Assessing Water Management Strategies under Water Scarcity in the Mexican Portion of the Colorado River Basin

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Abstract: The water management of the Colorado River is at a tipping point. This paper describes water management strategies in the Mexican portion of the Colorado River Basin considering water scarcity scenarios. A water allocation model was constructed representing current and future water demands and supply. The Colorado River system in Mexican territory is used as a case study, and all its water demands are characterized [Irrigation District Rio Colorado (DR-014), Mexicali, San Luis Rio Colorado, Tecate, Tijuana-Rosarito, and Ensenada]. Individual strategies were run by subsystem and then their impact was analyzed systemwide. Performance criteria and a performance-based sustainability index were evaluated to identify water stressors and management strategies to improve water supply for agricultural, urban, and environmental users. Analysis of results shows that the irrigation district (DR-014) is the most affected user due to water cuts because it has the lowest priority and, thus, any reduction in Colorado River allocations affects them directly. A range of water management strategies was investigated, including a no-action scenario. The current system depends on the long-term aquifer overdraft to supply water demand. The reduction of the cultivated area was the strategy that increased the sustainability index the most for DR-014. Agricultural to urban transfers, water use efficiency, wastewater reuse, and desalination are prime possibilities to improve the current water supply in the coastal zone (Tijuana, Rosarito, Ensenada). This research shows the spectrum of possible outcomes that could be expected, ranging from systemwide effects of inaction to the implementation of a portfolio of water management strategies. **DOI: 10.1061/JWRMD5.WRENG-5985.**

Author keywords: Colorado River; Mexico; Water management; Allocation model; Water scarcity.

Introduction

There is a growing crisis of freshwater availability throughout the world (Padikkal et al. 2018). Accessible water resources are becoming more vulnerable due to increased pollution, uncontrolled groundwater depletion, and climate change impacts on water availability patterns (Khan et al. 2017). Water availability is under constant threat from increasing domestic, agricultural, and industrial demands. According to the World Water Assessment Programme (WWAP 2015), water demand is predicted to increase worldwide by up to 55% by 2050. This prediction is based on the increment of the population from about 7.7 billion in 2019 to about 9.7 billion in 2050 and the subsequent increase in feed crop production to support animal-protein diets, energy demand, and economic-industrial activity. Moreover, intensified competition over water resources can increase water conflicts, which are predominant in transboundary waters (Padikkal et al. 2018).

Transboundary water resources are shared by more than 70% of the world's population and supply water for about 60% of worldwide food production (Earle and Neal 2017). There are more than 280 shared river basins increasingly subject to water-related conflicts (United Nations 2018). Along the border region between the United States (US) and Mexico, there are significant challenges including overallocation, rapid urbanization and industrialization, surface and groundwater pollution, groundwater overdraft and climate uncertainties (Wilder et al. 2010). The 3,218 km boundary between the two countries comprises four states in the United States (California, Arizona, New Mexico, and Texas) and six in Mexico (Baja California, Sonora, Chihuahua, Coahuila, Nuevo León, and Tamaulipas) (Wilder et al. 2019). Transboundary river basins along the border include the Rio Grande–Bravo Basin (RGB), the Tijuana River Basin and the Colorado River Basin (CRB). The Colorado River (CR) provides water to almost 40 million people in seven US states, 2.7 million people in two Mexican states

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Note. This manuscript was submitted on September 28, 2022; approved on April 11, 2023; published online on July 6, 2023. Discussion period open until December 6, 2023; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496.

(Baja California and Sonora), and 34 Native American Territories (Pulwarty and Maia 2015). The CR is a highly engineered system, with multiple reservoirs and enough storage capacity in Lakes Mead and Powell to supply water demands for a four-year period when both of them were at full capacity (Gerlak et al. 2021). However, in the last two decades, the river has been under great pressure from increasing demands and prolonged droughts (Berggren 2018; Udall and Overpeck 2017). In July 2022, the reservoirs were less than half capacity at their lowest historical levels (Bureau of Reclamation 2022). Climate change and sustained drought, population growth, management of the Colorado River delta, and stakeholder inclusion are some of the main challenges of the CR basin (Juricich 2022).

In recent years, increased awareness of overallocation and drought has catalyzed collaboration between the United States and Mexico (Bussey 2019). The 1944 Water Treaty signed by both countries provided a water allocation to Mexico of 1,850 million cubic meters per year ($\mathrm{Mm}^3/\mathrm{year}$) from the CR. The 1944 Treaty is a living document and agreement; *Minutes* are the instrument by which the United States and Mexico update the treaty.

One of the latest amendments through Minute 323 (IBWC 2017) describes the Binational Water Scarcity Contingency Plan (BWSCP) *to avoid reaching critical reservoir elevations at Lake Mead*, and specifies two main concepts for both countries: water savings and mandatory water reductions. Water savings is water that is stored and saved for later use for both countries to reduce Lake Mead releases under low elevations; these water savings are recoverable once reservoir elevation conditions improve. Mandatory water reduction is water that will be deducted from Mexico's water allocation without recovering it later. Based on the projected Lake Mead elevation by January 1, 2023, Mexico's water allocation will be reduced by 128 Mm^3 in 2023, with a mandatory water reduction of 86 Mm^3 and recoverable water savings of 42 Mm^3 (CILA 2022). Mexico will recover the water savings when the reservoir elevation in Lake Mead is projected to exceed 1,110 ft (335 m) above sea level. The water reduction (128 Mm^3) represents 6.65% of Mexico's total water allocation (1,850 Mm^3).

Minute 323 is not the only water shortage and saving plan for drought conditions in the CR basin. The minute applies the principles of shared shortage and surplus by creating additions and reductions to Mexico in proportion to the reductions outlined in the 2007 Interim Guidelines for the states of Arizona, California, and Nevada (Bussey 2019; Secretary of the Interior 2007), and it is an ampliation of Minute 319 (CILA 2012). Moreover, in 2019, the Upper Basin and Lower Basin Drought Contingency Plans (DCPs) were signed. The DCPs outline strategies to address the ongoing historic drought in the Colorado River Basin (Bureau of Reclamation 2023). The 2007 Guidelines, Minute 323 and DCPs, all expire in 2026 (Juricich 2022).

Moreover, Minute 323 also allows Mexico to temporarily store water in Lake Mead (Bussey 2019), and establishes measures to address Mexico's concerns over water salinity, which has been a longstanding problem since the enactment of Minute 242 in 1973. Moreover, both countries, in collaboration with a coalition of environmental nongovernmental organizations (NGOs), committed to fund and allocate water to the riparian and estuarine system within the Colorado River Limitrophe and Delta. The United States also agreed to provide Mexico with $31.5 million to develop conservation projects in Mexico, such as the modernization of irrigation districts, the creation of wetlands, wastewater reuse projects, among others (IBWC 2017). Minute 323 also establishes the Intentionally-Created Mexican Allocation (ICMA–Agua Mexicana Intencionalmente Creada) which is an instrument that allows Mexico to defer delivery of water volumes through adjustments to its annual delivery schedule, resulting from water conservation projects or new water sources projects. In this sense, Minute 323 has been criticized for setting a policy instrument that allows the United States to exchange money (funding for conservation, new water sources, and environmental projects) for water to fulfill Treaty obligations (Lewis 2019), considering the disproportionate difference in economic power between both nations.

In Mexico, Baja California is the main user of the Colorado River water. Surface water and groundwater of the Mexicali Valley aquifer and the San Luis Rio Colorado (SLRC) Valley aquifer serve 2.7 million people in Baja California representing 88% of the state's population, and more than 200,000 ha in the Irrigation District 014 (DR-014) (CEABC 2018). Due to water demand pressures and the modification of Mexico's water allocation under Minute 323, there is a need to evaluate how the CRB in Mexico will respond to these stressors considering the current water allocation policies, infrastructure, and alternative water management strategies.

An important step towards decision support is the use of water planning models to estimate the consequences of different management alternatives and their social and environmental implications (Reichert et al. 2015). Recently, Hadjimichael et al. (2023) presented an intercomparison of models, highlighting the limitations of large-scale hydrologic models and water systems models that emphasize the environmental, infrastructural, and institutional characteristics. The study evaluates two such representative models to assess water scarcity vulnerabilities in the Upper Colorado River Basin (Hadjimichael et al. 2023).

