readily available and sometimes did not match.

After many unsuccessful attempts to obtain water extraction data from the official sources or the irrigation modules a new strategy was adopted. Instead of direct quantification of the area and crops irrigated, the amount of hectares devoted to each crop was estimated through remote sensing. Satellite imagery was the best option for estimation, and the Landsat series are the longest available and have free public access through the USGS Earth Explorer portal on the Internet. This author

relied on field data to check and calibrate the remote sensing interpretation.

Landsat Satellite Imagery Series

It was difficult to obtain reliable annual amounts of hectares farmed for each irrigated crop in the Mexicali Valley. The Mexican government has reliable information for recent years, but the data have limited access. An alternative method to determine the annual areas of each crop is using remote sensing. Based on the existing satellite imagery it is possible to analyze and interpret the crop coverage. The USGS has an invaluable continuous record of global Landsat imagery series since 1972, and for multispectral imagery since 1982 when the Landsat 4 Thematic Mapper started operations Fig. 27.

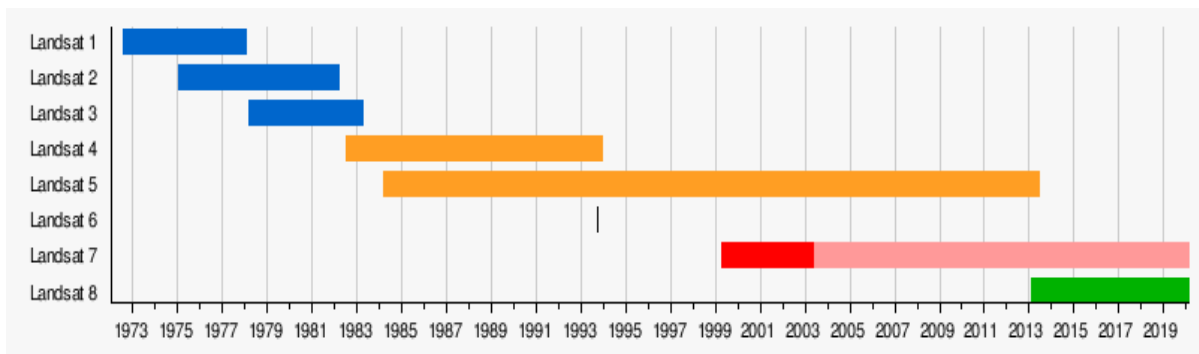


Fig. 17 Landsat Satellites Timeline. NASA, <https://landsat.gsfc.nasa.gov/>

In summary, Landsat surface reflectance data are available worldwide for the following satellite series:

Landsat 8 Operational Land Imager (OLI): April 2013 to present

Landsat 7 Enhanced Thematic Mapper Plus (ETM+): July 1999 to present

Landsat 5 Thematic Mapper (TM): March 1984 to May 2012

Landsat 4 Thematic Mapper (TM): July 1982 to December 1993

New Landsat series allow comparisons among multiple images over the same region, they can account for atmospheric effects such as aerosol scattering and thin clouds and help in the detection of Earth surface changes. Landsat 8 and Landsat 7 Real-Time scenes become available for processing within a few days of data acquisition, with few constraints: over high latitudes (> 65 degrees North or South), at low sun angle, with cloud contamination, extreme low radiance, or few extremely bright targets. Scientists continue improving the correction algorithms Soon there will be better methods to estimate land cover changes. The USGS Earth Explorer (EE) is a very effective online delivery service for satellite images. There are many different products from

studies and projects⁴. Up to February 2020 EE provided three science products: Level 1 is high quality Digital Numbers from satellite sensors; levels 2 and 3 are derived products: level 2 Surface Reflectance and Surface Temperature, level 3 is Dynamic Surface Water Extent, Fractional Snow Covered Area and Burned Area.

NDVI Normalized Difference Vegetation Index

Remote sensing scientists have developed different algorithms for land cover observation. Many vegetation and humidity indexes exist. The Normalized Difference Vegetation Index (NDVI) is one of the most used. One can compare past results with new ones and define time trends in agricultural practices to improve irrigation knowledge in the region. Since many crops have similar water consumption and phenological timing this author grouped them under a lead crop. The growing season of each group is different, making easier to distinguish the lead crop from other groups if specific crop vegetation maximum dates are used (Lenney, Woodcock, Collins, & Hamdi, 1996).

Mexicali Valley has three major crops: wheat, cotton, alfalfa, plus other minor crops like sorghum, corn, vegetables, and some fruit

⁴ USGS Earth Explorer is one of the most popular and well-designed interfaces for a big satellite imagery repository. The number of images and science material is so large than now it must be accessed through a digital system for discovery, and ordering. It supports the searching of satellite, aircraft, and other remote sensing inventories through interactive and textual-based query capabilities.
<https://www.usgs.gov/earthexplorer-0>

orchards. Each one of them has a specific solar radiation reflectance that is captured by the Landsat imagery as the spectral signature of the crop for a specific time. Studies have shown that is possible to distinguish between different crops combining time, plant phenology information, and the NDVI, which uses the red and near infrared wavelengths of reflectance from the crop. $NDVI = (NIR - R) / (NIR + R)$. Where, NIR = Near Infrared, R = Red band*. The satellite sensors register the surface reflectance and send back the digital values to the NASA/USGS land control centers, where specialized personnel confirm the quality of the images and process them. Surface reflectance is generated from Level-1 inputs that meet the <76 degrees Solar Zenith Angle constraint and include the metadata inputs to generate a scientific product before making them available through the USGS Earth Explorer site online.

Calculating NDVI from Landsat Using ESRI-ArcGIS

Once the method of analysis was established, it was necessary to find the best satellite imagery possible for the region. Landsat imagery has a 30m pixel resolution, and a sixteen-day repeat pass resolution, which are appropriate for a study about the type of crops cultivated, and for the extent of the Mexicali Valley. The most common crops in the valley are alfalfa, cotton, and wheat. The NDVI is a well-known remote

sensing technique to identify and estimate areas covered with a specific crop⁵. In summary, Landsat missions capture multispectral reflectance in the visible and infrared bands; the red and near infrared bands are positively correlated to the photosynthetic activity, leaf area index, and projective cover of the plants. This normalized index allows determining the health and vigor of plants. Usually in the range (-1, 1), the higher the index, the greater the photosynthetic activity.

Nowadays there are many ways to calculate the NDVI from Landsat images. In ESRI ArcGIS⁶ 10.2 and later versions, there is an Image Analysis toolbox, which has an NDVI option. This selects the Red Band and the Near Infrared Band, B-3 and B-4 for L4, L5, L7; and B-4 and B5 for L8. Image Analysis software has menus for improving the display of the NDVI image. In "Layer Properties", one can adjust the image assigning different colors to specific ranges of values and giving a class value to each pixel in the analyzed image. It is necessary to do a series of trial-and-error calculations with the number of classes and colors to map the average activity of each pixel. The ArcGIS software allows this adjusted classification, and to assign a color to each specific value range. Classification of the different crops are created, and saved as a raster file

⁵ NDVI techniques for classifying crops, see NDVI references

⁶ ArcGIS offers a set of capabilities for applying location-based analytics. <https://www.esri.com/es-es/arcgis/about-arcgis/overview>

in .tif (tagged interchange format). It is sound to preserve the name of the image in the NDVI file, allowing the location and date of the image to be preserved and retaining the process followed. This image displays on top of the other layers. On the Layers Properties menu the number of classes, and the threshold (using the slider), can be determined to differentiate each class in the Classification menu. In the Spatial Analyst Toolbox/ Map Algebra/ Raster Calculator, the number of pixels in each class are counted. The number of pixels of each class times the area of each pixel (30 x 30 m) gives us the total area of each crop. This information fills the crop/year table entry for that specific date. Since specific groups were under consideration, say, wheat, we choose the available dates when wheat is at its vegetative maximum, so that the NDVI is higher for wheat and smaller for other crops, which at that date are not at their maximum. No all wheat parcels have the same NDVI value due to variability in their phenological stage and corresponding reflectance. An interval of NDVI values was used to train these parcels so that the software classified similar values or spectral signatures. In order to estimate the possible error in the classification a series of known parcels with wheat at different stages in their growth was used, and the classification was assessed by finding the percentages True and False classification errors (T, T), (T, F), (F, T), (F, F). For specifics, (T, T) means a positive identification of true wheat, (T, F) means the case

where wheat was classified as non-wheat, (F, T) means something non-wheat was classified as real wheat, and (F, F) means non-wheat was classified correctly. The Spatial Analysis software can work with different classes at the same time and defines the percentage of error for each class. The major differences concern the (T, F) and (F, T) errors when one cover is taken for another or “confused”. This is more common when the NDVI values are close to the class limits. It is possible to do a reclassification process by looking for these specific parcels (and adjusting the NDVI interval limits), then by saving this layer to compare it later against an updated classification, when the possible crops should have a clearer difference in NDVI values. Then the trends in error can be checked and adjustments made to the original classification. The most common mistake was to confuse one crop with another, Rye grass instead of barley, for example. When converting these areas to volumes of irrigation, the differences were small, less than 0.5%. These refined studies can be useful for a different objective, such as quantifying specific crops. It takes one or two months until the NDVI of each crop is definitively distinct. For irrigation purposes, timely data are essential. The water master and the farmers require real-time data to open or close irrigation gates.

It is possible to refine the results by calibrating them with the field data, using training pixels where data were collected in the field. This requires strenuous work involving field data calibration. Technology has evolved to the point where this is possible on site. GPS systems give us precise locations of the parcels and an Internet connection allowed satellite imagery to be downloaded in the field at those points. Since 2020, the USGS has uploaded Level 2 and Level 3 images into Earth Explorer. These are images already processed, which saves a time and computational work to calculate the different vegetation and water indexes. GIS applications are common in many fields and trained personnel are increasingly available. People are now more familiar with satellite imagery due to the use of smart phone navigation. New constellations of commercial microsatellites will supply even more information. Such mobile data access would be a great leap towards more productive agriculture and better water use, such as in large irrigation districts like Mexicali Valley.

