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 since it has the lowest priority and, thus, any reduction in Colorado River allocations affect them directly. A range of water management strategies was investigated, including a no-action scenario. The current system depends on the long-term aquifers 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.

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 crops 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 over 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 3218 km boundary between the two countries comprises four states in the U.S (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 (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 its lowest historical level (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 US 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 (Mm^3/y) from the CR. The 1944 Treaty is a living document and agreement, *Minutes* are the instrument by which the US 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 feet (335 meters) 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 non-governmental organizations (NGOs), committed to fund and allocate water to the riparian and estuarine system within the Colorado River Limitrophe and Delta. The US 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 US 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, as well as more than 200,000 hectares 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; Shi et al. 2015). 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 since 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), as well as 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 Mexicali-SLRC groundwater system. Inefficiencies in irrigation infrastructure for agriculture constitute the primary source of aquifer recharge in the groundwater system (CEABC 2017; CONAGUA 2020b; Lesser et al. 2019). In addition, the recharge of the Mexicali Valley aquifer has been further reduced as result of the lining of the AAC (Leeser 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 mainly 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 All-American Canal (ACC) 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, while 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, since 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 (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, 2021), 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 2020a). In Maneadero Valley, the main crops are ornamental flowers, tomato, cucumber, asparagus, and brussels sprouts. The Maneadero Valley relies primarily on groundwater from 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: (a) data compilation, (b) model development, calibration, and validation, (c) evaluation of individual water management strategies, (d) evaluation of meta-scenarios, which are combination of individual strategies, and (e) 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 the diminished recharge of the Mexicali Valley aquifer due to the 2008 lining of the All-American Canal (AAC) (Lesser et al. 2019), which according to García, López, and Navarro (2009), contributed to 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 groundwater 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 aquifers recharge and storage. The present study does not consider modifying reservoir operation rules, it considers that water deliveries from the U.S. 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 into the model: Guadalupe Valley, Maneadero Valley, and 22 demands for each module of the DR-014 (19 modules in Mexicali Valley, and 3 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 (CONAGUA 2005). In Guadalupe Valley, the main crops are grapes and olives, which represents 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 US 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. 1a). 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(2020b) 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):

$$AS_t = Recharge_t - GW\ Extraction_t \quad (1)$$
$$Recharge_t = Recharge_t^{AgSW} + Recharge_t^{AgGW} + Recharge_t^{Conv\ Losses}$$

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

In addition, the Guadalupe and Maneadero aquifers are also overdrafted (CONAGUA 2020c; a). Groundwater extractions and the aquifers recharge were estimated considering the annual recharge reported by CONAGUA (CONAGUA 2020c; a) 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 to other studies (CEABC 2017; CONAGUA 2020b). 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: Subsystem I (SS1) comprising the DR-014, the Colorado Delta and the cities of Mexicali and San Luis Rio Colorado; Subsystem II (SS2) comprising the cities of Tecate and Tijuana-Rosarito; and Subsystem III (SS3) comprising by the city of Ensenada, and the agricultural regions of Guadalupe Valley and Maneadero Valley. Table 2 summarizes the water management strategies by sub-region 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).

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 criteria are expressed as a percentage between 0-100%; a non-failure state is considered 100% for reliability (volumetric and time-based) and resiliency, while for vulnerability and the maximum deficit criteria a non-failure 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 Jr 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 Mm^3/year, compared to 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 Mm^3/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 Mm^3/year (2008-2013), which is in between estimates from CEABC 2017 (132.27 Mm^3/year) (2006-2016) and CONAGUA 2020 (95.00 Mm^3/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

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Tables

Table 1. Urban demands of Baja California

	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 (2015)
[b]Based on CEABC (2017)