The Water Evaluation and Planning System (WEAP) platform has been used for water resources management due to its integrated approach, user-friendly interface, and good compatibility (Kou et al. 2018; Dehghanipour et al. 2019). In Mexico, the WEAP platform has been widely used, for instance, to quantify the vulnerability of water resources in the Guayalejo-Tamesí River Basin (Sanchez et al. 2011) considering the effects of climate change; in the transboundary RGB (Ingol-Blanco and McKinney 2011; Sandoval-Solis et al. 2013b) to evaluate the current water allocation system and alternative water management scenarios; and in the CRB (Sanvicente-Sánchez et al. 2009) to simulate the operational rules under water scarce conditions. However, this last study did not evaluate any water management scenarios because the main objective of the study was to replicate the Colorado River Simulation System (CRSS) (Bureau of Reclamation 2007) model and include the Mexican portion of the CR. Therefore, there is a need to evaluate the recent water allocation and agreements (e.g., Minute 232), and alternative water management strategies that consider the effects of climate change and preventing groundwater overdraft in the Mexican portion of the CR.

The overarching goal of the present research study is to evaluate the effect of current and future water management strategies in the Colorado River system that is located in the Mexican territory. The research question being: *In light of recent binational water agreements (e.g., Minute 323 and water allocation reductions), climate change, and other stressors, how will the water supply for the different users be affected when considering current and future water management strategies?* To address this question, the following objectives were defined: (1) construct a water resources planning model, (2) define and evaluate future availability and water management scenarios, and (3) identify key system stressors. The Mexican portion of the CRB is used as a case study. This research shows the impacts not only in this region but also some generalized water management strategies (e.g., reduction in water allocation or increased infrastructure capacity) that can affect the overall water supply in limited water resources systems.

Study Area

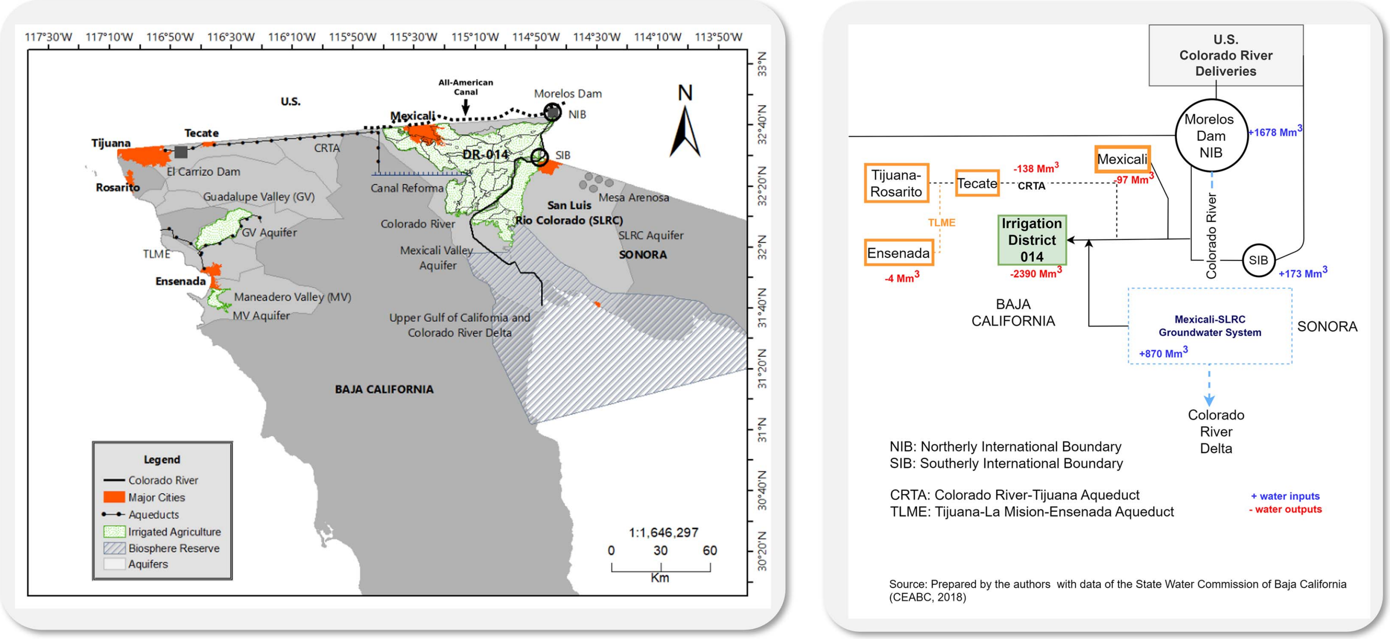
Northern Baja California and San Luis Río Colorado in Sonora are highly dependent on the Colorado River, mostly from Mexico's water allocation from the 1944 Water Treaty and supplemental groundwater out of the Mexicali Valley aquifer and the SLRC Valley aquifer (hereafter referred as Mexicali–SLRC groundwater system), within the Colorado River Delta. Both surface river water and groundwater are conveyed south through 2,562 km of canals for Irrigation District 014 Rio Colorado (DR-014) that expands over Mexicali and SLRC valleys, and to the west coast through the Colorado River-Tijuana aqueduct (CRTA) (Fig. 1). The study region consists of two climate regions, separated by the peninsular mountain range. The western region, adjacent to the Pacific Ocean, is considered a semiarid zone with a Mediterranean climate and annual average precipitation range within 200–400 mm (CEABC 2018). The eastern region, where Mexicali and SLRC are located, is considered an arid desert receiving less than 100 mm of annual precipitation.

The onset of climate change in the Colorado River basin has altered rainfall and temperature patterns, affecting water availability (Udall and Overpeck 2017). The total annual allocation of the Colorado River water resources (2,633 Mm^3) in the CRB corresponds to the sum of the surface water (1,850 Mm^3), which corresponds to the water right of the Treaty and is subject to reductions, and groundwater (783.12 Mm^3) uses (IMTA 2020). The main water user is DR-014 which receives 85% of the full water supply (surface and groundwater) (IMTA 2020). For groundwater extraction, the district has 489 federal wells (volume allocated by the federal government) and 220 privately owned wells. Although surface water is the focus topic in most of the Lower Colorado River basin conversations and is linked to groundwater, they are not managed conjunctively (Gerlak et al. 2021). The current cultivated area of DR-014 relies on groundwater overdraft from the Mexicali-SLRC groundwater system. Inefficiencies in irrigation infrastructure for agriculture constitute the primary source of aquifer recharge in the groundwater system (CEABC 2017; CONAGUA 2020a; Lesser et al. 2019). In addition, the recharge of the Mexicali Valley aquifer has been further reduced as the result of the lining of the All-American Canal (AAC) (Lesser et al. 2019). Moreover, mineralization of the shallow aquifer layers and soil contamination process are identified in Mexicali Valley (Ramirez-Hernandez et al. 2008).

DR-014 is integrated by the Mexicali Valley in Baja California and San Luis Río Colorado Valley in Sonora, and is the fourth largest irrigation district in Mexico, producing 3,078 tons of crops primarily wheat, cotton, and alfalfa and worth $435 million US dollars per year (CONAGUA 2016). However, given the potential reductions of the water allocations related to Lake Mead elevation, salinity problems in water and soil, and overexploitation of groundwater, the water supply of Mexican users are at risk. Despite the relevance of DR-014 in the use of water from the Colorado River, its participation in binational water agreements has been minimal, such as voicing their concerns when the AAC was lined (Cortéz Lara 2011).

The city of Mexicali is the state's capital and the second most populated in Baja California (Table 1). Although Mexicali has a relatively secure supply due to water rights transfers (agricultural lands that become urban transfer their irrigation permits to Mexicali), competition for water between the urban and agricultural sectors could compromise its water supply in the near future. The city of Tecate is also supplied with water from the CR through the CRTA. Tecate has experienced rapid urbanization, population growth, and industrialization, which has compromised the quality of its local water resources. In the 2000s, groundwater provided 30% of the drinking water for Tecate, whereas in 2015, it supplied only 20% (CEABC 2015). Pollution due to low-quality industrial wastewater discharges into the Tecate River reduced such reliance on groundwater, increasing the Tecate region dependence on imported CR water through the CRTA (Mahlknecht et al. 2018).

Tijuana and Playas de Rosarito are highly dependent on the CR imports, because nearly 99% of their available water comes from the CRTA whose current conveyance capacity is 5,333 L/s, and water demand is expected to exceed supply capacity in a few years



Source: Prepared by the authors with data of the State Water Commission of Baja California (CEABC, 2018)

(a)

(b)

Fig. 1. (a) Location map of the Colorado River system in Mexico; and (b) simplified distribution of the Colorado River System deliveries in Mexico.

Table 1. Urban demands of Baja California

Concept	Mexicali	Tecate	Tijuana-Rosarito	Ensenada
Population[a]	911,479 (28%)	102,406 (3%)	1,738,304 (54%)	486,639 (15%)
Water use per capita[b] (L/inhab/d)	284	221	181	147
Water supplies[b]	Colorado River diversion	CRTA aqueduct Tecate Aquifer	CRTA aqueduct Tijuana and La Mision Aquifers	Ensenada, La Mision, Maneadero Aquifers Desalinization Colorado River diversion

[a] Based on INEGI (2020).