Additional Software Packages for calculating NDVI

There are commercial packages like ENVY Analytics by L3Harris⁷, which is a geospatial analysis software that also calculates NDVI from

⁷ ENVY Analytics is an image analysis software

satellite images. ENVY has specific routines for pixel “supervised classification” according to the defined threshold values. For the Mexicali Valley’s images, reflectance values were assigned to training data located with a hand help GPS unit in the field. These points defined a range of spectral signature for each group of crops. The software evaluates each pixel and quantifies how many of them exist for each defined class in the image. This software offers other routines to build a flow chart with the procedures to reach the final crop map. It takes longer to analyze the first image, but once the procedure is automatic, it can process different images quicker. This allows for faster comparison of results with the field data. The algorithm for calculating NDVI is the same as that explained above, but the difference are in the initial values or parameters provided to the software, the thresholds that establish differences between crops, and how to manage the possible sources of systematic error. The fieldwork collected real data for each crop for the 2016-2017 and 2017-2018 agricultural years and was used to corroborate the spectral signatures at the different crop ages. When the ranges of each crop intersected, an additional satellite image was analyzed four or six weeks later to define the type of crop, once its phenological cycle was more distinctive. The average error was small, about 6.6 % for correct crop

<https://www.harrisgeospatial.com/Software-Technology/ENVY>

classification the first time, with 12.7 % of maximum range intersection. This gives about 0.9 % classification error overall. The error in water use due to misclassification was less than (+/-) 0.5 %, which is a good range for the purposes of this project.

Another source of error is counting a pixel in one class, when it has more than one crop or land cover present. This author applied the following criterion: when a pixel has more than one crop, it was assigned to the one occupying the largest portion. Since the Mexicali Valley has a large extension, the error due to rounded numbers was minimal due to error compensation.

This work focused on the methods to estimate number of hectares of each crop and calculations of the total used water for irrigation. We classified first the pixels of the area of interest and later quantified the areas of each crop.

After the image classification was made as described it was determined that the number of classes corresponds to the type of crops and land covers one must identify. This is an important decision related to the kind of study being conducted. If there are two crops with similar growth timing and water consumption, for example wheat and barley, it is possible to classify them together for general water consumption studies. If it is necessary to discriminate between them, one must use more

classes and more specific bandwidth ranges or a combination of different indexes. For total water usage, such fine differentiation was unnecessary, since one crop or another in the same group consumes a similar amount of water. After the trials it was herein determined that that seven classes contain the needed information with good precision and an excellent response time. For the farmers and irrigation activities timing is critical.

Field Data Collection, Image Selection, NDVI Calibration

The satellite image captures all f land covers at once. It is important to have field records for these specific spectral signatures, to identify and classify them correctly. Using GPS points of specific crops in the field allow us to do this matching. It is important to know the periodicity of the satellite pass and to gather the field information as close as possible. Other satellite imagery can be used to identify specific land covers of known urban, paved, open water, or desert areas, and these give us other important reflectance values, which are different from the NDVI values of vegetation cover. The field data took the form of a location, date, crop, reflectance geodatabase. It is important to visit the region on the main crops vegetative maximum dates. Doing so the point's database can be used to train the classification system. One must keep the same projection and geographic consistency of our region of interest,

using the same shape file to crop it from the satellite images. This produces layers of different dates stacked correctly. The field control points also help us accomplish this geometrically.

For the field data collection, this author visited the region during the critical time to differentiate the crops, late December- early January, when winter wheat, alfalfa and produce are present. Besides their reflectance, their distribution pattern allows identification, some are dispersed, and others come in furrows. In March, the winter wheat is at its maximum NDVI and is higher than cotton, which is only just breaking the soil. Alfalfa may be challenging, yet looking back to the January image one can discriminate it well using a logic operation on the specific pixels.

The study defined four major group crops for the Mexicali Valley with a leader crop in each group: winter wheat, cotton, alfalfa and produce vegetables. Each one of these crops has minor associated ones; all of them are irrigated at the same time with a similar amount of water per hectare. These crops were classified together using the training points from the field data collection.

Throughout their life cycle, plants have specific water requirements to be healthy and productive, and with these requirements, agronomists make hydrographs that represent the water demand of the crop. The

water masters accumulate and convert them to monthly operational hydrographs of the irrigation system. We must know the time-phenology of the local crops, especially when these crops are in their vegetative maximum, and the months when they are seeded, and harvested. The bottom line is that farmers want to supply the optimal water amount so they can get the best possible yield for their crops. Competition with other irrigation modules makes each one more efficient. Farmers must be present in their land when irrigation time arrives.

The Irrigation District hydrographs and a summary table with the dates for the best possible satellite images were prepared to identify each crop, discriminating it from the other areas. As an example, Mexicali's farmers plant winter wheat from November 15 through December 31. This wheat has a cycle of 153 days, about five months, after the third month the wheat has its vegetative maximum, when the NDVI will have the maximum value. Landsat imagery near this time, the first and second weeks of March, is best to classify winter wheat. Cloud cover is a factor that needs to be considered, if more than 20 or 30 %, a different satellite passes two weeks before or after, should be used.

Table 2. Periods for the Landsat images

Phenological Periods for the Landsat Images				
#	Water year	Month(s)	Leading Crop	Characterists
1	2016-2017	Mar-1/2 Apr	Wheat	Max vegetative. Spikelet
2	2016-2017	May-Jun	Cotton	Blossom-Ball
3	2016-2017	Aug-Sep	Alfalfa	Alfalfa is cut every 4-5 weeks
4	2013-2014	Mar-1/2 Apr	Wheat	Max vegetative. Spikelet
5	2013-2014	May-Jun	Cotton	Blossom-Ball
6	2013-2014	Aug-Sep	Alfalfa	Alfalfa is cut every 4-5 weeks
7	2006-2007	Mar-1/2 Apr	Wheat	Max vegetative. Spikelet
8	2006-2007	May-Jun	Cotton	Blossom-Ball
9	2006-2007	Aug-Sep	Alfalfa	Alfalfa is cut every 4-5 weeks
10	2000-2001	Mar-1/2 Apr	Wheat	Max vegetative. Spikelet

In Earth Explorer is possible to check the quality of the imagery before downloading it. There is also a satellite image series called "ARD", Analysis Ready Data, these are georeferenced and ortho-rectified images, and using this series can save a lot of processing time. During this study this data series was under development and the USGS had only limited data available, but definitively they will be a great advantage once the series is complete. The USGS is using automatic processing and artificial intelligence to expedite the processing of the vast amount of satellite information accumulated in all the years of spatial exploration and the data from the new sensors available.

Earth Explorer was used for the images of interest, IOI to the Earth Explorer web site. These were a combination of location, the Mexicali

Valley, and the time of the vegetative maximum for each crop. Based on the phenology and irrigation hydrographs the times of the maximum vegetative condition were established. With these initial dates, the closest available image was sought.

To prepare and receive this information takes only a few days. Once the images arrived, it is necessary to check the quality and location of each of them. Their official name gives us information about the sensor, date taken, location, date processed, and quality of the image. Our area of interest in Mexicali Valley requires two neighbor Landsat images.

Image Classification, NDVI Maps, Crop Areas

Once the images are ordered via the Internet (free of charge), the algorithms are prepared to work with the satellite data. ENVY and ArcGIS 10.6 were used at the UCSB computer Lab in the Department of Geography to process each pair of Landsat images for a complete scene of the Mexicali Valley. These were then joined, and the layers chosen for our study, in this case, the Red and Near Infrared reflectance. These files were more efficiently managed together and pre-joining was important to save storage and processing time.

It is imperative to define the Area of Interest AOI, in this case the irrigated part of the Mexicali Valley. A shape file was generated as the AOI, so anybody can reprocess the imagery and obtain similar results. NDVI gives us an idea of the plant and crop status specifically for the time of the image. Standard reference works were followed on how NDVI works and how it is possible to identify different crops. Sometimes, the reflectance is clear to discriminate the crop, other times additional tests are necessary for defining which crop is on a specific parcel.

The major NDVI reflectance comes from healthy vegetation with a high degree of photosynthesis. Sometimes two crops could have the same level of NDVI. In such cases, we should check what is happening with the parcel reflectance in the neighboring months. The changes will define the kind of crop. For instance, we may have similar high NDVI values in two neighboring parcels in April, but two months later one still has high values, meanwhile the other has declined dramatically. The initial high NDVI values indicate the parcel was cultivated, and both parcels had a crop in good vegetative status. In June, one parcel had a high NDVI meanwhile the other did not. That helps to decide whether the second parcel had winter wheat, which was in good vegetative status during April, but for June the wheat was already harvested or ready to

be. The crop that was in good shape in April and June is alfalfa, since cotton is still small at that time, and wheat already was harvested.

This is a summary of the NDVI techniques used for quantifying the crop surface each study year.

1. Define a polygon with the area of interest, in this case the Mexicali Valley. Prepare it as a shape file.
2. Prepare the graphs of the physiological cycles of every major crop. Defining the crop months in each biological stage.
3. Identify the satellite imagery needed for the scope of the project. Define the sensor according to the objective of the project.
4. Look in Earth Explorer for the satellite images that comply with the criteria of selection.
5. Download the satellite imagery with all the meta-data and keep an adequate and systematic record of them. Review the quality of the image, if is not good, look for additional ones.
6. Image treatment: If there is more than one image for the project, merge them, and then clip the merged result with the area of interest shape file. This can be done inside the software (ArcGIS 10.6 or ENVY).
7. The clipped image can save a lot of trouble and time, since we will be working inside the area of interest and the image treatment

software, we can calculate the NDVI for each pixel and generate a new raster .tif image with the NDVI values.

