Title
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Journal
Annals of the American Association of Geographers, 113(5)

ISSN
2469-4452

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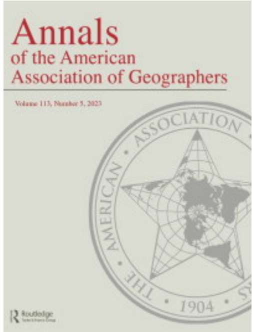
Publication Date
2023-05-28

DOI
10.1080/24694452.2022.2162477

Peer reviewed



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Annals of the American Association of Geographers

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/raag21

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To cite this article: Javier Rubio-Velázquez, Hugo A. Loaiciga & David Lopez-Carr (2023) Human-Induced Resource Scarcity in the Colorado River Basin and Its Implications for Water Supply and the Environment in the Mexicali Valley Transboundary Aquifer, Annals of the American Association of Geographers, 113:5, 1172-1189, DOI: 10.1080/24694452.2022.2162477

To link to this article: https://doi.org/10.1080/24694452.2022.2162477

Published online: 02 Mar 2023.

Human-Induced Resource Scarcity in the Colorado River Basin and Its Implications for Water Supply and the Environment in the Mexicali Valley Transboundary Aquifer

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The Colorado River delta is a sedimentary alluvial formation that embodies the Lower Colorado River transboundary aquifer. The Mexicali Valley overlies the Mexican part of the aquifer, and the Imperial Valley the aquifer's portion north of the Mexico–U.S. border. Mexico receives an annual water allocation from the Colorado River stipulated by an international treaty between Mexico and the United States. The Colorado River water allocation to Mexico is shared by farmers in the Mexicali Valley and by several border cities, rural communities, and industries in the northern region of the State of Baja California. Farmers withdraw groundwater from the Mexicali Valley's aquifer to make up for insufficient Colorado River water to grow their crops. Groundwater withdrawal has created overdraft of the Mexicali Valley aquifer with associated adverse impacts: sea water intrusion, declining groundwater levels, upwelling of brackish groundwater, land subsidence, degradation of groundwater-dependent ecosystems, and emigration of displaced farmers. This article reviews the natural and human histories in the Colorado River basin and the Mexicali Valley, and presents a methodology applying remote sensing, geographic information analysis, and hydrologic analysis to calculate the annual water deficit in the Mexicali Valley. Finally, this work evaluates the valley's annual water deficit in reference to current agricultural and socioeconomic trends observed in the study region. Aquifer and related environmental degradation have adversely affected small-scale farming and exacerbated demographic instability. *Key Words: Colorado River, crop pattern, groundwater overdraft, transboundary aquifer, water balance.*

This work examines the water use and supply situation of the Mexicali Valley aquifer and hydrologically linked populated areas, situated on the Mexican side of the binational (United States and Mexico) Colorado River basin. Figure 1 depicts the Mexicali Valley, located in the northern portion of the State of Baja California. Immediately adjacent to the north of the Mexicali Valley lies the Imperial Valley of Southern California. Both valleys overlie the Lower Colorado River transboundary aquifer formed in the river's delta, as depicted in Figure 1.

The Mexicali Valley is one of the largest and most fertile valleys in Mexico and houses its largest water district. National and international industries have invested in the Mexicali Valley and surrounding cities to take advantage of the tax-free status given to industry. The Colorado River and its tributaries in the United States provide water to nearly 40 million people for municipal use, and supply water to irrigate nearly 5.5 million acres of land. It is the lifeblood for at least twenty-two federally recognized tribes, seven National Wildlife Refuges, four National Recreation Areas, and eleven National Parks.

The Colorado River flow is diminished by frequent drought due to climate processes (U.S. Bureau of Reclamation [USBR] 2012; Udall and Overpeck 2017; Intergovernmental Panel on Climate Change [IPCC] 2021; Stokstad 2021) and to multiple diversions within its basin extending through seven states of the United States (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) and through northwestern Mexico before reaching the Gulf of California. Figure 2 depicts the Colorado River basin.

The Mexicali Valley lies within the portion of the lower basin (depicted in pink in Figure 2) south of the U.S.–Mexico border (see Figure 1). The upper basin (depicted in blue in Figure 2) comprises the land draining to Lees Ferry (elevation equal to 3,083 feet = 940 m) on the Colorado River.

This article was originally published with errors, which have now been corrected in the online version. Please see Correction (http://dx.doi.org/10.1080/24694452.2023.2191495)
Annals of the American Association of Geographers, 113(5) 2023, pp. 1172–1189
Initial submission, November 2021; revised submissions, April and July 2022; final acceptance, November 2022
Published by Taylor & Francis, LLC.

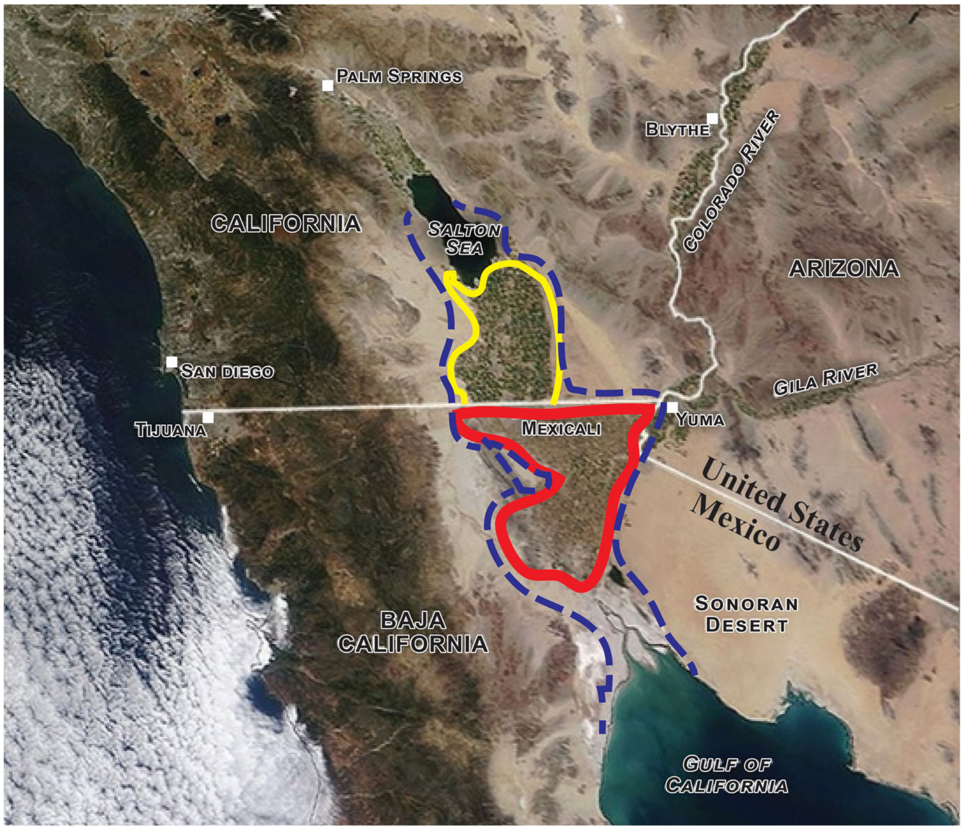

Figure 1. The Mexicali Valley (within red line) lies within the Colorado River delta. The perimeters of the Imperial Valley and of the Colorado River delta are respectively depicted within yellow and blue (dashed) lines. The aquifer studied in this work underlies the Mexicali Valley (within the red line).