[b] Based on CEABC (2017).

(CEABC 2018; Medellín-Azuara et al. 2009). Built as the final receiving reservoir of the CRTA, the El Carrizo dam is the primary supply reservoir for the cities of Tecate, Tijuana, and Playas de Rosarito (Malinowski 2004). El Carrizo provides 97% of Tijuana's water supply (CEABC 2015). The Abelardo L. Rodríguez (ALZ) reservoir is used for flood control and is generally considered an unreliable source (Malinowski 2004).

The city of Ensenada has experienced a considerable increase in population, groundwater overdraft, seawater intrusion in aquifers, unreliability of water supply, and institutional inefficiencies (Medellín-Azuara et al. 2013). In addition to local groundwater supplies, Ensenada has a water allocation of 9 Mm^3 from the SLRC aquifer (Mesa Arenosa) since 1996 (REPDA 2020) although, until recently, not all the allocated volume was being used due to the high urban demand of Tijuana and Rosarito that partially use the allocation to Ensenada. In 2015, the conversion of the Tijuana-La Misión-Ensenada (TLME) aqueduct (called inverse flux or *flujo inverso* in Spanish, as it used to carry water from La Misión aquifer to Rosarito) made it possible to import this water, at an average of 110 L/s (4 Mm^3 annually), which is lower than the aqueduct's capacity of 300 L/s (CEABC 2017). Ensenada is also supplied with desalinated water at 132–190 L/s (CEABC 2022), although the desalination plant capacity is 250 L/s (Private company: Aguas de Ensenada) and it is not fully used due to operational limitations. The Emilio Lopez Zamora (ELZ) reservoir is used primarily for surface water runoff collection.

The agricultural regions of the Guadalupe and Maneadero valleys, nearby the city of Ensenada, are economically important (Mendoza-Espinosa et al. 2019); the former being responsible for 90% of Mexican wine production (Plata Caudillo 2010) with an annual gross income of $6 million (CEABC 2018). All water used in Guadalupe Valley comes from the underlying aquifer, which is in an overdrafted condition (Campos-Gaytan et al. 2014; CONAGUA 2020b). In Maneadero Valley, the main crops are ornamental flowers, tomato, cucumber, asparagus, and brussels sprouts. The Maneadero Valley relies primarily on groundwater from the Maneadero aquifer that is experiencing seawater intrusion due to longstanding overdraft (Gilabert-Alarcón et al. 2018); reclaimed water (80 L/s) is used for ornamental flower production of 100 ha since 2014 (Mendoza-Espinosa and Daesslé 2018).

Data and Methods

Overall Method

The present study consisted of five major activities: (1) data compilation, (2) model development, calibration, and validation, (3) evaluation of individual water management strategies, (4) evaluation of meta-scenarios, which are combination of individual strategies, and (5) identification and evaluation of key system stressors, such as water allocation reduction, climate change, or reduction in irrigated area. A water resources planning model for the region was built in the WEAP platform (SEI 2020) to evaluate water management strategies and future strategies; it represents the water allocation system in northern Baja California and San Luis Rio Colorado, Sonora. Performance criteria were used to evaluate, compare, and synthesize results from water management strategies (Fig. 2).

Baja California Water Allocation Model

The Baja California water allocation model (Baja California WAM) represents the water management of the CR water resources in Mexico. The WEAP system simulated the water-supply demand for the study area. A 35-year period of hydrologic analysis was considered, from January 2015 to December 2050, according to projections and action plans of the Baja California Water Plan (CEABC 2018). Years 2008–2013 were used as a reference for model calibration (i.e., historical scenario); these years consider

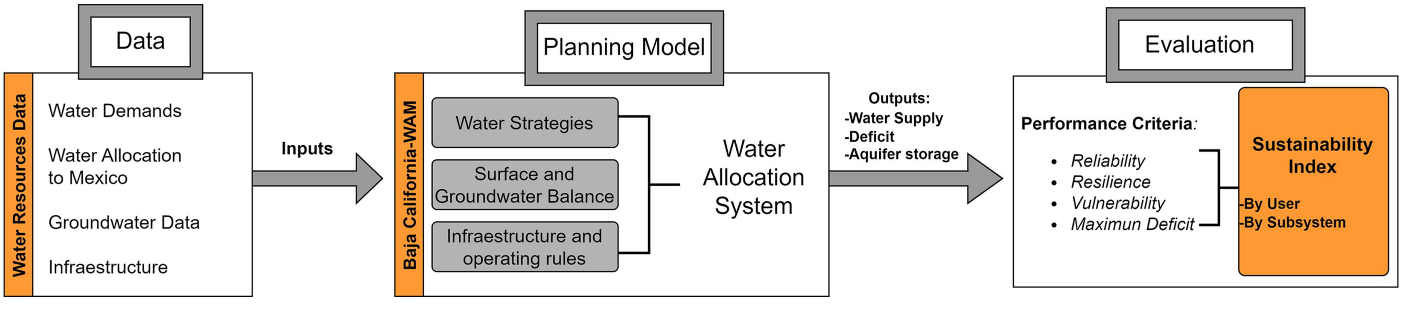


Fig. 2. Mexican portion of the Colorado River Basin study design.

the diminished recharge of the Mexicali Valley aquifer due to the 2008 lining of the AAC (Lesser et al. 2019), which according to García-Saillé et al. (2006), contributed 14% of the total recharge to the Mexicali Valley aquifer (when unlined). Field evidence and modeling suggested continuous drawdown after the conclusion of the lining in 2008, with a drop in the water table of 5.8 m after 4 years of monitoring (Lesser et al. 2019).

The input data consisted of water demands, surface water and groundwater hydrology, and water resources infrastructure (see Fig. S1). Model outputs were water requirements, supply delivered, and aquifer recharge and storage. The present study does not consider modifying reservoir operation rules; it considers that water deliveries from the United States will follow the water demand requirements.

Urban Demands

There are five urban service areas in Baja California WAM, namely, Mexicali, SLRC, Tecate, Tijuana-Rosarito, and Ensenada. WEAP allocates water using a priority system, where 1 represents the first priority. For all urban areas the set priority was 1, consistent with the National Water Law (CONAGUA 2012). Urban demands were estimated from data reported by the local operating agencies through the National Transparency Portal (PNT) from 2008 to 2015, and the reports of management indicators (CEABC 2015). Future water demands for the cities were projected for 2050 using the water use per capita (WUPC) for each city and populations projections by the National Population Council (CONAPO 2018). The local water agencies, Tijuana Water Commission (Comisión Estatal de Servicios Públicos de Tijuana—CESPT), Tecate Water Commission (Comisión Estatal de Servicios Públicos de Tecate—CESPTE), Ensenada Water Commission (Comisión Estatal de Servicios Públicos de Ensenada—CESPE), and Mexicali Water Commission (Comisión Estatal de Servicios Públicos de Mexicali-CESPM) reports provide water use for the residential, municipal, commercial, and industrial sectors.

Agricultural Demands

Twenty-four agricultural service areas were considered in the model: Guadalupe Valley, Maneadero Valley, and 22 demands for each module of the DR-014 (19 modules in Mexicali Valley, and three located in SLRC Valley). A water use priority of 2 was assigned consistent with the National Water Law (CONAGUA 2012). Agricultural demands were estimated from annual reports (2008–2015) of irrigated area and water use published by the Ministry of Agriculture (SIAP 2020) and the evapotranspiration estimates (2005–2008) of the principal crops published by the National Institute for Forestry, Animal Husbandry, and Agricultural Research of Mexico (INIFAP 2008). In DR-014, the three main crops are wheat, cotton, and alfalfa, which, in 2016 represented 83% of the total irrigated area (193,203 ha) (CONAGUA 2016). The share of surface and groundwater use for each module was derived from the Water Distribution Reports (C05). In Guadalupe Valley, the main crops are grapes and olives, which represent 84% of the total area (2,528 ha). In Maneadero Valley, the main crops are ornamental flowers, tomato, cucumber, asparagus, and brussels sprouts, which represents 68% of the total area (2,855 ha). Guadalupe and Maneadero valleys are not water users of the CRB; however, they are closely related to Ensenada's water supply and participate in interconnected water management strategies. Irrigation efficiencies (Sandoval-Solis et al. 2013a) and acreage factors (Lin et al. 2013) were considered in estimating the agricultural water demands.