8. On the NDVI image, define the number of classes and their range limits according to the number of relevant crops. Based on trial and error and improved techniques this author determine that seven classes are the best number for our project. We have all the classes of interest for different crops and non-farmed lands, water, urban, and desert.
9. Manually we can adjust the range of each class, to obtain better discrimination. Once this task is accomplished, the software can obtain the number of pixels for each class and multiply them for the 30 x 30 m spatial resolution of Landsat, to obtain the area for each class. It is important to ensure that some parcels are not 100% within only one class of land cover; one counts that pixel for the class with the largest percentage of coverage (majority rule). The large number of pixels compensates by rounding the differences yielding low average error values.
10. Find the coverage of each group of crop type. Repeat the above process for the other two lead crops: alfalfa and cotton.

Mexicali Valley Crop Map

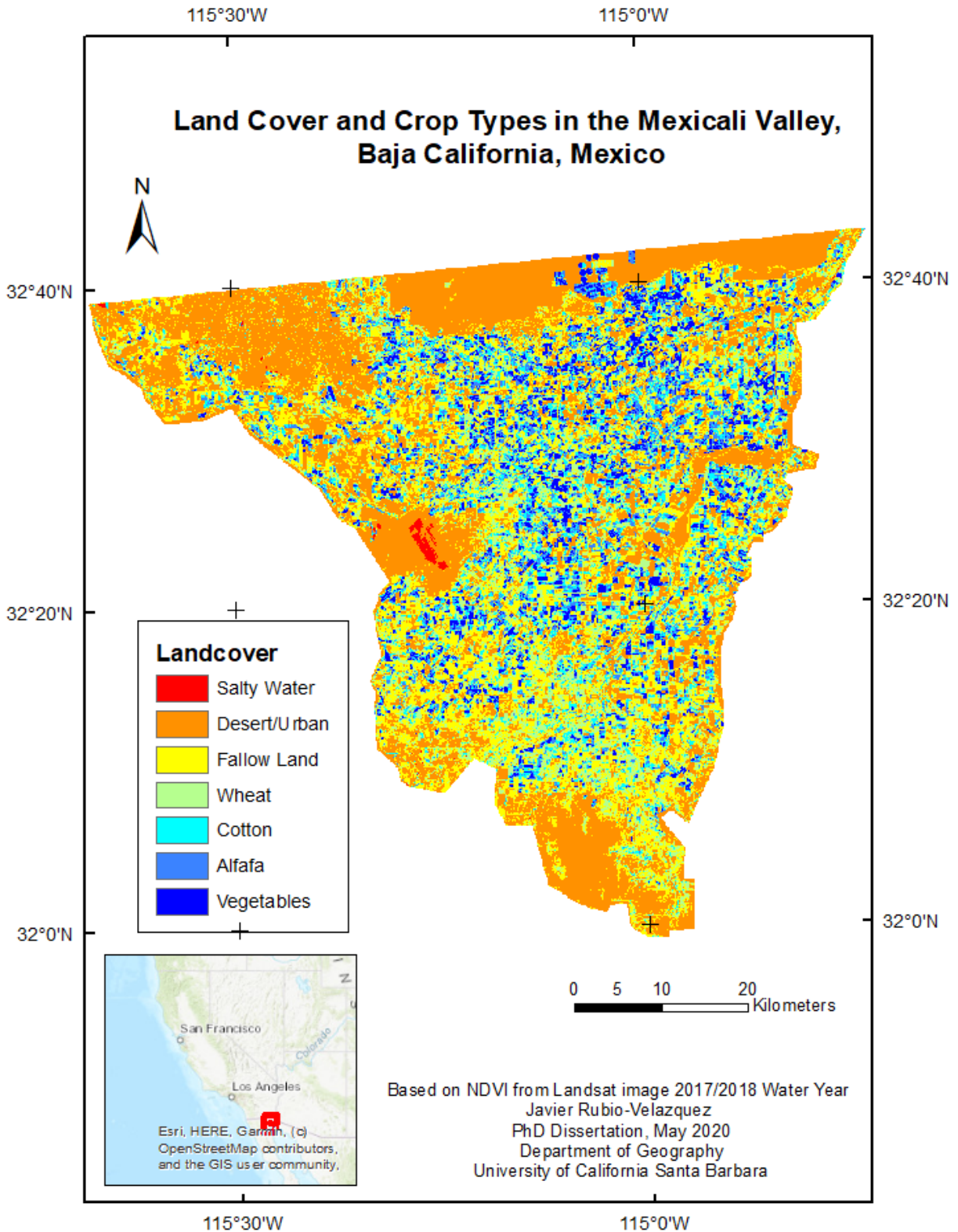


Fig. 28 Crop Classification on Mexicali Valley based on NDVI.

The maximum vegetative period for cotton is the last two weeks of June. For alfalfa, this is a three-year perennial forage; farmers cut it each month and irrigate it each month one to two weeks after the cut. Alfalfa has a unique phenology. The three crop groups cannot occur simultaneously in one water year in the same parcel, one can check this overlaying the maps of each crop and finding the intersections. The average error was small, 0.8% and most of the uncertainties stem from the alfalfa parcels, which easily can be discriminated with intervals of two or three months from the original maximum vegetative of wheat or cotton. Other sources of error are double low water crops in different seasons. The most common combination was winter wheat or barley, with summer-fall sorghum or late corn. There were just a small number of these double crops and they can be easily considered as perennial alfalfa without significant error. Currently, other crops exist in the Valley. These are fresh vegetables produce, which mostly are for commercial export. As explained earlier, this type of agriculture has specific water requirements and seasons. They deeply rely on groundwater and technologically specialized irrigation. Usually there are three or four harvests in the water year. Nevertheless, yearly water usage is not highly superior to a cotton crop. Water wise the possible error is still small, but it will grow with time if more area is cultivated with these crops.

Stablish a reference frame that covers the area of interest and includes a buffer area around the irrigation district, where changes in land cover are common. Some years the farmers extend their crop fields, other years the desert comes back. Local farmers argue many reasons for this dynamic: annual water availability: market prices for the crops, government stimulus, energy prices, and personal decisions.

Total Areas Main Crops in Mexicali Valley

Once the software determines the number of pixels per each crop/class in the Mexicali Valley it is possible to calculate the area of each crop multiplying by the pixel resolution, 30 x 30 m for Landsat. Table 3

Table 3. Crop areas in the Mexicali Valley. Cycle 2017-2018

#	CROP GROUP	PIXELS	AREA (Has)
1	Wheat	579,986	53,204
2	Cotton	447,533	40,282
3	Alfalfa	402,304	36,211
4	Fresh Vegetables	374,507	33,709
	TOTAL:		163,406

The phenological cycle of each group was observed to retrieve the imagery for specific dates that allow us to discriminate the different group of crops. For example, winter wheat has its most intense vegetative status (high chlorophyll, and photosynthetic activity) around the end of March or beginning of April. The group of cotton has the most intense vegetative period in June and July; new hybrid plants have a more extended period. The alfalfa-hay group occurs throughout the year, so in August and September is the best time for discriminating them with satellite imagery, when the other crops are not yet planted, or they were already harvested. Each region in the world has these specific phenology graphs for its crops, these graphs serve as guide for searching for the best dates for satellite images.

The US Department of Agriculture has records of water use indices per crop for the border region. The Irrigation District also has water records. This author visited the Mexicali Valley to check this information firsthand, to establish an average water use index for this specific region for each major crop.

Chapter 4

Total Water Use Estimation for Mexicali Valley

The objective of this chapter is to determine the total amount of water used in the Mexicali Valley. Irrigation water is determined based on crop type and areas irrigated during the annual cycle. Other water uses are aggregated to irrigation water to obtain an estimation of the regional water use. By comparing the total amount with the available water, it is possible to discern the current water balance in Mexicali Valley. Recall that the Colorado River watershed is by far the most relevant water source for the border region in Baja California, Mexico.

In the delta of the Colorado River surface and groundwater are closely interconnected. Over exploitation of either one would adversely affect the other. Notice that the surrounding areas to the Colorado River delta are desert, mountain ranges, or sea. The average annual precipitation is less than 20 cm, and the potential evaporation close to 200 cm. All the available fresh water in the Mexicali Valley is the sum of water from the Colorado River and groundwater from the Mexicali Valley aquifer. Once the total water use is determined deducting the total

surface water from it yields the amount of extracted groundwater. The only source for groundwater is the Mexicali aquifer.

Water in all its forms is considered in Mexico a natural resource. It is a national asset and falls under Federal jurisdiction⁸. There is a National Water Law that establishes CONAGUA as the water-administering authority. CONAGUA divides Mexico in 13 Hydrological Administrative Regions, such as the Peninsula de Baja California, which officially receives the Colorado River water from the International Boundary Water Commission (IBWC). The Commission communicates with the US Bureau of Reclamation (BOR), which operates Hoover Dam for all users in the lower basin (Nevada, California, Arizona, and Mexico), according to the approved annual master program.

Controlling the use and distribution of water requires measurement of water used by geographic location. There are control gates and measurement artifacts at strategic points in the delivery system. Specialized technicians operate delivery gates and report the status of the system⁹. Each time Hoover Dam opens or adjusts its water gates it

⁸ Ley Nacional de Agua. Diario Oficial Federación Mexico. Poder Legislativo. Camara de Diputados. Web page: <http://www.diputados.gob.mx/LeyesBiblio/ref/lan.htm> Original Law published in 1992, plus eight reforms. Last one published Jan 6, 2020.

⁹ Bureau of Reclamation web site. Colorado River Lower Basin. <https://www.usbr.gov/lc/> consulted April 10,2020. This web page keeps operational information updated. Navigating this page is possible to find data about each one of the reservoirs and water deliveries.

follows a well-defined energy production and water allocation-delivery program. All the water that passes through those gates have a clear objective and destine. Downstream the water is diverted according to an approved program. Many gates are operated remotely according to a precise delivery program.