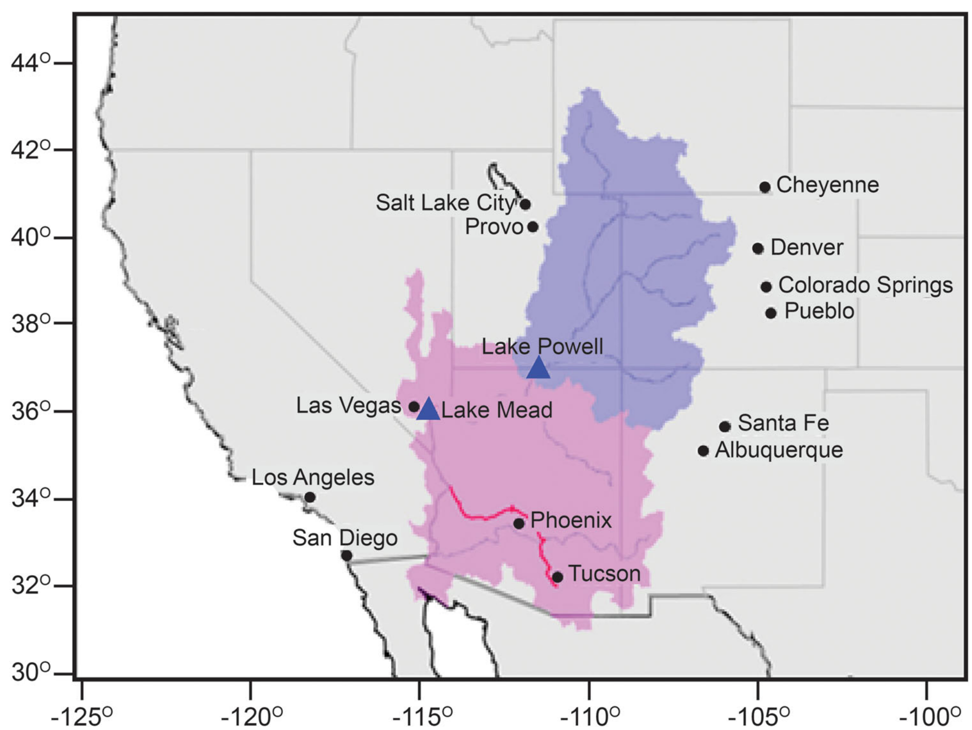

Figure 2. The binational Colorado River basin. The upper and lower basins are displayed in blue and pink colors, respectively.

Groundwater withdrawal from the Mexicali Valley aquifer has reduced its water storage chronically, a condition known as *overdraft,* whereby long-term groundwater withdrawal exceeds aquifer recharge, causes multiple adverse impacts (Zektser, Loáiciga, and Wolf 2005; Loáiciga 2017), and threatens the sustainability of the aquifer as a water source. The Colorado River was the first major river in the world to be controlled through a series of large dams (Owen 2017). The dams dramatically changed the streamflow regime and the ecology of the river and its delta. The extensive wetlands and estuaries that were part of the river system changed forever when its water was diverted for irrigation and urban uses. Following the construction of the Hoover Dam near the city of Las Vegas in 1936, the flows of the Colorado River became managed according to the needs of the southwestern U.S. region. The economic benefits and business opportunities created by Colorado River water were high, so much so that they eclipsed the environmental transformation and ecologic degradation of the river's delta region (Owen 2017). The USBR built more hydrologic infrastructure following the construction of the Hoover Dam. The development of the Colorado River was a milestone in the development of the southwestern United States. This development was influenced by Powell's (1879) Report on the Arid Lands of the United States. The Imperial Valley in the Colorado River delta is exemplary of regions recipient of Colorado River water. It became a major crop producer in the United States.

The government of Mexico assigned land and water titles to farmers in the Mexicali Valley after the Mexican Revolution of 1910 to 1920, creating an expectation of unlimited progress. On the other side of the border, U.S. officials envisioned this water for the use of the settlers of the country's arid lands, a stance that was rooted in the nineteenth-century manifest destiny doctrine, or belief that frontier settlers were destined to expand across North America. The Colorado River Compact of 1922 (see discussion later) allocated all of the Colorado River water to the seven states in the Colorado basin. At the same time, the Mexican government gave the river water to the communal farming settlements called *ejidos*. The Colorado River water had become overallocated; that is, water allocations exceeded the average annual flow of the river.

The 1944 international treaty between the United States and Mexico (see discussion later) established that Mexico would receive every year 10 percent of the average annual flow of the Colorado River, or 1.5 million acre-feet of water (1.850 km^3). This water was originally intended for farming. Over time, though, Mexican border's cities in the State of Baja California, such as Tijuana, Rosarito, and Tecate, imported Colorado River water through the Tijuana–Colorado River aqueduct as their local water supplies became insufficient (Cohen, Henges-Jeck, and Castillo-Moreno 2001). The water transferred to the cities reduced Colorado River water available for farming in the Mexicali Valley, a reduction that was made up by increased groundwater withdrawal. Groundwater withdrawal by farming and nonfarming interests rose rapidly, leading to the condition of aquifer overdraft and adverse impacts, such as the reduction of groundwater storage, higher energy costs of groundwater pumping, land subsidence, and deterioration of groundwater quality by sea water intrusion in the Mexicali Valley aquifer (Cruz-Ayala and Megdal 2020). Social and economic development in the southwestern United States and the Mexicali Valley made the demand for water surpass the available water supply in the 1990s. To compound matters drought has plagued the Colorado River for most of the twenty-first century (Instituto Mexicano de la Tecnología del Agua [IMTA] 2011; USBR 2012; IPCC 2021).

At the national level, the federal water authority in Mexico (i.e., the Comisión Nacional del Agua [CONAGUA]) regulates groundwater extraction. The CONAGUA regulatory framework had to be adjusted to accommodate the North America Free Trade Agreement (NAFTA) first signed between Canada, Mexico, and the United States in 1994, that spearheaded a boom of industries in the border region. The NAFTA created jobs, encouraged migration, and caused rapid urban growth. The industrial, municipal, and agricultural sectors in the Mexicali Valley region required more water, and CONAGUA authorized new wells to supply the packing and food industries and urban dwellers, and to enlarge irrigation systems to produce vegetables for the North American market.

The populated areas using Mexicali Valley aquifer groundwater and Colorado River water in northern Baja California have grown in the last decades, and industries are established and expanding in the border region of Baja California. It is imperative, therefore, to quantify the cultivated area and the water use by crops in a farming annual cycle in the Mexicali Valley and the water uses by populated areas and industries. Farmers in the study area do not disclose their water use, and its actual magnitude has remained uncertain prior to this study. It was therefore necessary to estimate the water use in Mexicali Valley in an indirect manner. Specifically, this work applies satellite imagery, remote-sensing techniques, geographic information systems (GIS), and hydrologic analysis that were supplemented by field surveys performed in 2018 and 2019 to determine the total surface area of major crops in the Mexicali Valley. In addition, the State of Baja California government releases population and economic data that were herein applied to estimate the municipal and industrial water uses in the populated areas linked hydrologically to the Mexicali Valley.

Study Objectives and Organization

This article reviews the natural and human histories in the Colorado River basin and the Mexicali Valley, and presents a methodology applying remote sensing, geographic information analysis, and hydrologic analysis to calculate the annual water deficit in the Mexicali Valley. Furthermore, this work evaluates the valley's annual water deficit in reference to current agricultural and socioeconomic trends observed in the study region.

The remainder of this article is organized as follows. We first review the natural history of the Colorado River basin, its delta, and the Mexicali Valley. We then present a summary of the human history in the Colorado River, its delta, and the Mexicali Valley. We describe a methodology based on remote sensing and GIS herein applied to calculate the areas dedicated to main crops in Mexicali Valley and then describe the methodology applied to calculate the total water use in the Mexicali Valley. We next delve into the implications of water use in the Mexicali Valley for its continuation as a farming region and its capacity to support a prosperous and sustainable quality of life. Finally, we present a set of conclusions.

The Natural History of the Colorado River Basin

The Geologic and Hydrologic Settings

The Colorado River basin is depicted in Figure 2. The headwaters of the Colorado River are in the Rocky Mountains in Wyoming, Colorado, Utah, and New Mexico, where elevations of the Continental Divide reach 14,000 feet (4,270 m). This alpine 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. The Colorado River's flow averaged 15 million acre-feet per year (MAFY; 18.5 km^3/year) prior to twentieth-century water development. Figure 3 depicts the pronounced interannual variability of the Colorado River flow measured at the U.S. Geological Survey's (USGS) Lees Ferry gauging station. The long-term declining trend of flow amounts to a reduction of flow of slightly over 50 million cubic meters per year since 1922. Flow records are supplemented with variables such as lake sediment deposits, tree-ring widths, and coral bands to reveal the incidence of drought in the Colorado River basin (Loáiciga, Haston, and Michaelsen 1993; Gray et al. 2004).