Hydrology and Calibration

Monthly surface water deliveries from the United States to Mexico at the Northern International Boundary (NIB) (Morelos Dam) and Southern International Boundary (SIB) were obtained from the International Boundary and Water Commission (IBWC). Additionally, Canal Reforma transports the water from the NIB to the CRTA. El Carrizo reservoir redistributes CRTA deliveries to Tecate and Tijuana-Rosarito, and then the water is diverted to Ensenada through the TLME aqueduct [Fig. 1(a)]. In terms of groundwater sources, the Mexicali-SLRC groundwater system was considered as a single groundwater system for planning purposes and given its close hydrologic connection (Ramírez-Hernández 2020; Sanchez and Rodriguez 2021). Groundwater extractions and aquifer recharge from irrigation were estimated and compared with CEABC (2017) and CONAGUA (2020a) that determined groundwater overdraft.

A mass balance approach to back calculate the groundwater use was applied to determine the change of aquifer storage (AS) [Eq. (1)]:

$$\begin{aligned}\Delta S_t &= \text{Recharge}_t - GW\,\text{Extraction}_t\\ \text{Recharge}_t &= \text{Recharge}_t^{AgSW} + \text{Recharge}_t^{AgGW}\\ &\quad + \text{Recharge}_t^{\text{Conv Losses}}\end{aligned} \tag{1}$$

where the change of storage (ΔS_t) is calculated by determining the Recharge_t^{AgSW} refers to the aquifer recharge due to irrigation losses from surface water use, Recharge_t^{AgGW} refers to the aquifer recharge due to irrigation losses from groundwater use, $\text{Recharge}_t^{\text{Conv Losses}}$ refers to the aquifer recharge due to conveyance losses in canals, and $GW\,\text{Extraction}_t$ refers to the groundwater extraction volume.

In addition, the Guadalupe and Maneadero aquifers are also overdrafted (CONAGUA 2020b, c). Groundwater extractions and the aquifers recharge were estimated considering the annual recharge reported by CONAGUA (CONAGUA 2020b, c) and the extractions reported by CESPE water agency (CEABC 2015). The model was calibrated for a groundwater balance that considered estimated aquifer recharge and historic water demand to determine groundwater overdraft and compared it with other studies (CEABC 2017; CONAGUA 2020a). Goodness-of-fit coefficients, such as the Nash-Sutcliffe coefficient of efficiency (NSE) (Nash and Sutcliffe 1970) and the Willmott index of agreement (Willmott et al. 1985) were calculated.

Water Management Scenarios

The study area was divided in three subsystems: (1) Subsystem I (SS1) comprising the DR-014, the Colorado Delta and the cities of Mexicali and San Luis Rio Colorado; (2) Subsystem II (SS2) comprising the cities of Tecate and Tijuana-Rosarito; and (3) Subsystem III (SS3) comprising the city of Ensenada, and the agricultural regions of Guadalupe Valley and Maneadero Valley. Table 2 summarizes the water management strategies by subregion that included strategies outlined in Minute 323 (IBWC 2017), the Baja California Water Plan (CEABC 2018), and strategies discussed in regional forums of the Secretariat for the Management, Sanitation and Protection of the Water (SEPROA) and Baja California and SLRC Basin Council (2020–2021). Individual strategies were run by each subsystem, and then their impact was analyzed systemwide. A baseline scenario was defined as the reference scenario representing the system without any alternative management strategy and considering that the water supply remains constant (2015–2050).

Table 2. Water management scenarios description

Subsystem	Scenario	Baseline value	Scenario value	Source
SS1	Reduction in Colorado River deliveries	Water allocation: 1,850 Mm^3	-55 to -339 Mm^3	Minute 323 (IBWC 2017)
	Increase in crop evapotranspiration $\mathrm{ET_C}$ (m/year) due climate change	$\mathrm{Wheat_{ETc}}$: 0.57	B1: 0.5898–0.5918 A2: 0.5872–0.5928	Based on García Ávila (2012)
		$\mathrm{Alfalfa_{ETc}}$: 1.93	B1: 2.0786–2.1034 A2: 2.0864–2.1067	
		$\mathrm{Cotton_{ETc}}$: 1.14	B1: 1.1675–1.1832 A2: 1.1705–1.1840	
		$\mathrm{Others_{ETc}}$: 1.19	B1: 1.2501–1.2644 A2: 1.2530–1.2661	
	All-American Canal (AAC) lining	Contribution of 0% in the aquifer recharge	Contribution of 14% in the aquifer recharge	Based on García-Saillé et al. (2006)
	Application efficiency (E_a) increase	E_a: 65%	E_a: Increases from 2.5% to 10%	Percentages proposed by the authors in compliance with CEABC plan (2018) and the Consejo de Cuenca de Baja California y Municipio de San Luis Río Colorado Sonora (2021) citizen consultation
	Irrigated area reduction	Total irrigated area: 192,214 ha	Decreases from 2.5% to 10%	Percentages proposed by the authors in compliance with CEABC plan (2018)
	Reduction in alfalfa irrigated area	Alfalfa irrigated area: 34,598 ha	Decreases from 2.5% to 10%	Percentages proposed by the authors in compliance with forage crops reduction CEABC plan (2018)
	Increase in water distribution network efficiency (E_n)	E_n: 83%	Increases from 2.5% to 10% in Mexicali	Percentages proposed by the authors
	Environmental water (delta)	Environmental water allocation: 0 Mm^3	Environmental water allocation: 27.5 Mm^3	Minute 323 (IBWC 2017)
SS2	Increase CRTA capacity	Capacity: 5,333 L/s	Increases from 2.5% to 10%	Percentages proposed by the authors
	Rehabilitation of Tijuana aquifer wells	Use of 0 L/s	Use of 270 L/s	SEPROA (2021)
	Increase in water distribution network efficiency (E_n)	E_n: 80%	Increases from 2.5% to 10%	Percentages proposed by the Consejo de Cuenca de Baja California y Municipio de San Luis Río Colorado Sonora (2021) citizen consultation
SS3	Full allocation from the Colorado River	Ensenada receives 116 L/s	Ensenada receives 285 L/s	Strategy proposed in compliance with REPDA water rights (2020)
	Seawater desalination	Use of 100 L/s	Use of 250 L/s	Strategy proposed by the authors
	Increase in recycled water use in Maneadero Valley	Use of 80 L/s	Use of 200 L/s	SEPROA (2021)
	Use of recycled water in Guadalupe Valley	Use of 0 L/s from Tijuana WWTP	Use of 1,000 L/s from Tijuana WWTP	Baja California state government plan as cited in Mendoza-Espinosa et al. (2019)
	Increase in water distribution network efficiency (E_n)	En: 83%	Increases from 2.5% to 10%	Percentages proposed by the Consejo de Cuenca de Baja California y Municipio de San Luis Río Colorado Sonora (2021) citizen consultation.

Note: B1 = low emission scenario; and A2 = high emission scenario.

Analysis of Water Management Scenarios

Five performance criteria were considered for each water user to evaluate the impact of each water management strategy: volumetric and time-based reliability, resiliency, vulnerability, and maximum deficit (Hashimoto et al. 1982; McMahon et al. 2006). These criteria relate water demand and water supplied for a given water user. Each performance criterion is expressed as a percentage between 0% and 100%; a nonfailure state is considered 100% for reliability (volumetric and time-based) and resiliency, whereas for vulnerability and the maximum deficit criteria a nonfailure state is 0% (Sandoval-Solis et al. 2011). Results for each water user were summarized into a single value from 0% to 100% using the water resources sustainability index (SI^{User}) which is the geometric mean of the (five) performance criteria. The sustainability index (SI) facilitates comparisons of performance among different water management strategies (Sandoval-Solis et al. 2011). The sustainability index by subsystem (SI^{SS}) was used to summarize the results of all users of a given subsystem into a single value; it is the weighted average of the SI values of individual users weighted by their water demand. The sustainability index by subsystem allows the comparison among different water management strategies and among subsystems. Definitions and procedures of performance criteria and SI are presented in Loucks (1997) and Sandoval-Solís et al. (2011).

Results

Model Performance

Model inputs are surface water allocation from the Colorado River, irrigated area by crop and module, crop coefficients, reference evapotranspiration and irrigation efficiencies. The estimated water supply from surface water and groundwater was compared against historical records to verify the model adequacy. Goodness-of-fit criteria were used to compare the observed (historical) and predicted values by the model over n time steps (Legates and McCabe 1999). The Nash-Sutcliffe coefficient and the Willmott index of agreement were 0.64 and 0.90, respectively, which are considered an acceptable performance (Moriasi et al. 2007). Overall, the surface and groundwater use for DR-014 (2008–2013) estimated in this study was 2,376 $\mathrm{Mm}^3/\mathrm{year}$, compared with CONAGUA's estimate of 2,479 Mm^3, a difference of only 4%. In addition, the aquifer recharge for the Mexicali-SLRC groundwater system estimated in this study (836.44 $\mathrm{Mm}^3/\mathrm{year}$) was broadly consistent with the range reported by Lesser and Associates for CONAGUA (2006) (902.6 Mm^3) and CEABC (2017) (766.29 Mm^3). Estimates of aquifer overdraft is 102.54 $\mathrm{Mm}^3/\mathrm{year}$ (2008–2013), which is in between estimates from CEABC (2017) (132.27 $\mathrm{Mm}^3/\mathrm{year}$) (2006–2016) and CONAGUA (2020a, b, c) (95.00 $\mathrm{Mm}^3/\mathrm{year}$).