Local channels and irrigation ditches may have manual gates and simpler systems, but they are part of a sophisticated water delivery network. Farmers understand the importance of keeping the system operating correctly and take care of their ditches and irrigation systems rigorously. The Colorado River Watershed is complex and a malfunction could leave the farmers without water for their fields. It is common to find resistance from the stakeholders to disclose the total amount of water they normally use, due to a strong sense of competition for it and their total dependence on the irrigation system. In the Mexicali Valley farmers and irrigation modules do not volunteer to disclose the amount of water they use in any water year.

An alternative method for estimating the amount of water used in agriculture is determining the area of each crop and multiplying it times the average irrigation volume of water used. Adding all the possible crops it is possible to estimate the total farming annual water used. The Mexicali farmers were solely benefited with the surface water from the

Colorado River. Due to a political decision, all the Mexican allocation of the Colorado River was given to the farmers. On the other hand, rural communities, cities, industry, and commercial operations in the region must pump water from the Mexicali aquifer. This situation has created an over exploitation of the aquifer causing aquifer abatement, subduction, seawater intrusion, and salt encroachment. All these pernicious effects damage the regional economy and endanger the local development. To attend these problems, it is imperative to determine the regional water use.

Estimating farming water use in the Mexicali Valley

From chapter three this author calculated the crops' areas for the water year 2018-2019. This information is applied to estimate the total volume of water used to irrigate these areas. See table of "Crops and Water Depths used in the Irrigation District 014 in Mexicali Valley Rio Colorado". The Irrigation District applies these average water depths for the annotated crops. These numbers were confirmed with the operations manager, Luis Arturo Garcia Vargas, and were compared with the average depths used in Imperial Valley California and Yuma Arizona, they were similar. Comparing these depths with the corresponding ones in

other farming areas, like the central part of Mexico, the ones used in the Delta of the Colorado River are bigger, since the heat and evapotranspiration is also much bigger in the delta region.

**Crops and Water Depths in the Irrigation District
014 in Mexicali Valley Rio Colorado**

#	Crop	Irrigation number	Total water depth (cm)	Crop Months	# Day of crop
1	Wheat	6	108	Nov 15 to Dec 31	153
2	Barley	5	86	Oct 20 to Jan 5	110
3	Cartamus	5	91	Oct 25 to Jan 10	140
4	Rye-Grass	6	89	Sep 20 to Nov 10	110
5	Green Onion	7	94	Sep 01 to Nov 30	100
6	Alfalfa	9	164	Jan 01 to Dec 31	365
7	Esparragus	8	151	Feb 01 to Ap 15	151
8	Grapes	8	153	Feb 25 to Ap 15	150
9	Fruit Orchards	8	146	Mar 01 to Ap 15	155
10	Cotton	7	142	Feb 15 to Mar 10	120
11	Early Grain Sorghum	6	117	Mar 01 to Ap 30	120
12	Late Grain Sorghum	6	113	Jul 01 to Ap 10	105
13	Early Forage Sorghum	6	115	Feb 15 to Ap 10	110
14	Late Forage Sorghum	5	99	Jul 01 to Ap 10	86
15	Early Corn	7	128	Feb 15 to Ap 10	110
16	Late Corn	6	113	Jul 01 to Ag 10	96
17	Winter Vegetables	7	99	Sep 01 to Nov 30	100
18	Others	7	122	Mar 01 to May 30	100

Farming outside the Mexicali Valley has independent water sources. Only the coastal cities receive water from the Mexicali aquifer. Most of the industry in the border is of the “maquiladora” type, which assemble products, and their water consumption is for operations and sanitation of the assembly plants, not for the fabrication processes. The city water districts supply water to these industries. The volume used by industries is part of the cities’ allocations. The thermoelectric generation plants take water from the aquifer and they have special energy production water titles. They deserve a special study due to the complexity of their operation in relation to groundwater, thermic field, and energy production

**Table 4. IRRIGATION DISTRICT 014 MEXICALI VALLEY
CROP AREAS AND WATER VOLUMENS CYCLE 2018-2019**

#	Crop	# Pixels	# Hectares	Average irrigation depth (cm)	Water Volume (10 ⁶ m ³)
1	Wheat	579,986	53,204	108	575
2	Cotton	447,533	40,282	142	572
3	Alfalfa	402,304	36,211	164	594
4	Fresh Vegetable	374,507	33,709	112	378
	TOTAL		163,406		2,118

Where: # Pixels detected by Landsat image 30 x 30 m resolution. # Hectares = # Pixels x 30 x 30/10,000. Average irrigation depth per crop in Mexicali Valley. Water Volume = # hectares x average depth (cm) / 100 (conversion factor) => Mm3 (Millions of cubic meters).

Estimating Drinking Water for Cities

According to the Mexican Drinking Water Norm 127-SSA1-1994 the daily per capita use of water equals 200 liters (L). In hot desert areas it rises to 250 L for the urban population, and it equals 200 L/person-day in rural areas. This volume is the sum of water for drinking, washing, cleaning, and residential and public gardening. Mexicali and San Luis Rio Colorado are in an extremely hot desert area. They receive 250 L/person-day, whereas the other coastal cities and rural communities receive 200 L/person-day. The following table summarizes the population supported by the Mexicali aquifer. Water districts monitor the amount of water they supply to the cities. In the rural communities there is a person who monitors the number of users, service expenses, and the number of invoices served to water customers. Sewage treatment in rural communities is through septic tanks. It is inefficient and may cause pollution of the aquifer. There are federal Mexican funds to assist communities in establishing a sewage collection system and water treatment plants. Table 5 presents data concerning drinking water and sewage servicing.

Table 5. POPULATION DRINKING WATER AND SEWAGE

#	CITY	Population (2018)	Water Supply L/person- day	Avg consumption per day (m ³)	Avg Consumption per year (km ³)	Average Sewage per year (km ³)
1	Mexicali	1,116,194	250	279,049	101,922	61,153
2	Rural Communit	313,303	200	62,661	22,887	11,443
3	Tecate	102,406	200	20,481	7,481	4,862
4	San Luis Rio Colorado	193,346	250	48,337	17,655	8,827
5	Tijuana	1,901,987	200	380,397	138,940	90,311
6	Rosarito	96,734	200	19,347	7,066	4,593
	Total:	3,723,970		810,271	295,951	181,191

Sewage discharge in the Border Region

Two hundred and fifty liters/person-day are used in hot desert areas. Coastal cities and communities use two hundred liters/person-day. 50 % of the water consumption in cities becomes sewage in desert and rural communities, and 65 % in major coastal cities. This sewage is treated in sewage treatment plants and is partially recycled. There are many sewage treatment plants along the US-Mexico border, the International Sewage Treatment Plant of Tijuana being the larger one. The treated water is used to irrigate green areas in San Diego County.

Even though it is technically feasible to reuse treated municipal sewage the public acceptance of such water has limited acceptance by the public. A substantial portion of the treated water is discharge to the ocean, to the Salton Sea, or it evaporates. Some of the treatment plants require modernization and expansions to be able to render reusable water of good quality. The State Planning Commission has considered reusing treated water, but funds have not been allocated. So far it has been easier to transfer water from farming to urban or industrial use. Such temporary transfer exacerbates the critical stress on the aquifer.

Water Balance in the Mexicali Valley

The Irrigation District uses all the surface water delivered through the Colorado River per concession from the Republic's President. The 1.5 MAFY allocation for Mexico equals 1,850 Million of cubic meters annually (Mm^3/year). The breakdown of water use is as follows: 2,118 Mm^3 for irrigation (Table 1) plus 181.2 Mm^3 for drinking water and industry (Table 2), not including the thermoelectrical plants. This gives a total of 2,299.2 Mm^3 minus the 1,850 Mm^3 from the Rio Colorado, implying a 449.2 Mm^3 annual water deficit, which represents 24.3 % of the Mexican allocation. The water deficit is extracted from the Mexicali aquifer through

deep wells called federal wells because they are part of a Federal decision to assist farmers in crop production in case of drought. The federal wells pump about one third of the total groundwater. They are an important part of the Irrigation District's water supply and are used almost regularly instead of serving as a drought emergency response tool.

Cities, communities, commercial operations, and industries rely on groundwater to cover their water needs. This additional extraction is increasing the risk of aquifer depletion, land subsidence, and salt intrusion, which it is polluting the aquifer progressively from the areas with high concentrations of salt. The western and southwestern regions of the aquifer already exhibit brackish water in their wells. In about five to ten years' time the problem could reach the center of the valley. This poses a serious threat since the coastal cities and Mexicali depend of this aquifer for their drinking water.

The CONAGUA official report of the annual groundwater use in the Mexicali Valley is 783.1 Mm³ versus the 449.2 Mm³ estimated with this thesis' method. CONAGUA adds all the authorized groundwater titles to estimate total extraction. The extraction is smaller, since many groundwater permits are not being used, or are used partially. City water districts, irrigation modules and small farmers ask for extended water rights when CONAGUA announced the strict limitation of groundwater

extraction in the late 1990s. This extended capacity was a preventive measure by the water users. Later it became a speculative asset, negotiable with new developers and farming companies, who buy the water rights to obtain the development permits or water volumes for intensive farming. Economic and political setbacks during the last two decades have caused slowdown in regional development and the demand for the additional water rights. Water speculators compete to sell their water rights, making the prices cheaper than expected, whoever buys the rights attempts to use them as intensively as possible.

Water Restrictions in Mexicali Valley

In 2003-2005 CONAGUA decided to limit strictly the groundwater withdrawal in the Mexicali aquifer. Many stakeholders, including the coastal and border cities like Tijuana, asked for extending their water rights into future water-use projections. In 2003-2005, however, water shortage and drought conditions were not as critical as they are in 2020. Political and economic pressure forced CONAGUA's water masters to concede the water rights as it was done in 2003-2005. The border region received foreign investment due to the NAFTA (North America Free Trade Agreement) and economic development was anticipated in this area.