The Colorado River has a length of 1,450 miles (2,334 km) and its basin encompasses 248,000 square miles (642,320 km^2). The upper and lower basins of the Colorado River basin encompass, respectively, 118,000 square miles (305,620 km^2) and 130,000 square miles (336,700 km^2). Ninety-five percent of the of the Colorado River basin lies within the United States and 5 percent lies within Mexico.

The Colorado River basin encompasses the Colorado Plateau geologic province, which extends through adjacent parts of Utah, Arizona, New Mexico, and Colorado over an area of 150,000 square miles (388,500 km^2). The Colorado Plateau was formed of flat-lying to moderately tilted rocks of Paleozoic and Mesozoic age (505 to 66 million years before present; Gordon 2000; Sylvester and O'Black Gans 2020). Mesozoic formations once covered the Colorado Plateau. These formations were eroded by streams rejuvenated by gentle, regional, uplift that started about 17 million years ago that directed the flow in the drainage network within the Colorado Plateau in a southwesterly direction (Cooper, Miller, and Patterson 1987; Gordon 2000), which currently discharges into the Gulf of California. The evolution of the Colorado River prior to about 6 million years before present is poorly known. The first evidence of the modern stream dates back about 6 million years and appears in the form of distinctive deposits found downstream of the Grand Canyon (Prisciantelli 2002; Belknap and Evans 2021).

Tectonic rifting between the Pacific and North American plates created the Gulf of California and the Salton Trough, a process that started about 6 million years ago in the late Miocene (Cooper, Miller, and Patterson 1987; Sylvester and O'Black Gans 2020). The Salton Trough underlies the

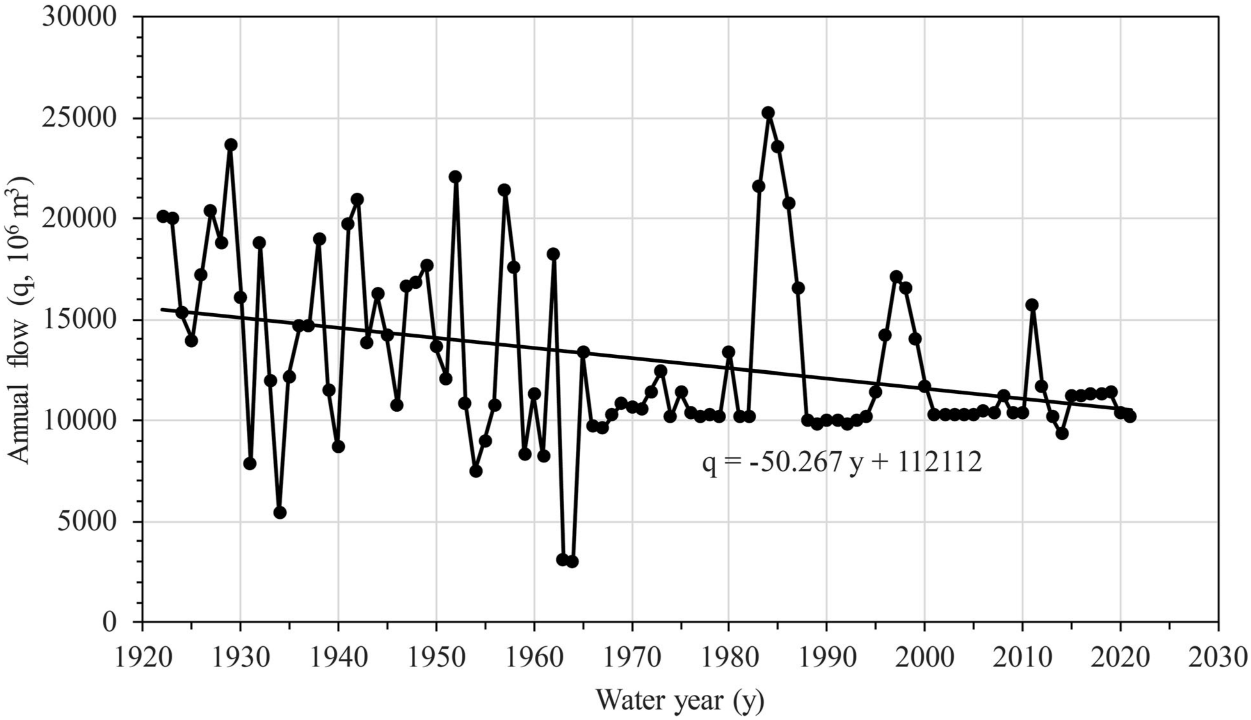

Figure 3. Annual Colorado River flow at Lees Ferry (1922–2020).

Colorado River delta with the depth of sediments filling the trough ranging from 7,000 feet (2,130 m) in the Coachella Valley in the northern part of the trough to 20,000 feet (6,100 m) in the northern part of the Mexicali Valley. Tectonic rifting and alternating marine and fluvial depositions are the geologic processes that formed the Mexicali Valley.

The Mexicali Valley and the Colorado River Delta

The Mexicali Valley features an arid climate, with long, hot summers and mild to warm winters. The annual average temperature is 22.9 °C, with lows in winter of 3 °C, and maximum during summer of 52 °C. Average annual rainfall equals 70 mm. Minimum precipitation on record is 56 mm (in 2009), and a maximum of 145.8 mm (in 1992). Evaporation varies from 304 to 380 mm per year. Potential evapotranspiration is about 2,000 mm per year due to the region's hot and dry climate. On average, winter freezes are fewer than one every five years, and about 120 days per year the temperature reaches or exceeds 38 °C (National Research Council 2007).

The Mexicali Valley encompasses the lower reach of the Colorado River south of the U.S.–Mexico border and it is geologically continuous with the alluvial deposits created by the Colorado River in the Imperial Valley of Southern California. These alluvial deposits were formed over 2 million years of Quaternary sedimentary deposition (Alles 2011). Figure 1 depicts the Colorado River delta as it was surveyed by the USGS in 1908, prior to twentieth-century water development in the Colorado River basin.

The Colorado River has changed its course within its delta many times (Cohen, Henges-Jeck, and Castillo-Moreno 2001; Thompson et al. 2008). The Colorado River delta covered 9,650 square miles (25,000 km^2) of alluvial sediments prior to twentieth-century water development. The area of active deposition has shrunk to less than 1 percent of its original size due to reduced flow reaching the Gulf of California. Changes in the Colorado River's hydrologic regime have dried up wetlands and destroyed aquatic ecosystems in its delta (Wheeler et al. 2007). During the glacial and interglacial ages of the Pleistocene (2.58–0.012 million years before present) the sea level declined and rose, respectively. The strata found in the Colorado River delta reflect the sedimentary history associated with sea-level fluctuation and marine deposition interspersed with fluvial deposition. The stratigraphy of the deltaic sediments in the Mexicali Valley aquifer consists of Quaternary alluvial and deltaic deposits with two predominant sedimentary units. In the northeastern region the sediments are alluvial with a large percentage of gravels, sands, and silts, forming a productive aquifer. To the west and south, the stratigraphy changes to lacustrine strata with higher contents of clays and silts of lower yield that cause localized aquifer confinement (Alles 2011). The presence of salty layers in the southwestern area of the valley is a limitation to farming (Moncada-Aguilar et al. 2010; CONAGUA 2015a). The western aquifer region, where geothermal fields are found, is of volcanic origin with groundwater laden with heavy metals. The compressible nature of several formations causes land subsidence in the delta when the groundwater level drops substantially. The aquifer is mostly unconfined, with minimum saturation thickness of 500 m and maximum thickness of about 6,100 m (Sylvester and O'Black Gans 2020).