Analysis of Scenarios

Baseline Scenario

The baseline scenario was the system without the implementation of any alternative policies (e.g., Minute 323). The water deliveries from the Colorado River are maintained constant (1,850 Mm^3), and groundwater overdraft is allowed. Agricultural water demands were also maintained constant, whereas urban demands increase as the population grows (growth rate: 1%, CONAPO 2018). By 2025, a decline in the water supply is noticed, which can be associated with the reduction in groundwater storage due to overdraft decrease in the Mexicali-SLRC groundwater system. By 2050, a water deficit of 321 Mm^3 is experienced, suggesting only 89% of the total demand is satisfied. Table 3 compares the performance of the baseline scenario for two aquifer conditions, with and without groundwater overdraft in the Mexicali-SLRC groundwater system. The water demand of DR-014 represents 85% of the total demand (2,778 Mm^3). In overdraft condition, the SS1 has higher performance (SI: 68%) during 2015–2050, yet (SI: 24%) when overdraft is not allowed. While apparently SS2 is not affected under nonoverdraft condition, Tijuana and Tecate have a water right transfer from the Mesa Arenosa of SLRC Aquifer (Mesa Arenosa), which is interchanged with surface water from DR-014. As SS2 has priority in the supply, the water demand is guaranteed from surface water through CRTA.

Table 3. Average annual water demand and sustainability index for water users in the baseline scenario

Subsystem	Water user	Demand (Mm^3)	Sustainability index (%) Overdraft	Sustainability index (%) Nonoverdraft
SS1	DR-014	2,362	66	18
	Mexicali	136	100	100
	SLRC	28	100	100
	Delta	27	100	100
	Subtotal	2,553	68	24
SS2	Tecate	11	33	32
	Tijuana	150	32	32
	Subtotal	161	33	
SS3	Ensenada	25	37	24
	Guadalupe V.	19	42	32
	Maneadero V.	20	43	33
	Subtotal	64	49	30

Individual Water Management Scenarios

Table 4 shows the Sustainability Index, SI (i.e., composite of performance criteria) for individual water management scenarios for each subsystem with and without groundwater overdraft. Performance criteria of each scenario are shown in the Appendix. For SS1, the reduction in the CR deliveries was the scenario with the lowest SI for both aquifers' conditions, whereas the reduction in the irrigated area (DR-014) had the highest score (94%) (as long as overexploitation is allowed). Volume reliability was the performance criterion with higher values, whereas resilience had the lowest (Table S1). Resilience criteria did not change compared with the baseline scenario, meaning that the deficit events (i.e., demand exceeds supply) and the probability of recovering are the same as the baseline scenario. The exception is the irrigated area reduction scenario, which increases resilience to 94% when groundwater overdraft is allowed. Increase in resilience does not happen without overdraft (resilience: 1%), indicating that SS1 never recovers when overdraft is not allowed. Furthermore, under no groundwater overdraft condition, the subsystem performance decreased from 68% (overdraft) to 24% in the baseline scenario; thus, SS1 is highly dependent on groundwater overdraft.

For SS2, the scenario that provided the most benefits was the increase in the water distribution network efficiency in Tijuana and Tecate (SI: 75%). For this study, the water distribution network efficiency is the percentage of the total water invoiced by the local water agencies divided by the total generated water in each city. Unlike the rest of the SS2 scenarios that increase water supplies, the increase in the water distribution network efficiency is directly related to the reduction of the amount required to meet the water demands, indicating that scenarios oriented to reduce the volume required to meet water demands to improve the subsystem performance more than those oriented to water supply. Results for both aquifer conditions are similar because SS2 relies on 90% of surface water.

Table 4. Evaluation of water management scenarios by subsystem

Subsystem	Scenario	Sustainability index (%) Overdraft	Sustainability index (%) Nonoverdraft
SS1	Baseline	68	24
	Reduction in Colorado River deliveries	43	19
	Increase in crop evapotranspiration (ET_C)	55	17
	Contribution of the AAC in the aquifer recharge	77	30
	Environmental water (delta)	60	24
	Cultivated area reduction	94	62
	Reduction in alfalfa production	65	18
	Increase in application efficiency	63	17
	Increase in water distribution network efficiency	66	18
SS2	Baseline	33	33
	Increased CRTA capacity	47	47
	Rehabilitation of Tijuana aquifer wells	46	46
	Increase in water distribution network efficiency	75	75
SS3	Baseline	49	30
	Full allocation from the Colorado River	72	57
	Seawater desalination	72	54
	Increase in water distribution network efficiency	65	42
	Increase in recycled water use in Maneadero Valley	52	42
	Use of recycled water in Guadalupe Valley	61	42

For SS3, the full allocation from the CR to Ensenada and the use of the total capacity of the desalination plant resulted in the highest subsystem performance. SS3 is highly dependent on groundwater (94% of the water supply); when overdraft is not allowed, the SI decreased from 49% (overdraft) to 30% in the baseline scenario.

Overall Results

The SI by subsystem was calculated for all the permutations of individual water management scenarios to quantify the variability in performance when scenarios are combined and to compare them with respect to the baseline scenario (Fig. 3). All the permutations of alternative water management strategies for SS1 have a lower performance than the baseline scenario, i.e., the strategies oriented to improve the subsystem performance were not able to offset the drawbacks from: (1) the reduction in CR deliveries, (2) the increase in crop evapotranspiration due to climate change, and (3) no groundwater overdraft. In contrast, SS2 and SS3 can improve their SI performance in relation to their baselines if individual or a combination of strategies are implemented up to 90% and 80%, respectively. Notice that the SI performance of SS1 and SS3 are severely affected when there is no groundwater overdraft; in the worst-case scenario, the SI decreased to 18% and 7%, respectively.

Subsystem 1: Mexicali Valley, San Luis Rio Colorado Valley and the Colorado Delta

The sensitivity analysis of scenarios for SS1 shows that the reduction in water allocation from the Colorado River was the strongest parameter. This variable has the largest standard deviation (SD) in SI results with respect to the baseline scenario ($SD^{SS1} = 16\%$). The model was run for different reduction levels in the water deliveries from the United States to Mexico according to Minute 323 considering all permutations of water management strategies (Fig. 4). In all cases, the performances of individual or combined strategies were lower than the baseline scenario. In general, the SI decreases as the water reductions from the CR increase. For instance, under overdraft conditions (Fig. 4), the subsystem performance decreases from 68% in the baseline scenario to 43% in the worst-case scenario when maximum reduction in the CR water allocation occurs (-339 Mm^3) and no additional actions

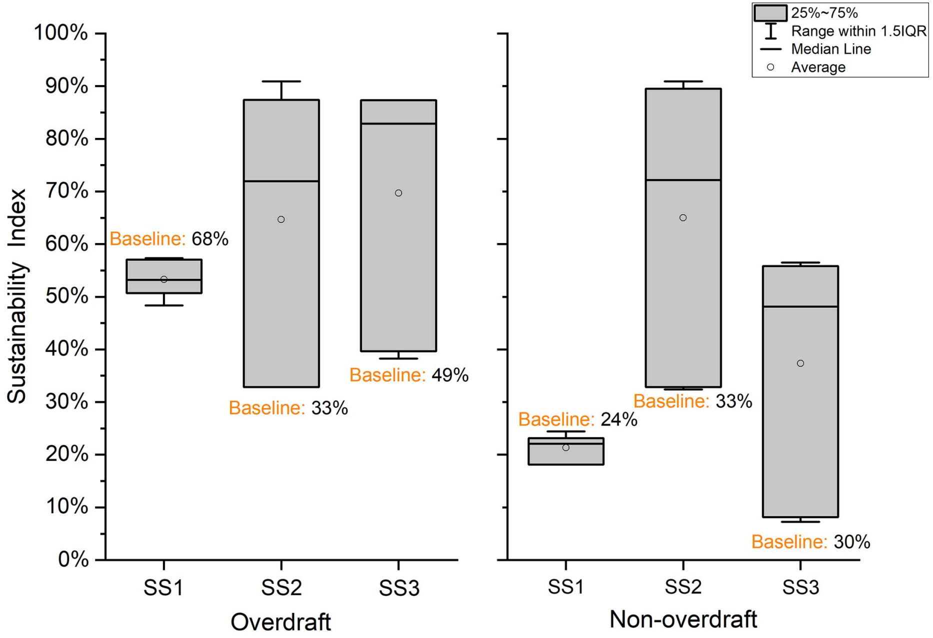


Fig. 3. Subsystems overall sustainability index (SI). SI is the arithmetic average of five performance criteria, namely: volumetric reliability (R_v), time reliability (R_t), resilience (Re), vulnerability (V), and maximum deficit (D_{max}).