Water restrictions were out of line with the national and regional policies seeking to attract foreign investment. The developers considered the aquifer as a valuable but limited resource. These developers interpreted forecasts of water shortage as a barrier to investment and acted to secure future water by asking for water rights in a speculative way. Before 2003, the water rights titles were “nominative”, that is, accorded to a recipient without specifying an annual fee. In 2016, the Federal Law on Water Rights changed, and the water rights recipient must pay fees for the title and for water extracted. The speculative title- holders faced higher costs of production and opposed the new fees. Some attempted to sell their water rights. New investors looking for water rights bought active and idle water rights titles and started to use them.

While these water trading occurred, the economy did not grow as fast as predicted in the early 2000’s. Economic recession hit Mexico and later the US in 2007-2008. Investments slowed down and so did the demand for water rights. The steady users of water were the farmers, who pay a small amount for their water rights. The new farming companies became the best possible buyers, and they acquired the associated water rights with the leased lands and additional idle water titles. These companies withdrew and continue to withdraw larger amounts of water because of their acquired water rights. The farming

companies are specialized producers, with a deep knowledge of their business and the land, and water they need for their operations. Small local farmers cannot compete with the large farming companies. The small local farmers have been forced to share the aquifer with the farming companies. Unfortunately, for the farmers downstream, those placed close to the river's delta in the Gulf of California, freshwater in the aquifer is retreating, allowing for the sea water to intrude the aquifer. These farmers withdraw water that is brackish and unsuitable for crop production.

IMTA Report on the Aquifer of Mexicali

In The 2019, IMTA's (Mexican Institute of Water Technologies) report assumed a 520.5 Mm³ aquifer annual recharge, which is an estimate derived before the All-American Canal was lined with concrete. The lining of this large canal, which supplies water to the Imperial Valley in California, was done to reduce the seepage losses along the canal. The seepage was a gain to the Mexicali aquifer. The lining project was partially financed by the San Diego Metropolitan Water District. This district appropriated the water recovered from seepage suppression. Considering a partial loss of the pre-lining seepage recharge part reduces

the difference between the CONAGUA's groundwater use estimate and this thesis' estimate. Both estimates represented elevated water deficits.

Water Allocation in the Irrigation District Mexicali

Every year the Irrigation District estimates the amount of water use in agricultural endeavors. It establishes a monthly general water balance in a spreadsheet, accumulating the input and outputs for the water activities of the Valley. Monthly inputs: water deliveries from the Colorado system, rain, groundwater extractions, and wastewater recycling. Monthly water outputs: the irrigation program, drinking water for cities and communities, plus water for commercial, industrial, and ecological services. In the last decade the farmed area has diminished 4.2 %, according to the Irrigation District data. Water usage raised by 5.4 % the amount of groundwater extraction. The comparable value of the crops has increased 11.8 % in the last 10 years. The operations director of the Irrigation District attributes these changes to the salinization of the southwestern part of the aquifer, where farmers have abandoned their parcels. Those irrigation modules have transferred their water rights to private agricultural companies who use the water on leased lands in the northeastern part of the aquifer farming fresh vegetables. The total

farmed area is smaller, but it is more intensively farmed with profitable production involving higher water use per hectare.

The estimation of total water use reported in this thesis represents a general approximation. The volumes of water for irrigation vary due to many operational factors. The main gate is at Hoover Dam, and the water flows through the lower Colorado River until reaching Morelos dam in the northeastern corner of Mexicali's irrigation district. Water moves through many jurisdictions before arriving to the farming parcels. There are water losses along the irrigation system due to evaporation, evapotranspiration, infiltration, and accidental overflows. The federal wells are used to augment the canal flows and guarantee water to the most distant parcels on the irrigation system. These wells are located at strategic points.

The commercial crops are sensitive to water stress. Yields diminish with decreasing irrigation water. Farmers aim to irrigate their crops for a bountiful harvest. Otherwise, they lose money and risk their way of life. Some cash crops, say, fresh vegetables, require highly efficient irrigation systems.

A traditional gravity irrigation system has a defined capacity depending on their canals and hydraulic infrastructure. The main canals bring the water to the irrigation modules where they use their local

channels and ditches. At the irrigation module level water distribution depends on the annual allocation, the timing of this allocation, with the most productive crops are irrigated first. The irrigation district takes care not to overflow the system since the spells are costly. The irrigation manager most practice the most efficient way to deliver water to the parcels. A few distant farmers do not justify filling the main canals. Large gravity irrigation districts are complex systems to manage. They operate massively and farmers must pay attention to the irrigation program. It is imperative to have an efficient logistical plan in the program operation. The federal wells allow for local adjustments when the large amounts of water move along irrigation canals. The water master orchestrates the water deliveries for the entire irrigation district. Some of the federal wells cover distant areas, although evidently all the wells withdraw water from the same aquifer.

New Crops in the Mexicali Valley

In the last decade, 2010-2019, Mexican and American farming companies started operating in the valley. They farm productive crops more economically, among them fresh vegetables. These new crops were introduced and expanded due to the investment in more sophisticated

agriculture, which usually requires a dedicated irrigation system that operates based on crop demand. Some of these farming companies are part of large agribusinesses that can export/import the crops to the US market and have access to food store chains. These companies or their contractors negotiate with the irrigation module to lease the land and the water rights for a specific number of years, usually five to ten years. Once they have the contracts, they invest on land preparation and irrigation system. They pay the rent to the irrigation module and they have the privilege of using more water if they can secure it from other modules. After the companies secure the water, they can use the irrigation canals or the deep wells up to the total volume of water in their contract and water titles. This type of agriculture is more intensive and productive, but also requires more water per hectare because the companies produce three and even four crops annually. These intensive-farming operations are labor, capital, and equipment intensive. The Mexicali and Imperial valleys have few freezing days during the winter allowing the production of most winter vegetables for the US Market, such as lettuce, tomato, onions, and other vegetables.

The Mexicali farmers have developed an interesting crop rotation system that allows them to replenish some soil nutrients depleted by specific crops and deposited by others. This system also rotates the

amount of water each farmer receives each year. It is common to see in a time series images that crops change position within a module, and in the whole district, but the average volume of water is nearly constant. This can be seen in the Google Earth Engine, a global-scale platform powered by Google's cloud infrastructure, and in the data from USGS Earth Explorer. Through this dynamic visualization, one can detect areas with strong variability and focus research on them specifically.

Federal Wells Groundwater Extraction

The federal wells complement the water brought in by the canals. These wells should operate on demand when the water in the canal is not enough to meet needs. This author witnessed these wells were operating constantly, adding water to the canals, during field visits in the high irrigation season. Most of the wells are concentrated on the northeastern corner of the aquifer where the river and main canals recharge the aquifer through infiltration. The irrigation district pumps groundwater. The farmers of the irrigation module paid the energy and infrastructure costs. Each year they approve and budget these costs. Farmers understand the effect of water shortage and they have cooperated to acquire groundwater wells to complement their irrigation. When the farmers notice water stress in their crops, they agree on paying groundwater

pumping energy to accelerate the irrigation process and adding more water to the canals.

Variable weather conditions can change the crops' water requirements between programmed irrigations. Some modules have groundwater wells they operate under special conditions. This additional water is very difficult to quantify because the farmers do not want to disclose the number of hours they pump, nor do the wells have water meters.

Moreover, cities, rural communities, and industries withdraw water from the aquifer. The best example is the Tijuana-Tecate-Rosarito aqueduct. That brings 135 Mm³/ year of water for the coastal cities and 255 Mm³ for the industries through a pipeline-aqueduct that crosses the peninsular sierra. These systems have evolved together with the economic development of the region. Some industries have bought land and water rights from previous farmers to install themselves close to the US-Mexico border. Mexicali, San Luis Rio Colorado, and the rural communities pump groundwater for drinking water. Mexicali city's water district receive the title and water rights from farmers.

CONAGUA has limited the amount of water that it is possible to withdraw from the aquifer aiming to reduce the water deficit and to

enforce the National Water Law. Farmers have opposed these measures delaying the installation of meters in the wells or arguing those do not work properly. Water regulations require accurate measurements and water quality testing, which reveals where wells pump fresh water or brackish water. Looking at the patterns in water quality in wells the Irrigation District and CONAGUA have delimited where salinization is a major issue. Wells and pumping logs reveal the increasing salinization, especially to the southwest where ancient Cahuilla Lake lied. In that area the Cerro Prieto thermoelectric plants aggravate the situation by pumping high temperature groundwater, which evaporates during energy production leaving salty brines in sedimentation ponds.

In summary, the 449.2 Mm³ water deficit is made up by groundwater withdrawal from the Mexicali aquifer, representing 24.3 % of the total water used in the water year 2018-2019. Thus, comparing the total water use estimated through the satellite imagery in this thesis with the water use officially reported it follows that the source of the difference between these two estimated uses lies in the amount of water recharged, which it is not possible to estimate through an indirect or remote method. IMTA reports a larger volume of groundwater extraction and compensates it with large recharge of the aquifer. The difference between the two methods deserves further analysis.

The major possible error of water use estimation is in the quantity of water used in irrigation. In general, the hydraulic infrastructure is old and rudimentary, the Irrigation District and the irrigation modules have basic technology and just a few meters, sensors, and automatic channel gates. Still the water master and irrigators are experienced, they know very well their land, type of soil, climate, and crops. Farmers monitor their crops and water them as efficiently as possible with the available technology. The Federal and State governments assist the farmers to be more productive by achieving plentiful harvests per hectare with soil nutrients and water. New high yield hybrid crops have replaced all traditional strands, demanding more water per growth cycle and increasing the water deficit.

Water Restrictions in the Colorado River Allocation

The 2018-2019 deficit compounds previous years' deficits, and most likely it will increase due to the water restrictions in the Colorado River watershed drought contingency plan, which will reduce the allocation to Mexico by 50 Mm³ in its first stage. This contingency plan has been established for the 2019-2020 water year. This coming summer (2020) is the first year of water reduction. Groundwater withdrawal in the

Mexicali water district will increase to compensate for the reduction in Colorado River water. The State Water Commission and the CONAGUA are pressing for improvements in irrigation efficiency. Even a small percentage of improvement in irrigation efficiency would cover the water reduction from the contingency plan, which this year (2020) amounts for 50,000 acre feet, about 4% of the total Mexican allocation.