Natural Hazards in the Mexicali Valley and the Delta Region

Heat waves are a common threat during the hot summers, when diurnal temperatures reach 45 °C. Flash flows are frequent in the Mexicali Valley and delta region, where the soil is dry and hard and has low water-storage capacity. Small but intense tornadoes in the study area disrupt traffic, degrade air quality, and propagate brush fires.

The northern portion in the Gulf of California has tidal elevation fluctuations of about 9 m, which drives strong currents along the dry channel of the Colorado River. The currents constitute a hazard to people and wildlife and cause estuarine erosion (Nelson et al. 2013). There are endemic marine coastal species that are at risk of extinction due to habitat losses (González-Olimón and Santiago-Serrano 2017; Lau and Jacobs 2017).

Earthquakes constitute a hazard in the Mexicali Valley region. The El Centro earthquake occurred on 18 May 1940, on the border town of El Centro. It had a moment magnitude of 6.9 and caused widespread damage to irrigation canals and nine deaths. The earthquake caused damage to infrastructure by liquefaction, a phenomenon whereby saturated sands (in this case belonging to the transboundary aquifer) become fluidized by dynamic shaking (see, e.g., Kramer 1996). The latest major earthquake was in April 2011 (7.2 on the Richter scale) with an epicenter within the San Jacinto Fault in the Cocopa Sierra (Moncada-Aguilar et al. 2010; Miranda-Herrera 2015). Interruption of the aqueduct servicing Tijuana and other border cities due to a major earthquake is a relatively high-probability hazard.

Human History in the Colorado River and Its Delta

The Colonization of the Southwestern United States

Native American tribes inhabited the Colorado River basin and traded actively. The Cocopa Indian Tribe, known as the River People, have lived along the lower Colorado River and delta for centuries, maintaining their traditional and cultural beliefs throughout many political and environmental changes. Spanish soldiers and missionaries were the first immigrants to settle in the Colorado River basin. The Spaniards introduced irrigated agriculture in areas where soil, water, and labor availability permitted it. Over the last 200 years the territorial control of the lower Colorado River basin shifted from Spain to Mexico in 1821, and to the United States in 1848 following the Mexican-American War. These changes in political control modified boundaries, land tenure policies, and economic activities (Potter 1997).

Farm Settlement in the Colorado River Delta

During the last decades of the 1800s a large number of pioneers settled in the southwestern United States. They introduced improved agricultural technology in the delta region (Brown 1985). The U.S. Congress authorized storage and irrigation projects in the arid lands of the western United States with the passage of the 1902 Reclamation Act, which funded reclamation programs that would encourage western settlement, making homes for Americans on family farms as envisioned in the 1879 Powell report (La Rue 1916; Potter 1997). The 1905 flood caused the Colorado River to overtop its riverbanks and directed the river toward the north for three years forming the Salton Sea (shown in Figure 4), and displaced the residents from the flooded land. The U.S. government relocated farmers who operated in the flooded land and intervened to return the river to its previous course discharging to the Gulf of California. This event prompted the U.S. government to engineer and tame the Colorado River to extract beneficial use of its water. The linchpin of this program was the Hoover Dam, which was authorized by the U.S. Congress in 1928 and was completed in 1936 (Alles 2011). Hoover Dam created Lake Mead, with a storage capacity of 32 million acre-feet (39.471 km^3). The USBR built other dams to

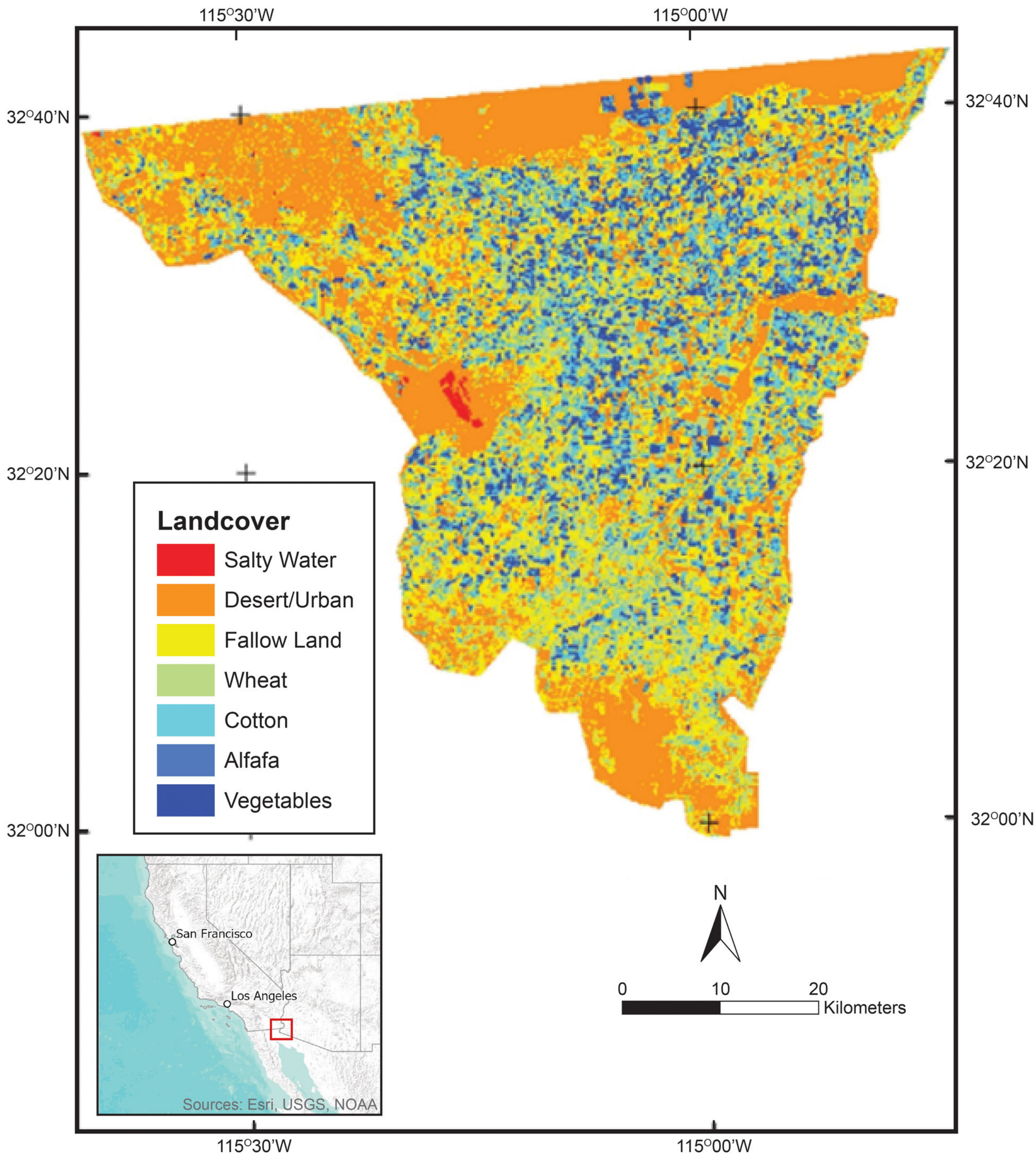

Figure 4. Map of the crop types and land cover determined for the Mexicali Valley.

generate hydropower and provide storage for water supply (Udall and Overpeck 2017). Key among those was Glen Canyon Dam (USBR 2008), which was completed in 1966, some 361 miles (581 km) upstream of the Hoover Dam along the Colorado River's course. Glen Canyon created Lake Powell in the upper part of the basin with a storage capacity of 30 million acre-feet (37 km^3).