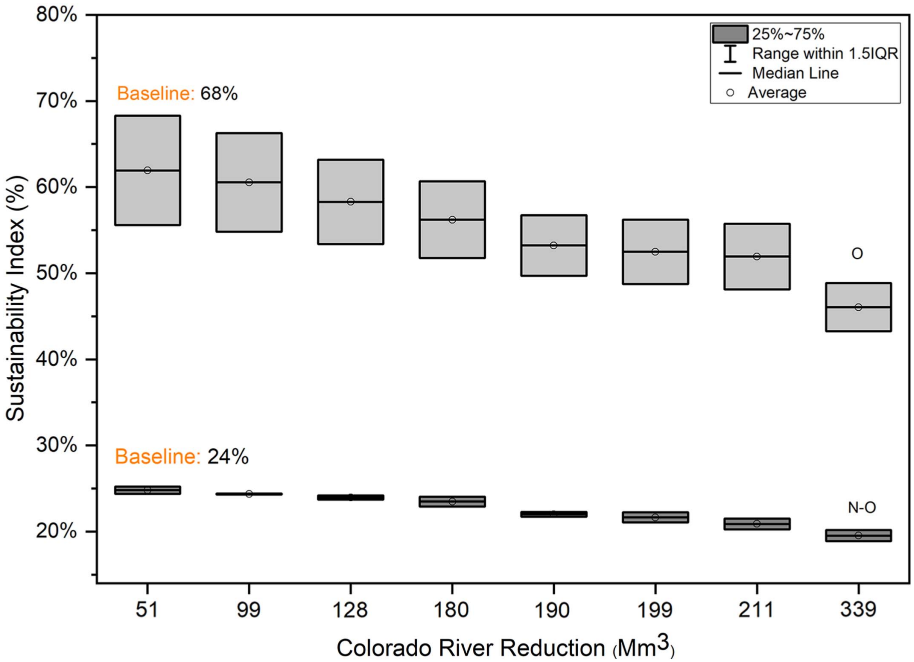


Fig. 4. Sustainability Index for SS1 associated with Colorado River water supply reductions to Mexico (O = overdaft and N-O = nonoverdraft).

are implemented. In the scenario with no groundwater overdraft (Fig. 4), the subsystem performance plummeted, from 24% in the baseline scenario to 19% in the worst-case scenario, highlighting the high reliance on groundwater overdraft. In the case where there is a maximum reduction in water deliveries (-339 Mm^3) and no groundwater overdraft is allowed, a water demand deficit of 868 Mm^3 will be experienced by 2050, meaning that only 63% of the total demand can be satisfied.

Results of volumetric reliability are presented in Fig. 5, which represent the overall volume of water supplied with respect to the sum of all water demands. For instance, a volumetric reliability of 70% indicates that over the period of hydrologic analysis (2015–2050), 70% of the total water demand volume was supplied, resulting in a criterion to understand the overall amount of water supplied in comparison with the baseline water demand. The minimum volumetric reliability for the maximum reduction with and without groundwater overdraft was 78% and 61%, respectively, meaning important reductions in the water supply under these conditions are expected. The median volumetric reliability declines linearly under overdraft and no overdraft conditions.

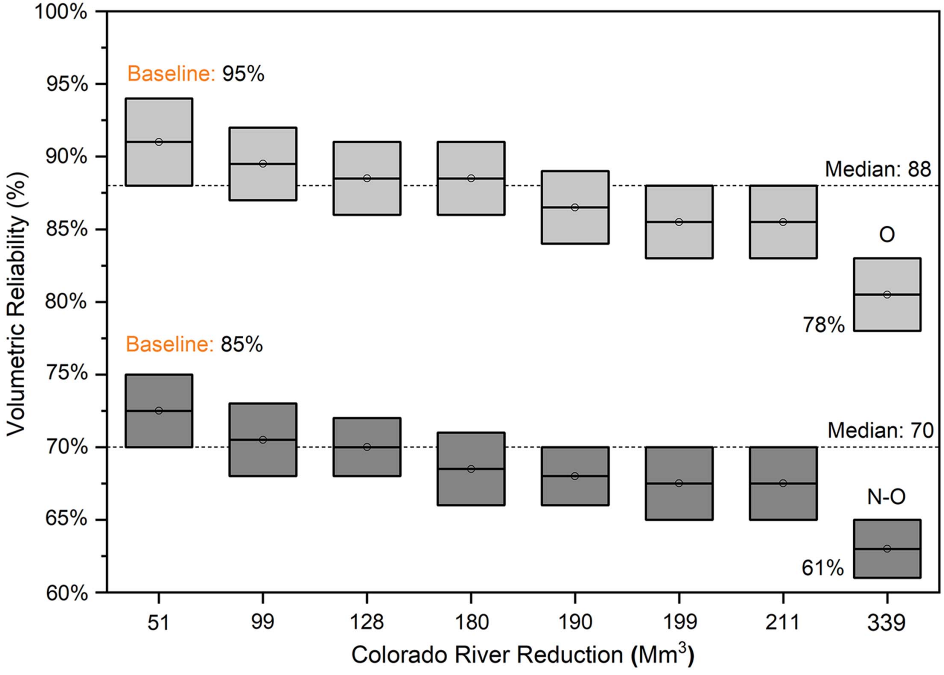


Fig. 5. Volumetric reliability associated with Colorado River water supply reductions to Mexico (O = overdaft and N-O = nonoverdraft).

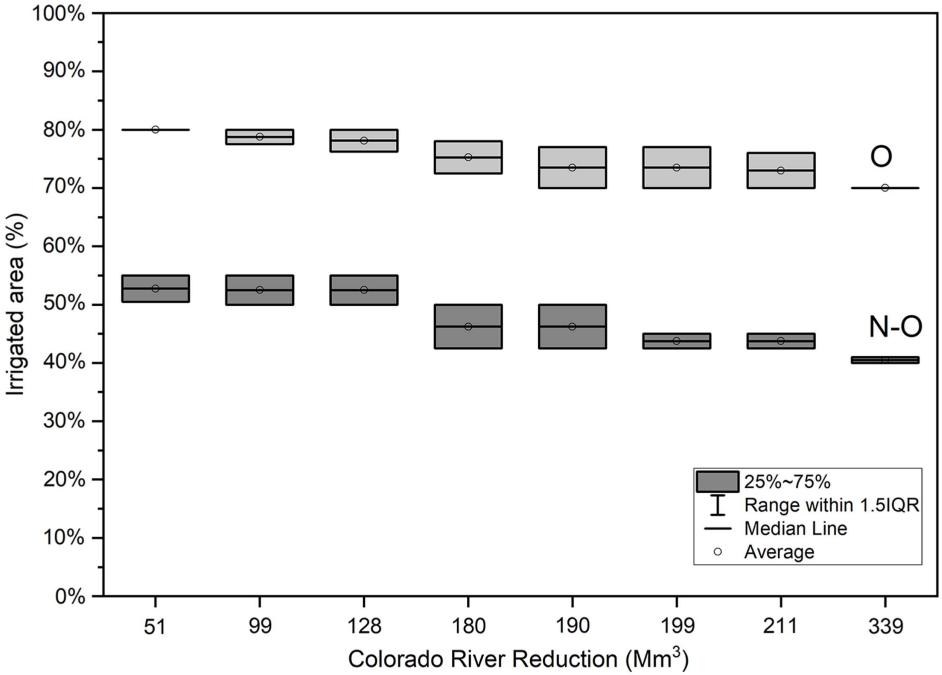


Fig. 6. Percentage of irrigated area supplied with Colorado River water supply reductions to Mexico (O = overdaft and N-O = nonoverdraft).

In terms of irrigated area, a reliability analysis was performed to estimate the cultivated area of DR-014 that could be fully supplied for each water allocation reduction, i.e., volumetric reliability equal to 100% (Fig. 6). From an initial area of 192,214 ha in the baseline scenario to 153,771 ha for the best-case scenario (a reduction of 20%), up to 134,460 ha for the worst-case scenario (a reduction of 30%) (Fig. 6). Under nonoverdraft condition, the reduction in the cultivated area would be more severe, guarantying the supply to only 105,718 ha for the best case scenario (reduction of 45%) and to 76,886 ha in the worst case scenario (reduction of 60%) with the current crop production pattern (Fig. 6).