The State government received federal resources to support laser leveling of the parcels, which would allow for better irrigation efficiencies and better harvest yields. The real problem is the deficit of 449 Mm³, which roughly represents 30% of the allocated water from the Colorado River. Even without reductions in the Colorado River watershed Mexicali Valley is using more water than that required to achieve a sustainable condition? This situation is compounded by a regional drought for the last nineteen years in the southwestern US. The outlook for water supply Vis a Vis water use in the study region appears dismal.

Chapter 5

Conclusions

Water Deficit

The aim of this research was to estimate water usage in Mexicali Valley, this study has found that farming uses more than the total water allocated to Mexico through the Colorado River. The results showed an overexploitation of the aquifer, which causes its depletion and a series of associated adverse impacts for all users in the Mexico-US border region. In the last two decades the irrigated area has remained nearly constant, but the farming is more intensive with high-yield, water-intensive crops. To meet the growing water demand farmers enlarged the groundwater wells. They drill new wells when an existing well begin to fail and then transfer the water rights from the old well to the new one, which is more productive than the old well. This replacement activity increases the farming water deficit, which adds to the groundwater extraction for urban and industrial users. It is urgent to return to a sustainable extraction, otherwise the aquifer could be contaminated by seawater intrusion or existing brackish water lenses in the Mexicali Valley aquifer.

Salinization Risks

Contamination of the aquifer will bring major economic hardships for the Mexicali Valley and the whole border region because it is the major source of drinking water. Economic motivation is just one side of the urgency to evolve towards a more efficient and sustainable water usage in the Mexicali Valley and border region. The environmental side is also a strong motivator. If the irrigation district, cities, and industries do not improve and reduce its water usage, the risk of environmental collapse will increase dramatically, especially for low elevation areas within the valley. Areas of the aquifer in the southwestern Mexicali Valley are already yielding brackish water. Farmers in those areas cannot irrigate their crops with this water any longer. Seawater intrusion is encroaching on the farmland and pushing farmers to the Northeast part of the valley, where the Colorado River encounters the Mexicali Valley. Farmers who lost their land due to salinization are in a dire situation.

Seawater intrusion and existing lenses of salty water are causing salinization of groundwater in the aquifer; this is an imminent risk in the Mexicali Valley, which borders the Sea of Cortez. Most of the Valley is close to sea level, 12 m above average elevation, due to the geologic history of the Colorado River Delta. Salinization of the aquifer will affect farming, drinking water for cities, rural communities, and industries, as

all of them rely on this aquifer. The salinization risk varies within the Valley. Irrigation modules and communities located in southwestern Mexicali Valley face a more severe condition. This is especially true of the wells that are in the zone local farmers call "the salt road", which delimit the ancient Lake Cahuilla. The water districts avoid pumping in that zone, where wells report higher salt concentration than the wells on the northeastern upper section of the irrigation district (personal communication with Jose Martinez-Gasca, Ejido Campeche. Irrigation District 014, Valle de Mexicali, Junio 2018). Most of the federal wells are in the northeastern portion of the aquifer. This situation is degrading the aquifer in that area and generating discomfort among the local landowners.

Sea Water Intrusion

Seawater intrusion is a pervasive problem in Baja California. By the mid 1980's, CONAGUA authorized the use of groundwater for irrigation and drinking water for cities. The resulting intense water extraction lowered the water levels in the aquifers, especially those on the west coast of the Peninsula. Groundwater solved temporarily the demand for water in the coastal cities. In the 1980's Ensenada, a major city in the west coast of Baja California, felt the effects of sea water intrusion in its

coastal aquifers. A similar situation took place in some wells in the Tijuana area. The Mexican government intervened and authorized a new aqueduct from the Mexicali Valley to the coastal cities. The Tijuana Aqueduct project draws its water from a battery of 67 deep wells, through an agreement between the Mexicali Irrigation District and the State Water Commission of Baja California. The well battery is in the "Mesa Arenosa" aquifer, East of San Luis Rio Colorado, Sonora, and South of Yuma, Arizona. This same aquifer underlies the Mexicali Valley, since the Colorado River is the border between Baja California and Sonora states and the aquifer developed in the river alluvial sediments. Strategically this battery of wells was set as far of the Sea of Cortez as possible.

There are other three areas with a large concentration of wells. First, the northeastern corner of Mexicali Valley, close to the border California -Baja California Mexico. Second, the "Mesa de Andrade", southern side of the All-American Canal that irrigates the Imperial Valley. Third, near the geothermal plants in the Valley's southwestern region. According to the Water Law in Mexico the driller and the owner of the well must provide well and strata information to the CONAGUA. Based on the information from the drillers the Valley features two major sedimentary units: the northeastern region, which is closer to the Colorado River, where the sediments are alluvial with a large percentage of gravels,

sands, and silts, making a productive aquifer. To the west and south, the stratigraphy changes to lacustrine strata with more clays and silts making a less productive aquifer. On the western aquifer region, where the geothermal plants are found, there are heavy metals from volcanic origin

Most of the groundwater wells in the Mexicali Valley are less than 200 m deep. The federal wells are 10 to 12 inches in diameter and they pump between 90 to 120 liter per second, adding this water to the irrigation channels. On the northern region, seepage was a common phenomenon in the All-American Canal until its lining in 2007. Due to the terrain topography and regional strata, farmers in the Mexicali Valley benefited from the aquifer recharge by canal seepage, and they were affected when the All-American Canal was lined. There were intense protests in Mexico, nevertheless the lining project was completed and the recovered water was sent to San Diego, since the Metropolitan Water District of Southern California financed most of the lining project. CONAGUA authorized additional ground water extraction to compensate for the loss of canal seepage.

The Dry Channel of the Colorado River

The intense groundwater extraction has dried out the lower part of the Colorado River. Rivers and aquifers are part of the same hydrogeological cycle. The streams recharge the aquifer. If the river dries less water replenishes the aquifer, such is the case in the Colorado River delta. Extracting water constantly without replenishing depletes the aquifer in a relatively short time. In recent years, the riverbed is completely dry downstream from Morelos Dam where is located the major Irrigation District diversion 1.3 MAFY, 0.2 MAFY are diverted in the border with Sonora. There are State and Federal funds supporting water saving works such as parcel leveling, channel lining, and irrigation controls. There is not artificial or managed aquifer recharge (MAR) in the Mexicali Valley. In general, locals understand how important it is to preserve the aquifer, yet, up to now, reducing consumption has not been an option. CONAGUA authorized private landowners and the Irrigation District to drill wells in the upper zone where the aquifer has suitable water quality, this zone has a high density of federal, and private wells. The aquifer level is going down, up to one meter per year in certain zones due to intense pumping.

Water demand is intense in the region, urban water districts and developers seek expanded water rights constantly. The irrigation modules

and the cities or industries work together to find water sellers, and they work out legal agreements to transfer the water rights. There are twenty-two irrigation modules and about seventeen thousand farmers with water titles in the Mexicali Valley, which means that there are numerous possibilities of finding someone willing to sell their water rights to solve the water demand from cities and industries. The irrigation module informs CONAGUA the water transfers, which update the records and the diversion amounts. Nevertheless, the overexploitation of the aquifer and its associated deleterious effects continue. Water rights transfers from rural uses to the urban and industrial activity had help the economic development of the border region. This continuous transfer has reduced the percentage of total water used in farming, which has decreased from 85% two decades ago to about 80% nowadays.

Water Markets

The Mexicali Valley is evolving from a primary economic activity to secondary and tertiary ones; therefore, farming is now combined with agroindustry and food processing. Maquiladora industry, energy production, and assembly plants are flourishing in the Baja California State. Service industry is growing rapidly. The added value of secondary and service economic activities in the urban and municipal areas can offer

a higher price for fresh water than farming. This economic water transfer should be controlled and taxed in such a way that promotes improvements in irrigation and farming systems. In Mexicali Valley exists an incipient water market, there the irrigation modules function as negotiators and sellers of water titles. The water buyers visit the irrigation modules to buy additional water rights.

There are proposals to create an institutional water market, where sellers and buyers could meet and negotiate volume, price, and conditions, yet water in Mexico is a Federal matter and it would require a Federal agreement. Not all the water uses are equally valuable, some farmers could agree to sell their water rights temporally or definitively if the price and conditions were right. According to Mexican laws water is a natural resource and a national asset, which has been allocated to specific uses and users by the Federal Government (CONAGUA). When a transfer occurs, usually from farmers to urban and industrial developers, there is an outcry from other farmers who do not receive enough water, and against the water sellers. Concerning water sustainability in Mexicali Valley, the best Mexicans can do is to be flexible and resilient in facing the new ways and limits to water usage. In the last three decades urban and industrial developments have taken place on previous farming areas. Farmers sell their land and water rights to developers, and frequently

migrate with their families to urban areas to engage in new economic activities.

Coastal cities ask for water rights titles to the developers, who buy them in the Mexicali Valley and turn the permits over the State Water Agency CESPT, which aggregates the new titles to their general water rights. This agency pumps the water from the Mexicali Valley over peninsular mountain range, La Rumorosa, to Tijuana drinking water reservoirs. To this date, increasing the capacity of the Rio Colorado Tijuana Aqueduct (ARCT) has been the faster and cheaper solution for additional water supply. Water stress will continue shifting water rights from farmers to urban and industrial uses. If CONAGUA keeps firm and does not authorize new wells, the common source of water rights will be the disappointed farmers from the southern side, who struggle with water salinity. Denial of new permits would increase the percentage of municipal water use and reduce that of farming. Nevertheless, farming water use will be dominant for the near future.

Some areas, like near the geothermal energy plants, are experiencing land subsidence. This is clearly notorious along the master irrigation canal, whose shoulders have been elevated many times to convey the water to the irrigation zones. In the irrigation district, groundwater pumping is restricted along the main canals. However, the

geothermal plants have a different agenda than irrigation modules: each of them follows their own programs, yet all of them use the same aquifer to make up for the water deficits.