The 1922 Colorado River Compact

The U.S. Congress approved the Colorado River Compact in 1922. The Colorado River Compact divided the river into an Upper Basin (Colorado, New Mexico, Utah, and Wyoming) and a Lower Basin (Arizona, California, and Nevada), established the allotment for each basin, and provided a framework for the management of the river. The Compact is the cornerstone of the so-called Law of the River, a generic term encompassing the agreements, federal laws, treaties, court decisions and decrees, contracts, and regulatory guidelines that regulate use of the Colorado River water (Hundley 1975). The 1922 Compact estimated the average annual river flow as 15 million MAFY (i.e., $18{,}500 \times 10^6$ m^3/year = 18.500 km^3/year) at the Lees Ferry site. The U.S. government allocated 7.5 million acre-feet (9.251 km^3), or 50 percent of the average annual Colorado River, to the upper basin states (Colorado, New Mexico, Utah, and Wyoming) and the same volume to the lower basin states (Arizona, California, and Nevada). The annual water allocations made to Arizona, California, and Nevada were respectively equal to 2.80, 4.40, and 0.30 MAFY (3.454, 5.427, and 0.370 km^3/year), and those to Colorado, New Mexico, Utah, and Wyoming were respectively equal to 3.88, 0.84, 1.72, and 1.06 MAFY (4.786, 1.036, 2.122, and 1.307 km^3/year). Colorado River water for Mexico was not officially recognized by the United States until 1944, as described later.

Transformation of the Colorado River Delta

The flow regime of the Colorado River changed dramatically following the start of Hoover Dam operation in 1936. Without the natural flows and sediment load the ecology of the Colorado River delta and estuary changed radically (Kerig 2001). In the late 1930s, and following the Mexican Revolution of 1910 to 1920, the Mexican government allocated land to cooperative farming in the Mexicali Valley. The United States objected to this agrarian socialist system and the apportionment of land and water that it engendered (Martínez-Zazueta, Osorno-Covarrubias, and García-Reyes 2016). Before agricultural development and the construction of the Hoover Dam, the Mexicali Valley was a desert delta-riparian system, with about 115 km of riparian environments, close to 7,800 km^2 of estuaries and wetlands that throve with aquatic life. Hydraulic infrastructure transformed the delta into a farming region. On the other hand, the ecological cost was high, and many native species, terrestrial and marine, were adversely affected (Glenn et al. 2001).

The 1944 International Treaty and Post–World War II Water Use

Mexico and the United States signed an International Treaty for the utilization of waters of the Colorado and Tijuana Rivers, and of the Rio Grande, in 1944. The treaty authorized the two countries to construct, operate, and maintain dams on the main channel of the Rio Grande and changed the name of the International Boundary Commission to the International Boundary and Water Commission (IBWC). The treaty specified a water allocation equal to 10 percent of the average annual flow of the Colorado River to Mexico; that is, 1.5 MAFY (1.8502 km^3/year). Each basin state prepares an annual water budget up to the limit of their respective allocation, specifying monthly and weekly deliveries, and indicating the location and the time for the delivery. The USBR prepares an annual master plan to meet the water demands to the extent possible. The major consumer of water is irrigation, yet the reservoirs are multifunctional; they supply municipal water; serve environmental, industrial, and recreational uses; and generate hydropower. Reservoirs and aquifers have met water demands that sometimes surpass the natural water supply in the Colorado River basin. Lake Powell and Lake Mead have long-term storage capacity, but their storage has been in decline (Robison and Kennedy 2012). In August 2021 the U.S. government declared a water shortage in the Colorado River for the first time. This means that states that rely on the river for their water supply are likely to face cutbacks as drought continues in the river's basin (National Research Council 2007; Samaniego-López 2008; USBR 2012; Walsh 2013; Castle et al. 2014).

By the second half of the twentieth century, the Colorado River delta was under irrigated agricultural by virtue of the river's water (Robison and Kennedy 2012). The Mexicali Valley, in particular, developed an irrigation district that outgrew its water allocation from the Colorado River. The Mexican government allowed the use of groundwater to meet the demand for irrigation water. In the last four decades the groundwater extraction has risen to the point of causing the chronic decline in phreatic levels and has deteriorated groundwater quality. At the same time, the socioeconomic development in the lower Colorado River border region between the United States and Mexico has increased the demand for freshwater and accentuated its scarcity with the recurrence of droughts (National Research Council 2007).

The Onset of Water Deficit in the Mexicali Valley

Most of the surface water that enters the Mexicali Valley is through the Colorado River allocation. Evapotranspiration is significant, and it constitutes the primary factor in water consumption in the valley. The valley is one of the sunniest places in the world, which creates conditions that are favorable for growing winter vegetables. The Irrigation District in Mexicali Valley has title to all the Colorado River water that crosses the U.S.–Mexico border. In actuality, that water is shared with border cities and other populated areas. Farmers make up for the Colorado River water diverted by nonfarming stakeholders by withdrawing groundwater from the Mesa Arenosa aquifer, east of San Luis Rio Colorado (State of Sonora) and south of Yuma, Arizona. A battery of deep wells withdraws groundwater by virtue of an exchange agreement between the Mexicali Irrigation District and the State Water Commission of Baja California. Strategically, this battery of wells was set as far from the Sea of Cortez as possible (Rubio-Velázquez 2020). The implications of declining groundwater levels, higher pumping costs, land subsidence, wetlands desiccation, and sea water intrusion threaten the economic, social, and environmental well-being in the Mexicali Valley (Medellín-Azuara, Lund, and Howitt 2007).

The State of Baja California and CONAGUA have issued new well permits to reduce the social and political pressure (CONAGUA 2015a). The new wells increase groundwater withdrawal and accentuate aquifer overdraft, and, with it, protests and social unrest. The Mexican government allocates water to specific uses and users following priority rules (Spring 2014). Existing users have priority over newcomers (the doctrine of prior appropriation: "first in time, first in right"; see, e.g., Meyer 1984). In actuality, however, the water use in the Mexicali Valley has been largely dictated by social, political, and economic factors (Rubio-Velázquez 2020).

Evolution of Farming Trends in the Mexicali Valley

Large Mexican and U.S. farming companies started operating in the valley following the approval of the NAFTA. These companies grow cash crops (e.g., fresh vegetables) more efficiently than traditional growers (Lugo-Morones 2006). Some of these farming companies are part of large agribusinesses that can export farm products to the U.S. market and have access to food store chains. These companies negotiate with the irrigation modules to lease their land and their water rights for a specific period, usually five to ten years (Rubio-Velázquez 2020). This type of agriculture requires more water per hectare because the companies produce three and even four crops annually. The Mexicali and Imperial valleys have few freezing days during the winter, allowing the production of most winter vegetables for the U.S. market such as lettuce, tomato, and onions. These trends in agricultural production in the Mexicali Valley signal increasing exploitation of its aquifer and worsening overdraft (Lesser, Mahlknecht, and López-Pérez 2019).

Estimating the Areas of Major Crops in the Mexicali Valley

Crop Water Use and Requirement

The volume of water used by crops is a function of environmental conditions for a specific crop, place, and time. Each phenological or growth stage of a crop has an optimal moisture level, which depends on the soil–water–atmosphere continuum. The water applied per unit of cultivated area with a crop, or crop consumptive use, equals the volume of water assimilated in plant biomass and transpired by the plants plus the water evaporated from the soil in the cultivated area over the annual or growth cycle divided by the cultivated area (Jensen and Allen 2016). The crop water requirement is the volume of water used over the extent of the cultivated area during an annual or growth cycle. The irrigation requirement equals the crop water requirement minus rainfall, and the difference is adjusted (i.e., divided) by the irrigation efficiency.

The Mexicali Valley Irrigation District

The Mexicali Valley Irrigation District (i.e., District 014) receives an average allocation of 117 cm of water depth per hectare (ha $= 10^4$ m^2), which is modified according to the type of crop, such as wheat, cotton, alfalfa, vegetables, and other minor crops. Modules (i.e., a group of agricultural parcels managed collectively by their owners) constitute the spatial arrangement of agricultural production in the Mexicali Valley. There are twenty-two irrigation modules, each with an annual volume of water allocation. Parcel 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 totals the water requirements of the twenty-two modules and petitions CONAGUA to approve the requested water. CONAGUA reviews the module's request and forwards its approved version to the IBWC and the USBR. Every year the USBR receives the water and energy requests from the seven U.S. basin states, Native American nations, and Mexico and evaluates them. The USBR establishes the operational program for the coming year after evaluating all the water requests. The USBR informs all the parties of their approved allocations. The water allocation for Mexico is communicated to the IBWC, which in turn informs CONAGUA, and the latter informs the Irrigation District about its water allocation.