Table 2. Water management scenarios description

Subsystem	Scenario	Baseline Value[1]	Scenario Value	Source
	Reduction in Colorado River deliveries	Water allocation: 1850 Mm^3	-55 to -339 Mm^3	Minute 323 (IBWC 2017)
	Increase in crop evapotranspiration ET_C (m/year) due climate change	$Wheat_{ETc}$: 0.57	B1[1]:0.5898-0.5918 A2[2]:0.5872-0.5928	Based on García-Ávila (2012)
		$Alfalfa_{ETc}$: 1.93	B1: 2.0786-2.1034 A2: 2.0864-2.1067	
		$Cotton_{ETc}$: 1.14	B1:1.1675-1.1832 A2:1.1705-1.1840	
		$Others_{ETc}$: 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 (2009)
SS1	Application efficiency (E_a) increase	E_a: 65%	E_a: Increases from 2.5-10%	Percentages proposed by the authors in compliance with CEABC plan (2018) and the municipality of San Luis Río Colorado Sonora Basin Council (2020-2021) citizen consultation.
	Irrigated area reduction	Total irrigated area: 192,214 ha	Decreases from 2.5-10%	Percentages proposed by the authors in compliance with CEABC plan (2018)
	Reduction in alfalfa irrigated area	Alfalfa irrigated area:34,598 ha	Decreases from 2.5-10%	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 2.5-10% 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)
	Increase CRTA capacity	Capacity: 5333l/s	Increases from 2.5-10%	Percentages proposed by the authors
SS2	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 2.5-10%	Percentages proposed by the authors in compliance with the Baja California and the municipality of San Luis Río Colorado Sonora Basin Council (2020-2021) citizen consultation.
	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)
SS3	Use of recycled water in Guadalupe Valley	Use of 0 l/s from Tijuana WWTP	Use of 1000 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 2.5-10%	Percentages proposed by the authors in compliance with the Baja California and the municipality of San Luis Río Colorado Sonora Basin Council (2020-2021) citizen consultation.

[1]B1: Low emission scenario; [2]A2: High emission scenario

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

	Water User	Demand (Mm^3)	Sustainability Index (%)	
			Overdraft	Non-overdraft
SS1	DR-014	2362	66	18
	Mexicali	136	100	100
	SLRC	28	100	100
	Delta	27	100	100
	Subtotal	**2553**	**68**	**24**
SS2	Tecate	11	33	32
	Tijuana	150	32	32
	Subtotal	**161**	**33**	**33**
SS3	Ensenada	25	37	24
	Guadalupe V.	19	42	32
	Maneadero V.	20	43	33
	Subtotal	**64**	**49**	**30**

Table 4. Evaluation of water management scenarios by subsystem

Scenario		Sustainability Index (%) Overdraft	Sustainability Index (%) Non-overdraft
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

Table A1. Performance criteria of water management scenarios

	Scenario	Reliability V (%)	Reliability T (%)	Resilience (%)	Vulnerability (%)	Max. Deficit (%)	Sust. Index (%)
		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 production	96	44		10	30	**65**
	Increase in application efficiency	95	39	6	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**
		Non-overdraft					
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**

(Performance Criteria (%) spans Reliability, Resilience, Vulnerability and Max. Deficit.)

Figure Captions

Fig. 1. a) Location map of the Colorado River system in Mexico. b) Simplified Distribution of the Colorado River System deliveries in Mexico

Fig. 2. Mexican portion of the Colorado River Basin Study Design

Fig. 3. Subsystems overall sustainability index. 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, N-O: Non-overdraft)

Fig. 5. Volumetric Reliability associated with Colorado River water supply reductions to Mexico (O: Overdaft, N-O: Non-overdraft)

Fig. 6. Percentage of Irrigated area supplied with Colorado River water supply reductions to Mexico (O: Overdaft, N-O: Non-overdraft)