Subsystem 2: Tijuana and Tecate

Similarly, a sensitivity analysis of scenarios was performed for SS2, by using the water distribution network efficiency as the sensitive parameter, which has the largest standard deviation (SD) in SI results with respect to the baseline scenario ($SD^{SS2} = 29\%$). The model quantified the SI for a set of increases in the network efficiency considering the individual implementation or combination of rehabilitation of wells in Tijuana and the increase in CRTA capacity (Fig. 7). The current water distribution network efficiencies of Tijuana and Tecate (January 2022) are 80% and 81%, respectively (CEABC 2022). Increases in efficiency from 2.5% to 10% improved the SI performance. In the best-case scenario (maximum increase in efficiency and CRTA capacity expansion), the SS2 has a SI performance of 90%. The combination of strategies improves the SI performance to 90%, whereas the efficiency of individual scenarios was 75% (Table 4).

Subsystem 3: Ensenada, Guadalupe, Maneadero

For SS3, two sensitive variables were identified: the full allocation from the Colorado River (285 L/s or 9 Mm^3/year) and the use of water from the desalination plant at full capacity (250 L/s or 7.9 Mm^3/year), both variables with a SD of 30% with respect to the baseline scenario. These two variables were evaluated with individual or a combination of the remaining strategies, which are the use of recycled water and increase in the water distribution network efficiency (Fig. 8). Results show that the use of the full allocation of 9 Mm^3/year improved the SI performance for SS3. Moreover, the use of the desalination plant located at full capacity (250 L/s) also improves the sustainability index. When groundwater overdraft is not allowed [Fig. 8(b)], the overall performance reduces significantly, showing SS3 dependence on groundwater overdraft. An aquifer recharge decrease will significantly reduce the SI performance for both aquifer conditions and sensitive

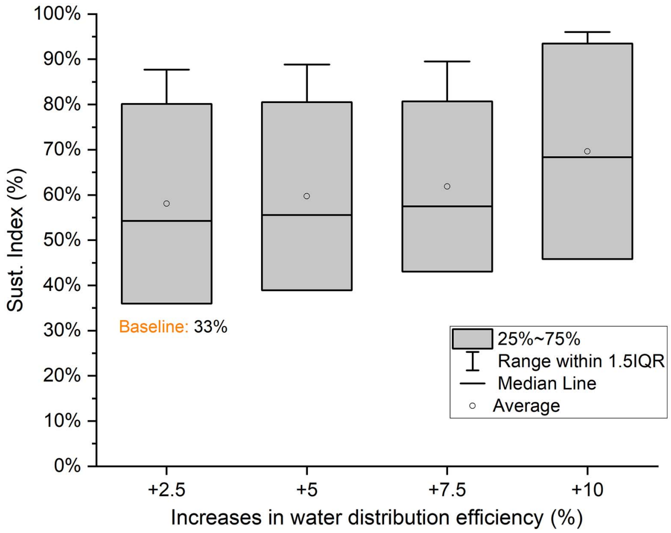


Fig. 7. Sustainability index for SS2 associated with change in water distribution efficiency.

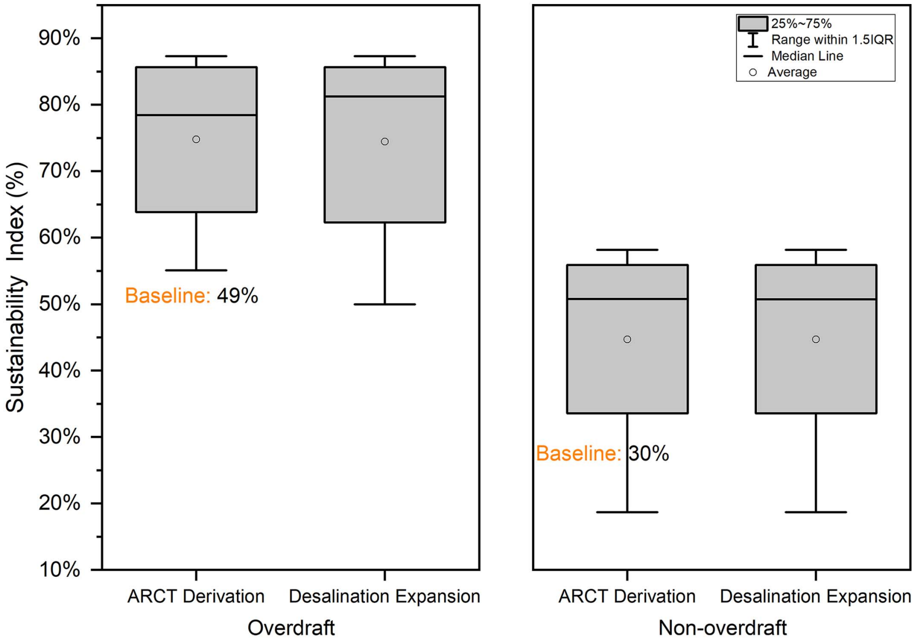


Fig. 8. Sustainability index for SS3 associated with full allocation from the Colorado River and full capacity of seawater desalination.

variables. However, when all the water management strategies are applied, the performance of the system improves.

Discussion

Colorado River Reductions

The agriculture sector will be the most affected water user for two reasons: (1) it has the lowest priority and thus any reduction in CR allocations affects them directly; and (2) the cultivated area (primarily forage crops with high water demand such as alfalfa) exceed future water availability in the region and heavily relies on groundwater overdraft. The reduction of the cultivated area was the strategy that increased the sustainability index the most for DR-014 (Table 4). This scenario reduces the total irrigated area evenly across the 22 modules considering the current crop production. A similar conclusion was reached by the Imperial Irrigation District, CA, which temporarily takes active farmland out of production (fallowing) and forecasted nonagricultural use in five-year increments from 2010 through 2050 (Imperial Irrigation District 2021). Moreover, Cortés-Ruiz and Azuz-Adeath (2021), estimated a reduction of 35,558 ha even without considering the water allocation reductions in the CR. The present study went one step beyond and estimated the firm yield (Liu et al. 2018; US Army Corps of Engineers 2019) that guaranteed a 100% water supply reliability in DR-014 under current groundwater overdraft conditions, DR-014 should reduce from 38,443 to 57,664 ha; representing 20%–30% of the cultivated area to cope with the lowest (51 Mm^3) and highest (339 Mm^3) water allocation reductions if the current crop production is maintained. This situation worsens when considering no groundwater overdraft, because DR-014 should reduce from 86,496 (45%) to 115,328 ha (60%) of cultivated area when producing the current types of crops. The reduction in the cultivated area of DR-014 will have significant social and environmental impacts that are out of the scope of the present study. However, the authors recommend future research to define policies that can improve prospects for environmental and social justice to the region.

Although urban demands are less likely to be affected by reductions in the CR water allocation reductions, this is only true if urban water demands remain a priority (CONAGUA 2012). If other water users decide not to obey the law, as it occurred in other Mexican states such as Chihuahua (López Obrador 2020), the increasing urban demands in SS2, particularly Tijuana-Rosarito metropolitan area, will be affected because the CR represents their main water source. Therefore, Tijuana and its metropolitan area are strongly linked to decisions and policy actions related to agricultural water management in Mexicali and San Luis Rio Colorado Valleys.

Groundwater Overdraft

Sustainable water management strategies should not allow for aquifer overexploitation. The Mexicali-SLRC groundwater system is in overdraft condition, and there is no question that at this rate of use groundwater will be exhausted, yet a question remains about the time horizon of such depletion. As presented in the results section for SS1, the system performance worsens when groundwater overdraft is not allowed; cultivated area reduction for DR-014 is the strategy that provides the most benefits in the long term. However, this strategy would have significant social and economic costs and it would be essential to involve farmers in a collaborative process.

The sustainability of water resources in SS1 also depends on the ability to monitor the aquifers, regulating groundwater extractions in each irrigation unit, law enforcement and the understanding of groundwater and surface water hydrologic connections. Ramírez-Hernández et al. (2013) conducted a hydrologic analysis of water releases from Morelos Dam (2009–2010), characterized the relationship between surface flows and its effect on the groundwater storage and infiltration rates. They determined a strong correlation between the volume of the water (up to 60.49 Mm^3 from November 2009–April 2010) released from Morelos Dam and the increase of groundwater levels. Thus, further reductions in the CR allocation to Mexico could negatively impact the groundwater elevation and storage.