The Colorado River constitutes the only surface water resource for Mexicali Valley, which has been allocated to the irrigation district. Any new development for Baja California must rely on a legal, fair, and efficient water transfer system, effectively limiting the over-extraction from the aquifer, and returning to a sustainable level of groundwater withdrawal. This is process that involves all affected parties. Nowadays, there is an excess of water rights. No all of them will survive, nor should they. Salinity will deteriorate their value and keep all of them at low prices. The strategy followed for many farming companies, urban and industrial developers is to buy water rights from poor farmers located in areas with brackish water, once they negotiate the water titles, usually attach them to existing water titles in better water locations. They pump water, or get it from the irrigation channel, up to the limit of their accumulated titles. Their neighbors resent this practice, seeing how their own groundwater levels decline. Coastal cities have bought more water rights than they need as a future protection for water shortages. More water rights do not generate more water, only increases the risk of groundwater depletion when many speculative water rights tenants seek easy economic profits.

The calculations and comparisons of chapter four showed that many water titles are idle, about six to seven percent of all titles are in fact idle. Some farmers do not use their total water rights. CONAGUA keeps a record of all titles but does not control how much water is pumped from the aquifer; many wells do not have meters, even though it is mandatory. Law enforcement is weak and moves too slow to avert a critical situation. The aquifer is a common good and the CONAGUA is in charge of its administration.

While most of the water is used on the farmlands, people live mostly in urban areas. Drinking water is a big concern for them. The coastal cities, Tecate, Tijuana, and Rosarito and their industrial corridor depend on the Colorado River Aqueduct (ARCT) for water supply. Developers in these cities must secure water rights, which they purchase from the irrigation modules. These rights are submitted with their development permit. The city water district applies to CONAGUA for the titles' transfer, which accrues to the city allocation of water deliveries. The Baja California State Water Commission delivers the water to each city's water district, which oversee drinking water quality, distribution, and administration. The city council and State Water Commission fix the water service prices. Urban and light industries discharge their sewage on

the city sewage collection system. City water districts are responsible for sewage treatment and recycling.

Sewage Treatment Plants

Major cities along the border must build and operate efficient wastewater treatment plants and recycle treated water and sludge. Supported by the USEPA's US-Mexico Border 2000 Program most cities in the border region have developed wastewater treatment systems with various levels of efficiency. These cities outgrow in just few years the capacity of their sewage treatment systems, periodic capital investments are required to comply with service levels and USEPA's and SEMARNAT Mexico's regulations.

The coastal cities use about 12% of the total water. If they would treat 100% of their sewage this would create an additional water source of about 40% to 50 % of their urban water requirements. The coastal cities use a small portion for gardening and park irrigation. Competition for water resources would make more attractive the recycling option for landscaping projects and irrigation of public parks.

Mexican environmental protection laws and international protocols require coastal cities to build sewage treatment plants. Tijuana and

Rosarito have sewage treatment plants at strategic locations. The largest is in San Diego County that treats the sewage, which discharges to the Tijuana River. This is a modern and major sewage treatment plant and treats South San Diego sewage and Tijuana River effluents. Tecate has a water treatment plant and reuse program that requires expansion. East Tijuana is downstream Tecate, it is therefore necessary to have good sewage water treatment. Using efficiently treated sewage is a pending assignment for the coastal cities in Baja California. San Diego and the coastal cities in Southern California already make a good use of this valuable resource. It is a matter of environmental knowledge and time for the Mexican authorities to reuse more intensively the treated water; there are proposals for this that require investment.

In Mexicali, the Capital City of Baja California, the sewage system is divided. One effluent goes to the "Las Arenitas" water treatment plant, southwest of the city, which has basic treatment and requires expansion and investment in modern water treatment technology. Most of its effluent is lost to evaporation in the hot desert. The other effluent of Mexicali goes to the New River, which crosses the border towards The Salton Sea in southern California. This river is heavily polluted with farming tailings and Mexicali sewage and should be treated before crossing the border and before discharging into the Salton Sea that

already is in a critical condition. Mexicali should clean all its sewage; it could have an ecological park with this water and clean the New River that flows and pollutes the Salton Sea.

There are many rural communities in the Mexicali Valley, some of them with 5 to 10 thousand inhabitants. This is a large population to rely on septic tanks and precarious sewage collection systems without sewage treatment. The Valley requires a major program to attend this condition. CONAGUA should check that water quality at Morelos Dam complies with international standards, and then evaluate the main canals at strategic points before they reach the irrigation module diversions. Any decrease in water quality should be analyzed and corrected at the polluter expense, CONAGUA has the legal attributions to control and enforce water quality. This is the law in Mexico; he who pollutes the water has the responsibility of cleaning it. Users downstream must monitor their water quality and report any trouble to the CONAGUA or the Health Department. There is a sampling and testing cost, and the users can easily pay this, especially if it is for drinking water. As farming evolves to fresh vegetables, water quality becomes critical. The cleaning costs are the responsibility of the polluters. An interesting example is "Los Algodones", this is an international border community, with a large medical and dental tourism operation for many retired "baby boomers" called "snowbirds" since they

migrate during the winter months to Southern California and Arizona. "Los Algodones" easily can pay for the sewage treatment and give the treated sewage for irrigation or public gardening. The communities downstream of the irrigation canals will have to do the same, that is, check the water they receive and report their quality to CONAGUA.

Change in Water Availability Perception

Water has been treated as a disposable matter, being that is a precious resource in this US-Mexico border region, this misconception should change. The social and politic establishment regarding water allocation should consider responsible use. Water users cannot ask for clean and sufficient water if they do not respect the sanitation norms for sewage and farming tailings, or the water quality for irrigating fresh vegetables. City dwellers who use small amounts of water have clear legal responsibilities about sewage treatment and water bills. CONAGUA and the State government should conduct themselves accordingly to the national laws, or work to change them towards a better administration. Drilling a new well or buying farming water rights has been the fast solution that is evolving into a risky situation. Trying to outsmart other users or the law and authority will bring the collapse of the water system. Most of the possible solutions require a change in attitude regarding

water use, this change involves most of the actors: Federal and State governments, the irrigation and water districts, the urban, rural and environment users. Since 2008, due to the Law of Public Information, federal agencies including the USGS and the BOR publish their research, control data, and operations, so that Information is available for the public. Today, anyone can monitor the water levels of each reservoir online and prepare for critical conditions.

Mexicali is not the first region to struggle and maybe collapse due to water shortage, there are many cases of critical collapses and of exemplar adaptations to water limitations. Discussion and analysis of some of these cases could bring a better idea of how to manage this situation, but it would only be effective if the community wants to learn and cooperate to avert the crisis. In the past, it was difficult to establish a general framework for the hydrologic condition in the delta region. Nowadays it is possible to find information about the general condition of the Colorado River watershed and use it as a starting point for action.

The Colorado River watershed provides fresh water to forty million people. It is under great pressure, since future precipitation estimates for the southwest are highly pessimist through to climate change models. In the past, the Upper Colorado River States transferred water to the Lower States. Things have changed: water reserves are low in the Colorado

basin; all the states are struggling due to low precipitation during the last two decades. The US Department of the Interior asked all states in the watershed to voluntarily reducing their allocation. Since September 2019, the BOR and the State Water Commissions implemented the Drought Contingency Plan, which is a reduction proposal on the function of precipitation and the water level at Hoover Dam at the beginning of the water year¹⁰. In the 2020 water year, there will be water reductions for all the States including Mexico. Mexicali Valley will receive about four percent less water, due to Hoover Dam level in August 2019 and January 1, 2020¹¹. According to this plan, reductions will increase until a new balanced level is reached. It is urgent to develop a sustainable operation plan in each state as soon as possible.

All states use their allocated water intensively, yet nobody wastes it. There could be more productive uses of water, but the original water rights have priority. Farming users were first in time. It was the dominant activity when water rights were allocated. There is no free water left, all the water is used in different activities, increasing the volume of water for some users' means diminishing those for others or diminishing the reserves for the future. The best way to transfer water from one use to another is transferring the water rights, without increasing the total

¹⁰ Colorado River Drought Contingency Plan. Minute 323

¹¹BOR Hoover Dam reserve levels.

amount used. Water prices must be more competitive to increase the economic incentives for modern irrigation systems and sewage treatment and recycling, currently underutilized.

In the Mexicali Valley crop selection and irrigation technology are evolving. While alfalfa is a profitable crop the pressure for water has kept its total farmed area constant. New more economically productive crops continue to expand in the valley. Large farming companies are introducing new crops and more efficient irrigation systems. The required investment per hectare of a modern irrigation system makes it difficult for many farmers to transfer themselves to these new highly commercial crops. Still, technological diffusion is taking place in the valley and more efficient irrigation systems will continue to expand. Many factors will promote or limit this expansion. Among them are farm product markets, and the ability to export fresh vegetable products to the US East coast and the Midwest, especially during the wintertime. This farming transition will take time, but it is in a state of development. For many more years Mexicali Valley will be a hybrid farming region. The existing irrigation district infrastructure will compete with the modern irrigation systems, which do not have such economies of scale and existing capital invested in irrigation canals and ditches. Currently, the Irrigation District and its twenty-two irrigation modules are a dominant force in the valley. Water

scarcity, high water costs, stronger competition, salinization problems and urban development will be limiting factors for a transition to highly efficient agriculture. Governmental programs supporting water efficiency will help to this transition. There is a parcel-leveling program RIGART that uses federal funds and laser technology. This program has helped water consumption and better agricultural practices. Education and training also will encourage the farming transition, farming schools and higher levels of general education will bring new business opportunities and a new vision of how to use water more efficiently. Capital investment is growing in the area. New agribusiness are introducing new equipment and technology. Economic development is pushing for a more efficient use of local resources and has developed important infrastructure like roads, bridges, irrigation canals, farming and harvesting equipment, warehouses, energy plants, communication systems, health facilities, and a more complex social structure in search of a better way of life and better levels of sustainability and environmental protection.