Colorado River water flows from the Hoover Dam to the Morelos Dam in the town of Nuevo Algodones across the Colorado River from Yuma, Arizona, and adjacent to the U.S.–Mexico border, once the required authorizations are issued. From Morelos Dam the water is conveyed to the Mexicali Valley's individual parcels. The irrigated area in the Mexicali Valley exceeds the area that could be cultivated with the allocated water from the Colorado River. This assertion is established by comparing satellite imagery of the Imperial Valley with that of the Mexicali Valley, which cover similar areas. Yet the Imperial Valley receives 3.3 MAFY ($= 4.07\,\text{km}^3$/year) of allocated water compared with the 1.5 MAFY ($1.8502\,\text{km}^3$/year) for the Mexicali Valley. This is a remarkable difference in water volume considering that both valleys have similar climate, crops, soils, and aerial extent. The Mexicali Valley supplements the Colorado River water with groundwater. It is impossible to ascertain how much water is extracted from the aquifer from well-extraction records. The irrigation modules possess that information and treat it confidentially Even the number of existing and operating wells proved elusive to determine. It is known, however, that three types of wells operate in the Mexicali Valley: federal, private, and municipal. The Irrigation District operates the federal wells. Independent farmers (i.e., not part of the irrigation district) and industrial and commercial agencies, including the geothermal energy plants, run private wells. The State of Baja California government operates municipal wells that supply populated areas.

CONAGUA has issued regulations to limit the volume of groundwater that is withdrawn from the aquifer, aiming to alleviate the overdraft. Measurement of groundwater withdrawals by wells is a key component of effective enforcement. Yet farmers have opposed the measurement of groundwater withdrawal by delaying the installation of water meters or by not using them. Gathering groundwater withdrawal data and well data would require accessibility privileges and well-metering actions that call for improved institutional policies and enforcement. Carrying out a survey of wells (location, number, depth, installation details, geologic strata penetrated) and their withdrawals would be a laborious and possibly infeasible campaign even with the well owners' cooperation. CONAGUA and the State of Baja California Agricultural Department locate many wells and their water use, but the data are not readily available and contain inconsistencies. This study, therefore, estimated the areas cultivated with major crops and applied their consumptive use to obtain the amount of water used in farming in the Mexicali Valley. The area devoted to each crop is herein calculated through remote sensing by processing Landsat images available for the study areas. We gathered field data to check and calibrate the remote-sensing interpretation as described in what follows.

The Landsat Imagery Series

The USGS has produced a continuous record of public, global Landsat imagery series since 1972, and for multispectral imagery since 1982 when the Landsat 4 Thematic Mapper started operations. Landsat surface reflectance data are available worldwide for the following satellite series: Landsat 4 Thematic Mapper (TM; July 1982–December 1993), Landsat 5 TM (March 1984–May 2012), Landsat 7 Enhanced Thematic Mapper Plus (ETM+; July 1999–present), Landsat 8 Operational Land Imager (OLI; April 2013–present). The Landsat imagery has a 30 m pixel resolution, and a sixteen-day repeat pass resolution, which are appropriate for discerning the crops cultivated in the Mexicali Valley. Landsat missions capture multispectral reflectance in the visible and infrared bands, from which the normalized difference vegetation index (NDVI) is calculated, as explained next.

The Normalized Difference Vegetation Index Applied to Crop Classification

The main crops in the Mexicali Valley are alfalfa, cotton, and wheat, which account for about 80 percent of the planted area (Secretaría de Agricultura Ganadería Desarrollo Rural Pesca y Alimentación

[SAGARPA] 2006). High-value crops such as asparagus and green onion contribute significantly to agricultural revenue (Brun et al. 2010). Other minor crops include sorghum, corn, rye grass, and fruit. This study defined four major crop groups for the Mexicali Valley, each with a lead crop. The lead crops are winter wheat, cotton, alfalfa, and vegetables. The minor crops lumped with a lead crop to form each of the four major crop groups were determined based on their phenological affinity with the lead crops (Rubio-Velázquez 2020).

The determination of the areas planted with various crops is based on the NDVI, which is calculated with the formula $NDVI = (NIR - R)/(NIR + R)$, where $NIR =$ near infrared radiation, and $R =$ red band radiation reflected by vegetation, where a band denotes a range of wavelengths in the electromagnetic spectrum. The R and NIR bands are positively correlated to the photosynthetic activity, leaf area index, and projective cover of the plants. Usually in the range (–1, 1), the higher the NDVI, the greater the photosynthetic activity. The satellite sensors register the surface reflectance and send back the digital values to the National Aeronautics and Space Administration (NASA)/USGS land control centers, where the quality of the images is verified and the images are processed. Surface reflectance is generated from Landsat Collection 2 Level 2 inputs that meet the $< 76°$ solar zenith angle constraint and include the metadata inputs to generate scientific products before making them available online through the USGS Earth Explorer site.

Each crop has a specific solar radiation reflectance that is captured by the Landsat imagery as the spectral signature of the crop at a specific time. The spectral signature is converted to an NDVI, which allows distinguishing between different crops by combining time, plant phenology information, and the NDVI itself, thus leading to a classification of the pixels in remote-sensing imagery by crop type. Adding the areas of the pixels for each crop type in the images covering the study area (i.e., the Mexicali Valley) yields the areas covered by various crops. Once the crop areas are known, one applies the crop consumptive use to each area to calculate the water requirement during a given period. This is the approach applied in this work to calculate the areas of cultivated crops and their water requirements in the Mexicali Valley. One can compare past NDVI values with new ones and define temporal trends in agricultural practices to improve irrigation knowledge in a region (Lenney et al. 1996). The following subsections describe the crop classification approach in detail, including errors in classification.

Image Processing and Crop Area Determination

The software ArcGIS 10.6 and ENVI were used to process and to geoposition each pair of Landsat images for a complete scene of the Mexicali Valley. These images were then joined and the R and NIR reflectance layers were chosen for NDVI analysis and crop classification. The following ten steps summarize the processes followed for quantifying the crops' areas.

1. Define a polygon with the area of interest, in this case the Mexicali Valley. Prepare it as a shapefile.

2. Prepare the graphs of the phenological cycles of the crop groups (wheat, alfalfa, cotton, and vegetables). These graphs serve as guide for searching for the best dates for satellite images with which to classify the crops. For example, winter wheat has its most intense vegetative status (high chlorophyll, and photosynthetic activity) at the end of March or beginning of April. Cotton has the most intense vegetative period in June and July. Hybrid groups have a more extended period. The alfalfa group occurs throughout the year. August and September are the best months for discriminating them with satellite imagery, when the other crops are not yet planted, or have already been harvested. The USBR and the Mexicali Valley Irrigation District have estimated the consumptive use of crops in the border region (USBR 2014). These data served to establish an average water use by each crop in the study region.

3. Identify the satellite imagery needed for the scope of the project. Define the sensor according to the objective of the project.

4. Search in Earth Explorer for the satellite images that comply with the selection criteria.

5. Download the satellite imagery with all the metadata and keep an adequate and systematic record of them. Review the quality of each image. Search for images of good quality to replace those of poor quality.

6. Merge images where there are more than one available. Clip the merged result with the area of interest shapefile with ArcGIS.

7. 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 NDVI classes and their range limits according to the number of relevant crops. It was determined based on trial and error that seven NDVI classes represented the best choice for this study. These classes are alfalfa, cotton, vegetables, wheat, salty water, desert/urban, and fallow land.

9. The range of the NDVI classes is manually adjusted to obtain better discrimination. Once this task is accomplished, ArcGIS and ENVI calculate the number of pixels for each class and multiply them by the 30 m × 30 m spatial resolution of Landsat to calculate the area for each class. Some parcels are not 100 percent within only one class of land cover, in which case one counts that pixel for the class with the largest percentage of coverage (i.e., apply a majority rule). The large number of pixels compensates by rounding the differences, yielding low average error values.