As shown in Fig. 8, the performance of SS3 decreases when overdraft is not allowed. This trend was also observed by Medellin-Azuara et al. (2008). The authors ran nonoverdraft scenarios, finding that agriculture in Guadalupe and Maneadero were severely affected, and the increment of urban scarcity costs for Ensenada (Medellin-Azuara et al. 2008). In the present study, when no groundwater overdraft was allowed, the combination of water management strategies such as desalination, water reclamation and new infrastructure, improved the performance nearly to the baseline scenario of the overdraft condition. Users in the Guadalupe Valley have the higher potential to improve their water supply due to the use of reclaimed water (Mendoza-Espinosa et al. 2019). In addition, water exchanges between the Guadalupe Valley aquifer and the adjacent Mision aquifer need to be determined (Daesslé et al. 2020). Finally, the increase in reclaimed water use in Maneadero Valley (200 L/s) should be accompanied by a water right transfer to Ensenada to benefit the city's water supply.

Model Limitations

Like all quantitative models (Loucks and Van Beek 2017), the results of Baja California WAM have limitations. The main uncertainties are associated with finer spatial resolution groundwater representation, long-term data series, monitoring, lack of economic representation, and system simplifications (i.e., social, political, and economic dimensions not addressed here).

The present study considered a mass balance approach to determine aquifer storage, recharge, and extractions; it provides an overall water budget for each of the aquifers analyzed. Future analysis should include the hydrodynamics of the surface and groundwater (Bushira et al. 2017). The lack of comprehensive hydrological data is a common limitation identified by modelers in Mexico, especially when characterizing aquifers and groundwater data due to the lack of financial resources and monitoring culture in the country (Carrera-Hernández et al. 2016; Medellín-Azuara et al. 2009; Molinos-Senante et al. 2014; Wurl et al. 2018). The present study considered the recharge of the Mexicali-SLRC groundwater system from irrigation runoff. It is recommended to include all the Cuenca Baja del Rio Colorado Transboundary Aquifer System (the Mexican and US portions) to fully represent the dynamics of regional groundwater systems. If there is a need to determine groundwater dynamics at a smaller scale resolution, a fine-detail aquifer characterization is needed to determine groundwater extraction rates and potential aquifer recharge necessary for all the aquifers included in the model. Groundwater quality should be added into further model runs, particularly salinity considerations in Mexicali Valley, in coastal aquifers, and RW quality for reuse in crop irrigation or aquifer recharge.

Data for DR014 represents a source of uncertainty because this study used the data reported by the water authorities, specifically the water distribution reports for the irrigation modules (CONAGUA 2005). Carrillo-Guerrero et al. (2013) argued that CONAGUA accurately measures the water delivered to DR014 from federal wells, but private wells, which contribute 10%–20% of groundwater wells, are not as closely monitored. In addition, the application of water to individual fields is subject to uncertainty because water is measured at irrigation modules but not to individual fields. The present study used records of diverted water at individual modules.

Despite their limitations, models are useful tools for making informed decisions. Currently, there is no model for water resources planning for the state of Baja California. The current study provides insights on the impacts of the reductions in the Colorado River deliveries from the United States to Mexico and promising water supply portfolios for Baja California considering the major water users. The capital cost of alternatives was not considered because institutional agencies already consider most strategies in their planning and budgeting efforts. However, a basic economic analysis could be beneficial to represent the tradeoffs involved in each strategy. Economic-engineering optimization models have been applied in Baja California to explore water supply options for environmental restoration of the Colorado River Delta (Medellín-Azuara et al. 2007).

In addition, citizen participation can improve the quality of government decisions, incorporating different resources and capacities, and developing learning among stakeholders (Villada-Canela et al. 2019). Finally, making water planning tools available to stakeholders could embrace the region's decision-making process related to water management.

Conclusions

The Mexican region of the Colorado River including the northern region of Baja California and San Luis Rio Colorado in Sonora is highly dependent on the Colorado River water supplies. The water management of the Colorado River is at a tipping point.

The present study highlights the effect of current and future water management strategies in the Mexican portion of the Colorado River. A water resources planning model that represents the system and facilitates its updating and the incorporation/removal of water management scenarios was developed. The study explored a range of strategies, from a no-action scenario to a combination of all available water management strategies. The agriculture sector (DR014) has the biggest challenges ahead. In the most pessimistic scenario (maximum reduction and no additional actions), the sustainability index decreased from 68% in the baseline scenario to 43%, which represents a water deficit of 643 $\mathrm{Mm}^3/\mathrm{year}$ by 2050 (30% of the total demand). The current system has a better performance (SI: 68%) at the expense of long-term aquifers overdraft, without overdraft the SI decrease to 24%. Agricultural to urban transfers, water use efficiency, wastewater reuse, and desalination are prime possibilities to improve the future water supply, especially for the coastal zone.

For Tecate and Tijuana-Rosarito area, increasing the efficiency of the water distribution network, rehabilitating wells, and expanding the capacity of the CRTA increased the sustainability of the subsystem from 33% (baseline) to 95% in the maximum efficiency scenario. Ensenada and its agricultural valleys increased their sustainability from 49% (baseline) to 88% by increasing water use efficiency, expanding reuse in the agricultural valleys, receiving the full allocation of the Colorado River resources, and the full use of the desalination plant capacity. This analysis revealed the importance of mixed strategies across the interconnected subsystems.

Appendix. Individual Water Management Scenarios

Table 5 shows the performance criteria (volumetric and time-based reliability, resiliency, vulnerability, and maximum deficit) and sustainability index for each individual water management scenario per subsystem. Each performance criterion is expressed as a percentage from 0% to 100%, a nonfailure state is considered 100% for reliability (volumetric and time-based) and resiliency, whereas for vulnerability and the maximum deficit criteria a nonfailure state is 0% (Sandoval-Solis et al. 2011). The sustainability index by subsystem (SI^{SS}) was used to summarize the results of all users of a

Table 5. Performance criteria of water management scenarios

Subsystem	Scenario	Performance criteria (%)					Sustainability index (%)
		Reliability					
		V	T	Resilience	Vulnerability	Max. deficit	
	Overdraft						
SS1	Baseline	95	39	6	11	31	68
	Reduction in Colorado River deliveries	83	18	6	23	47	48
	Rise in crop evapotranspiration (ET_C)	92	27	6	13	33	55
	Environmental water (delta)	97	39	6	12	33	60
	Irrigated area reduction	100	94	94	1	1	94
	Reduction in alfalfa productionIncrease in application efficiency	96	44	6	10	30	65
	95	39	11	30	63		
	Increase in water distribution network efficiency	96	39	6	11	30	66
SS2	Baseline	87	27	4	10	29	33
	Increase in ARCT capacity	95	53	6	4	21	47
	Rehabilitation of Tijuana Aquifer wells	94	50	7	5	22	46
	Increase in water distribution network efficiency	93	47	12	6	22	75
SS3	Baseline	85	41	15	12	31	49
	Full allocation from the Colorado River	92	74	42	6	18	72
	Seawater desalination	92	73	41	6	12	72
	Increase in water distribution network efficiency	91	41	15	6	13	65
	Reuse expansion in Maneadero Valley	87	73	41	10	18	52
	Wastewater reuse in Guadalupe Valley	87	55	38	10	27	61
	Nonoverdraft						
SS1	Baseline	85	1	1	13	36	24
	Reduction in Colorado River deliveries	73	1	1	25	51	15
	Rise in crop evapotranspiration (ET_C)	82	1	1	16	38	17
	Environmental water (delta)	92	7	1	10	28	24
	Irrigated area reduction	91	31	1	9	33	62
	Reduction in alfalfa production	86	1	1	12	36	18
	Increase in application efficiency	83	1	1	14	39	17
	Increase in water distribution network efficiency	86	1	1	11	33	18
SS2	Baseline	87	27	4	10	29	33
	Increase in ARCT capacity	95	53	6	4	21	47
	Rehabilitation of Tijuana Aquifer wells	94	50	7	5	22	46
	Increase in water distribution network efficiency	93	47	12	6	22	75
SS3	Baseline	83	15	12	15	32	30
	Full allocation from the Colorado River	84	51	21	13	24	57
	Seawater desalination	84	48	18	17	27	54
	Increase in water distribution network efficiency	89	42	11	15	20	42
	Reuse expansion in Maneadero Valley	84	25	11	12	30	42
	Wastewater reuse in Guadalupe Valley	84	25	11	16	20	42

given subsystem into one single value; it is the weighted average of the *SI* values of individual users weighted by their water demand.

Data Availability Statement

The code that supports the findings of this study is available from the corresponding author upon reasonable request. Model inputs, units, expressions, and data source are available from Hernández-Cruz et al. (2023).

Acknowledgments

AHC is grateful to the Mexican National Council of Science and Technology (CONACYT) for a scholarship grant for her Ph.D. studies at Universidad Autónoma de Baja California (UABC-Mexico). This material is based upon work supported by Grant CN-20-278 from the University of California Institute for Mexico and the United States (UC MEXUS) and the Consejo Nacional de Ciencia y Tecnología de México (CONACYT).

Supplemental Materials

Fig. S1 is available online in the ASCE Library (www.ascelibrary.org).

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