Packing and food processing will flourish, warehousing, refrigeration, ag-supplies, gas and diesel stations, commercial banks and financial services, insurance companies, will expand. The economy will grow and diversify; more companies and people will be using water, and cooperating to preserve it. They will have political and administrative

representatives who will press for a more sustainable use of water. Nobody wants to overwhelm the capacity of the irrigation system and pollute the aquifer with seawater intrusion. There will be collective action to discuss and limit the use of water in the Mexicali Valley. Appropriate information is key for a correct decision-making. Social groups will evaluate and influence important decisions. This information should be presented to the water authority and to the water stakeholders. Young local students should know how to search the relevant sources of information about water availability in the basin. They will discuss and educate common citizens about the importance of water.

In the Mexicali Valley, there are relevant threats that will slow the farming transition. The traditional social structure of communities and irrigation modules, which already have their expertise, have been producing in the same old way for many years. Sure, there will be gainers and losers in this farming transition. Some associate services, like fresh vegetables and fruits produce mean that transportation will thrive. Some water users are in, strategic locations, and advantageous position, they will resist the change from their comfort zone. CONAGUA can modify this, but the establishment is too strong, and social resistance continues growing. A major event or a break point could be the spark for initiating the change.

New tools in hydrology, geographic information systems, remote sensing, agriculture, and telecommunications allow a better estimation and understanding of water usage. This research project has brought together important developments in these areas to determine total agricultural water usage per year in the Mexicali Valley. Since 2016, the USGS supported by powerful new mainframes has been reorganizing the Landsat series in “Data Collections” and data level series. Collection 1 ensures radiometric and geometric quality for long time series excellent for visualizing global land surface change. The USGS will deliver Collection 2 new data products from Landsat global sensors early yearly in 2020. Some products, like vegetative indices can be obtained on demand.

The extensive USGS global archives of Landsat images allow us to monitor hot spots of land use/land cover and perform spatial analyses. Institutions like the United Nations FAO (Food and Agriculture Organization), and the ERI (Environment Research Institute) at UCSB are well positioned to call for international cooperation and review the dependency of food production and food security on groundwater irrigation. According to FAO records¹² food and agriculture are by far the largest consumers of water, with up to 70 percent of the freshwater use

¹² <http://www.fao.org/3/Y4683E/y4683e07.htm#TopOfPage> The World Water Development Report. UN FAO 2003, updated Feb 2020.

globally goes to irrigation. Global food production has kept pace with population growth and pressures on food security, but as population shifts from rural to urban environments, we will need more food and thus more water. Farming irrigation should evolve to a more efficient production without compromising the environment.

In the border region the water used by urban and irrigation districts are interconnected. Both rely on the Colorado River and the Mexicali aquifer. Annual reductions to the allocation in the Colorado River should adjust the water budgets, and cheating on water extraction should be avoided. Baja Californians should know the conditions of their water sources and make informed decisions about them.

The Colorado River Integrated Watershed Management

Climate change and market instability could bring additional struggles to the Colorado River watershed. The precipitation prediction models show lower precipitation in the basin in the next ten years. They are models, and reality could be different. Still, given the great uncertainty about future precipitation, the best strategy is to prevent a critical situation. All possible water sources should be reviewed, water reuse and recycling should be promoted intensively as a basic option for a

larger supply, even the use of water for landscaping and irrigation of public green areas, and for human reuse.

All the States in the basin are implementing drought strategies trying to mitigate the drought effects. The rains and snowfalls of winter 2018 brought a little relief to the basin, but it remains in a much-compromised condition, although 2019 and 2020 precipitation has been about average. The reservoirs are still at low levels. The California Drought Monitor (USGS) is an excellent reference source. The Bureau of Reclamation controls the hydropower generation system, it reports in its web page the amount of water released and the water levels in Lake Mead/Hoover, which define the water allocations and shortage decision for the lower States including the Mexicali Valley. According to the Drought Contingency Plan, restrictions for the water of the Colorado River will come in growing tiers that will get stricter as the lake levels recede. The Colorado River basin requires an Integrated Watershed Management System (IWMS), which is a methodology that allows balancing the use of water in the whole basin. The States and Federal Agencies and Water Commissions on both sides of the border only monitor within their respective jurisdictions. The river and watershed cross the border and the IBWC is an International Commission that could make a stronger link between both countries, and their respective users. An IWMS requires

intense participation of all stakeholders, also strong commitment and collaboration between the involved countries.

Reducing irrigation water in a farming valley will generate outcries and debate. Baja California Peninsula has other important natural resources, such as, the energy sector, with renewable sources now in large demand in the country, both for electricity production and transportation. Solar and wind energy fields are developing in the area, albeit not so intensively as in California. The new lower prices of natural gas and oil, during the first months of 2020 have slowed down this important conversion. Geothermal energy requires investment for updating the old plants and make them more efficient. Tide generation offers opportunities: the high tides in the delta rise about 30 ft. due to the large longitude of the Gulf of California. Finally, the delta has potential oil fields that have been under study for many years.

Local people, stakeholders, and users, are the best positioned to decide how water should be allocated, used, and how good users should be compensated, and abusers punished. Overexploiting the aquifer means harder troubles ahead. Under pressure, most people will act irrationally and will harden their stance to protect their interests even if that damage the commonwealth. The Mexicali aquifer is a classic example

of the Tragedy of the Commons¹³, if users care only for their own benefit, then, they could over exploit the aquifer. They would seek their maximum personal benefit possible. That would cause the collapse of the aquifer, which would be polluted and damaged. It is more appropriate to inform the people of the water situation. Collective action is a better way to proceed. It requires a lot of work, but it will avoid harder difficulties. Cities, water authorities, and social leaders should develop a water security plan for drought scenarios and commit to this plan.

The misbalance in water resources and water usage in the border region will bring economic stagnation and related social problems. The region attracts many migrants from different parts of Mexico and Central America, who are settling in this region for undefined time. Some of them stay for many years; meanwhile others attempt to migrate to the US. The region serves as a buffer to hold the migration waves, and many people look for jobs to make a living. They are established or passing through the region. Farms, especially more modern farms become training sites for other jobs. Many workers learn about hard and productive work skills that later transfer to other activities like packing, food processing,

¹³ The Tragedy of the Commons. Hardin, Garret. 1968. American Association for the Advancement of the Sciences.

transportation, landscaping and construction. It is in the best interest of the regional economy to keep a sustainable water usage.

Groundwater Irrigation and Food Security

Irrigated zones are the backbone of food, forages, and fibers that help nations to thrive and develop. The Industrial Revolution helped farmers to harness the power of tractors, fuels, and technology to become more productive and develop a surplus that helped some nations to attain better living standards and increase in population. Two centuries later the Green Revolution helped the farmers to become even more productive with new high yield crops, use of fertilizers, pesticides, and better seeds. All these improvements generate better harvests, yet they required more water, better irrigation systems, and modern farming techniques. Agriculture in all developed countries has evolved and it is highly productive. In the last fifty years, global population has increased in developing countries; this has brought an intense demand for fresh water, food, and basic services. Timely innovations and discoveries like the Green Revolution, sanitation programs, vaccination, education, food preservation, international trade and investment have supported this increase in population, especially in developing countries. Thus, the increase in food production has been supported in a large percentage by

groundwater, whose depletion is a pervasive issue in irrigated regions of the world. Some regions have collapsed economically and ecologically. The Aral Sea is a sobering example in Central Asia. Other regions have imposed strict laws to avoid depleting aquifers or to refurbish them, for example some aquifers in California and the Midwest. Many countries have already legislated regarding "Safe Yields" for groundwater extraction. It has been difficult to comply with those limits due to the socio-political power of the irrigation districts and farmers. Legislations have acted to protect their aquifers, but law enforcement is difficult and expensive. In international watersheds, conflicts due to water extraction are commonplace. On one hand, free trade of foods, especially grains, has helped to reduce food insecurity in developing countries and allow farmers to rotate crops and try new ones with a higher market price. On the other hand, economic ambition could swindle other users and the aquifer.

In conclusion, fresh water is a limited resource in many regions of the World. It can be the source of scalable conflicts. Nations could declare war to each other. The visible future will bring more water conflicts especially in areas where water demand is growing faster than supply. A prolonged shortage in the water supply for a region could bring irreversible adverse changes and unintended consequences. Food security

is closely related to farm irrigation and precipitation. New farming communities, infrastructure, including new crops, irrigation systems and aqueducts have flourished. However, the farmland in the southern part of the aquifer has been abandoned due to salt intrusion, and the Laguna Salada (Salty Lake) west of Mexicali has disappeared and become a dryland spotted with salt deposits.

Based on the conclusions it is required to define the safe yield or sustainable level of exploitation of an aquifer carefully, out of the scope of this project. Other activities should strengthen water efficiency, with a change in attitudes towards water conservation. Nevertheless, it is fair to state that extraction overpasses the safe yield level if the phreatic levels are in general decay, or if water sources such as springs, lakes, or water sinks like rivers, and sea or lake discharges are decreasing. As this thesis has shown, once those aquifers are dry or polluted, it will take decades or centuries to recover.

Even with the Mexican Government resolution to limit groundwater extraction from the Mexicali aquifer, the over drafting has still not been resolved. The risk of salinization is still growing, and will continue to do so until the extraction is reduced to a sustainable level. People involved need to change and be supported by an interdisciplinary group of professionals to develop and implement social, agricultural and economic projects to

provide an integral solution. This will require time and effort to convince the stakeholders to review their water allocations, check the water deficit, and define a sustainable extraction level. The risk of depletion cannot be fully solved until the deficit is balanced. That will require important agreements and commitments. Once the Mexicali Valley aquifer is in equilibrium this region could participate in a general balance and restoration project for the delta and an integrated watershed management of the Colorado River. Other sub-basins are also doing their part and soon could be a convention of all the State representatives for this objective.

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