10. Find the coverage of each crop group. This ten-step process is applied to identify and calculate the areas of wheat, alfalfa, cotton, vegetables, and other land uses (salty water, desert/urban, and fallow land).

It is necessary to carry out a series of trial-and-error calculations with the number of classes and colors to map the average activity of each pixel. Crop classification is performed and saved as a raster file in a .tif format. It is sound to preserve the name of the image in the NDVI file, thus preserving the location and date of the image and retaining the process followed. The ArcGIS Layers Properties menu determines the number of NDVI classes and the thresholds used to differentiate them in its classification menu. The ArcGIS Spatial Analyst Toolbox/Map Algebra/Raster Calculator counts the number of pixels in each class. The number of pixels of each NDVI class times the area of each pixel (30 × 30 m) gives the total area of each crop. This information fills the crop/year table entry for a specific date. The algorithm for calculating the NDVI with ENVI is explained earlier, except for the specification of (1) the initial values or parameters provided to the software, (2) the thresholds that establish the differences between crops, and (3) the managing of possible sources of systematic error.

Four crop groups were considered in this study and each group has a lead crop. For instance, (winter) wheat is one of the lead crops. In this case one chooses the dates when wheat is at its vegetative maximum, so that the NDVI is higher for wheat and smaller for other crops that do not climax vegetatively at the same time as wheat. Not 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 ArcGIS classified similar values or spectral signatures. A series of known parcels with wheat at different stages in their growth was used to estimate the possible error in the classification, and the classification was assessed by finding the percentages of 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 that wheat was classified as nonwheat, (F, T) means something nonwheat was classified as wheat, and (F, F) means nonwheat was classified correctly. The spatial analysis can process several NDVI 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." It is possible to carry out a reclassification process by looking for these specific parcels (and adjusting the NDVI interval limits), and saving this layer to compare it later against an updated classification when the possible crops have a clearer difference in NDVI values. Therefore, the trends in errors can be checked and adjustments made to the original classification. The most common mistake is to misclassify a crop as a different one; for example, barley misclassified as rye grass. When converting these areas to volumes of water for irrigation the differences are small, less than 0.5 percent.

Sometimes the NDVI ranges of crops overlap. In this instance it is necessary to analyze an additional satellite image corresponding to a date four or six weeks later, once the phenological cycle of the crops is clearly distinct. Another source of error is assigning a pixel to one crop type when it has more than one crop present. This was resolved in this study by assigning a pixel to the crop occupying the largest portion of the pixel. The error introduced by rounding off numbers in this manner is minimal due to error compensation in an area as large as the Mexicali Valley.

Field data were collected during 2018 and 2019 and were used to corroborate the spectral signatures at different crop ages. The crop classification error was approximately 0.9 percent. This level of classification error is excellent for regional water-balance calculations of the type undertaken here (Hao, Wang, and Niu 2015). Figure 4 depicts a map of the crop types and land cover determined for the Mexicali Valley applying this work's methodology. Table 1 lists the calculated crop areas.

Water Uses by Agriculture and Populated Areas

Water use in the Mexicali Valley is made up of irrigation and nonirrigation water uses. Irrigation water is determined based on crop type and areas irrigated during the annual cycle. Other water uses are added to irrigation water to obtain an estimation of the regional water use. All the available freshwater in the Mexicali Valley is the sum of water from the Colorado River and groundwater from the Mexicali Valley aquifer. Once the total water uses by farming and populated areas are determined, as done in this work, the amount of extracted groundwater is obtained by deducting the Colorado River supply from the total water use.

Table 1. Crop areas in the Mexicali Valley

No.	Crop group	Pixels	Area (ha)
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

Note: 1 ha = 10^4 m^2.

Estimating Agricultural Water Use in the Mexicali Valley

The crops' areas in the Mexicali Valley water were estimated earlier. The crops' areas are multiplied by their corresponding consumptive use to calculate the irrigation water. Table 2 lists the consumptive uses for the major crops (A. Garcia Vargas, Irrigation District operations manager, personal communication, June 15, 2018).

The consumptive uses listed in Table 2 were applied to the crops' areas listed in Table 1 to yield the annual water volumes used by crops in the Mexicali Valley, which are listed in Table 3. The agricultural water use is added to the water use by populated areas served by Colorado River water and Mexicali Valley's groundwater to produce the total water use. The water use by populated areas is discussed next.

Estimating Water Use in Populated Areas

The daily per-capita use of water equals 200 L according to the Mexican Drinking Water Norm (127-SSA1-1994). In hot desert areas it rises to 250 L for the urban population, and it equals 200 L per person, per day in rural areas. This volume is the sum of water for drinking, washing, cleaning, and residential and public gardening. The city of Mexicali and the neighboring city of San Luis Rio Colorado are in a hot desert area. Their daily per-capita use is 250 L per person, per day, whereas the coastal cities and rural communities receive 200 L per person, per day. Water

Table 2. Annual consumptive use of Mexicali Valley crops

Crop	Consumptive use (m)	Growth period (days)	Annual duration (days)
Wheat	1.08	15 November–31 December	153
Alfalfa	1.64	1 January–31 December	365
Cotton	1.42	15 February–10 March	120
Winter vegetables	0.99	1 September–30 November	100

Table 3. Agricultural annual water uses in the Mexicali Valley

Lead crop	Area (10^6 m^2)	Average consumptive use (m)	Water use (10^6 m)	% of water use
Wheat	532.04	1.08	575	27.13
Cotton	402.82	1.42	572	27.00
Alfalfa	362.11	1.64	594	28.03
Vegetables	337.09	1.12	378	17.84
Total	1634.06		2,119	100.00

districts monitor the volume of water they supply to the cities. Table 4 summarizes the populations and their corresponding calculated water use.

Water Balance in the Mexicali Valley and Populated Areas

The annual agricultural water use was reported in Table 3 to be 2,119 million cubic meters (Mm^3). The annual water use in populated areas was reported to be 295.8 Mm^3 in Table 4. Notice that the agricultural water use is slightly over seven times the water use by the populated areas. The sum of the annual agricultural water and populated areas water use amounts to $2{,}119 + 295.8 = 2{,}415\ Mm^3$ (rounded to the nearest integer number).

Recall the Colorado River annual water allocation equals 1,850 Mm^3. This means the annual water use exceeds the Colorado River annual water allocation by $2{,}415 - 1{,}850 = 565\ Mm^3$, which is supplied by groundwater. This level of groundwater withdrawal exceeds the sustainable yield of the aquifer, which is defined as the maximum quantity of water calculated over a base period representative of long-term conditions in the basin and including any temporary surplus that can be withdrawn annually from a groundwater supply without causing an undesirable result (Loáiciga 2017).

Discussion

Sensitivity of the Water Balance

The estimation of total water use reported in this work can be refined to account for water losses and irrigation efficiency. The 1.50 MAFY (1.85 km^3/year = 1,850 Mm^3/year) water allocation to Mexico is measured at the Hoover Dam. From there water travels through the Colorado River to the Morelos Dam in Mexico. Water is conveyed from the Morelos Dam to the irrigation district. Water moves through many jurisdictions before arriving in the farming parcels. Federal wells augment the canals' flows with groundwater along their way to deliver water to the parcels in the irrigation system. There are water losses along the Colorado River and irrigation canals due to evaporation, seepage, and accidental overflows. These losses reduce the volume of Colorado River water that reaches the farming fields, which is less than the nominal 1,850 Mm^3/year allocation. The water requirement of crops calculated earlier (2,119 Mm^3/year) could be affected by the in-farm irrigation efficiency, which is unknown. Assuming an average irrigation efficiency equal to 0.95 means that the irrigation requirement would be $2{,}119/0.95 = 2{,}231\ Mm^3$/year. The annual water use by irrigation and populated centers would be in this instance equal to $2{,}231 + 295.8 = 2{,}527\ Mm^3$. Furthermore, assuming that losses reduce the Colorado River water allocation of 1,850 Mm^3/year by 5 percent means that an actual delivery of river water would be 1,758 Mm^3/year. This implies that the annual deficit between water use and water availability would be $2{,}527 - 1{,}758 = 769\ Mm^3$, which compares with the 565 Mm^3/year calculated earlier, ignoring irrigation efficiency and water losses. CONAGUA (2015b) estimated the annual water deficit at 783.1 Mm^3/year, an amount that was calculated by adding all the authorized groundwater titles, whose actual water use is uncertain (Rubio-Velázquez 2020). The 769 Mm^3 refined estimate of the water deficit being less than CONAGUA's does not constitute solace for the future of the Mexicali Valley aquifer in view of ineffective aquifer regulations and new trends in agricultural production in the valley.

Table 4. Estimated average annual water use in populated areas

City/town	Population (2018)	Average daily per-capita use m^3/per person, per day	Average daily use (m^3)	Average annual use (10^6 m^3)
Mexicali	1,116,194	0.250	279,049	101.853
Rosarito	96,734	0.200	19,347	7.062
San Luis Rio Colorado	193,346	0.250	48,337	17.643
Tecate	102,406	0.200	20,481	7.476
Tijuana	1,901,987	0.200	380,397	138.845
Rural	313,303	0.200	62,661	22.871
Total	3,723,970		810,272	295.8

Federal Regulations and Their Impact on the Mexicali Valley Water Use

CONAGUA announced regulations on groundwater extraction in the late 1990s. Urban and rural water districts, irrigation modules, and small farmers petitioned for larger water titles. These petitions were a preventive measure by the water users, who anticipated imminent cutbacks. The larger water titles became speculative assets, negotiable with new developers and farming companies, which buy water titles associated with leased lands and idle or partially used water titles to obtain the development permits or water volumes for intensive farming (Rubio-Velázquez 2020). These companies grew in size and number with their expanding water titles. The farming companies are specialized producers experienced in production and marketing who outcompete small local farmers (Almaraz 2015), some of whom are displaced permanently (Faret 2009). Political and economic pressure forced CONAGUA's officials to concede the expanded water titles petitioned by many stakeholders. The border region received foreign investment due to the NAFTA and economic development was anticipated in this area. Water restrictions were incompatible with the national and regional policies seeking to attract foreign investment, and the latter policies prevailed, worsening the water supply situation in the study area.

The farmed area in the Mexicali Valley diminished by 4.2 percent, but groundwater use and crop revenue rose by 5.4 percent and 11.8 percent, respectively, over the last decade according to the Irrigation District data we gathered. The decline in farmed area was caused by sea water intrusion in the southwestern part of the aquifer where farmers have abandoned their parcels. Those irrigation modules have transferred their water titles to private agricultural companies who use the water on leased lands in the northeastern part of the aquifer for growing vegetables.

Conclusions

This work estimated the annual water use in the Mexicali Valley and neighboring populated areas that are hydrologically connected to the delta's aquifer. It was herein determined 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 U.S.–Mexico border region of northern Baja California. Wells tapping the aquifer in the southwestern Mexicali Valley and in the vicinity of the prehistoric Lake Cahuila are already yielding brackish water (José Martínez-Gasca, Ejido Campeche, Irrigation District 014, personal communication, June 2018). Farmers in those areas cannot irrigate their crops with this water any longer, and they are being displaced to other regions. Farming has become more water-intensive with high-yield crops. Well owners drill new, larger wells when an existing well fails and transfer the water titles from the old wells to the new ones. This replacement activity increases the water deficit in the study region.

Groundwater withdrawal in the valley's western region causes land subsidence. It is notorious along the master irrigation canal, that has been elevated more than once to maintain its conveyance capacity. Water diversions have dried the lower Colorado River downstream from the Morelos Dam. The reduction in Colorado River flow and the declining groundwater levels have reduced aquifer recharge in the Mexicali Valley, while the aquifer is dewatered by ever increasing groundwater withdrawals. The groundwater level is declining by up to 1 m per year in certain zones due to the heavy extraction and overdraft demonstrated in this work (Rubio-Velázquez 2020).

Locals understand how important it is to preserve the aquifer; yet, up to now, reducing water use has not been an option. Water demand is intense in the Mexicali-Tijuana region. Urban water districts and developers seek expanded water titles constantly. The irrigation modules and the cities and industries work out legal agreements to transfer the water titles. There are twenty-two irrigation modules and about 17,000 farmers with water titles in the Mexicali Valley, which means that there are numerous possibilities of finding someone willing to sell their water titles to the cities and industries. The transfer of water titles from farmers to nonfarmers has reduced the percentage of the water used in farming, from 85 percent two decades ago to about 80 percent currently.

The water trade has accelerated the overexploitation of the Mexicali Valley aquifer and has worsened its deleterious effects (Rubio-Velázquez 2020). The water supply dilemma in the Mexicali Valley is worsened by climatic change and reduced precipitation that sustains Colorado River streamflow (see Figure 3), the main source of surface water to Mexicali Valley. The growing scarcity of Colorado River water has forced the authorities managing its water to reduce water deliveries below the targets prescribed in international treaties and interstate compacts. All the indications to date point to less surface water for the Mexicali Valley in the future, thus, increasing the pressure on its aquifer and exacerbating the struggle to sustain a healthy economy and environment, especially in the languishing Colorado River estuary that has been suffering a slow death due to lack of river streamflow.

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 Baja California. The services industry is also growing rapidly. Over the last three decades urban and industrial developments have taken place in what were previously farming areas. Farmers sell their land and water titles to developers, and frequently migrate with their families to urban areas both in Mexico and the United States to start a new life (Faret 2009).

What lies ahead for the Mexicali Valley in view of its water and environmentally related challenges? On the supply side, the historical evidence and climate projections indicate declining Colorado River flow as a result of climate change and the drying of the U.S. southwest. Water storage in Lake Mead is at a historical low. The USBR has implemented a Drought Contingency Plan since 2019 that prescribes reductions in water deliveries as a function of precipitation and the water level at the Hoover Dam at the beginning of the water year. In the 2020 water year, the Mexicali Valley received about 4 percent less water from the Colorado River. The contingency plan calls for continued reductions until a recovery of water storage in the Hoover Dam is achieved. Therefore, it is clear that water supply from the Colorado River to the Mexicali Valley and other Mexican users is on the decline. Coastal cities such as Tijuana and Rosarito have not been able to implement large-scale sea water desalination in spite of plentiful solar power available, nor has sewage reuse been implemented at a significant level to diminish the reliance on Colorado River water imports. On the demand side it is clear that as population and industries expand so will their water usage. The agricultural water use has evolved with the introduction of more profitable crops and the installation of efficient irrigation technology. Many factors promote the upgrade of irrigation technology, such as the opening of farm-product markets and the ability to export fresh vegetable products to the United States, Europe, and China, especially during the winter.

The Mexicali Valley most likely will remain for some time a hybrid farming region growing traditional crops, such as alfalfa, while expanding more profitable crops such as winter vegetables. The existing irrigation district infrastructure competes with the modern irrigation systems, the former enjoying the capital invested in irrigation canals and other infrastructure over many decades. Governmental programs supporting water efficiency might help the transition to more efficient and profitable agriculture. Education and training encourage the farming transition, and farming schools and higher levels of general education bring new business opportunities and a new vision on how to use water more efficiently. Economic development has created modern infrastructure in transportation, irrigation canals, farming, and harvesting equipment, warehouses, energy plants, communication systems, and health facilities. This economic modernization has occurred alongside social changes striving for a better way of life, sustainability, and environmental protection. The water deficit in the Mexicali Valley remains a challenge; yet, conditions there are poised for change driven by water-rights transfers to higher value urban water uses and by the continuing evolution of the agricultural system to greater efficiency and to higher value crops.

Funding

Javier Rubio-Velázquez received support from a doctoral fellowship from the Government of Mexico and from block grants from the University of California.

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