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

Figure_1

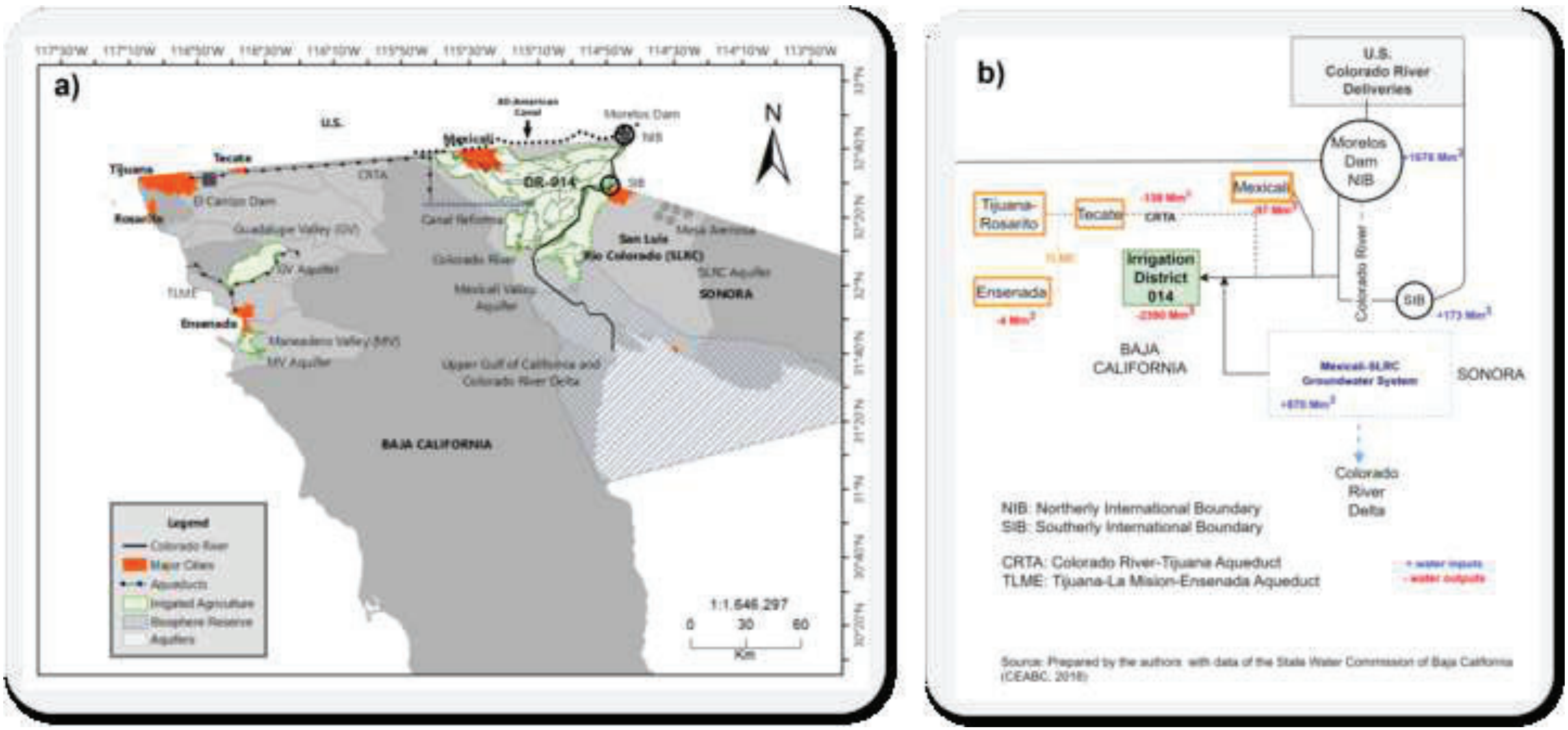

a)
U.S.
Tijuana
Tecate
Rosarito
Mexicali
DR-014
Morelos Dam
NIB
SIB
CRTA
TLME
Ensenada
San Luis
Rio Colorado (SLRC)
SONORA
BAJA CALIFORNIA
Legend
1:1,646,297
Km
0
30
60
N
b)
U.S.
Colorado River
Deliveries
Morelos
Dam
NIB
SIB
Colorado River
Tijuana-
Rosarito
Tecate
Mexicali
CRTA
Ensenada
Irrigation
District
014
BAJA
CALIFORNIA
SONORA
Colorado
River
Delta
NIB: Northerly International Boundary
SIB: Southerly International Boundary
CRTA: Colorado River-Tijuana Aqueduct
TLME: Tijuana-La Mision-Ensenada Aqueduct

Figure_2

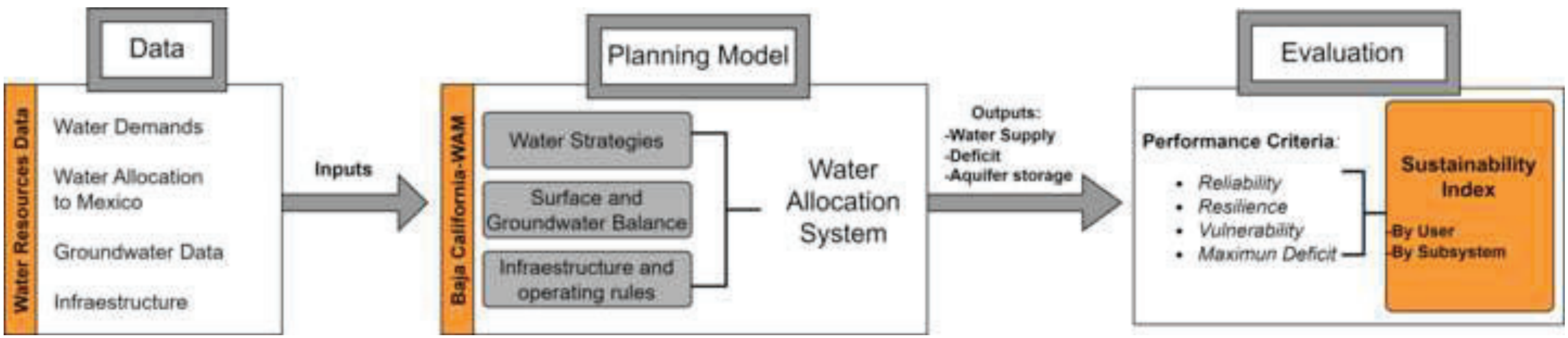
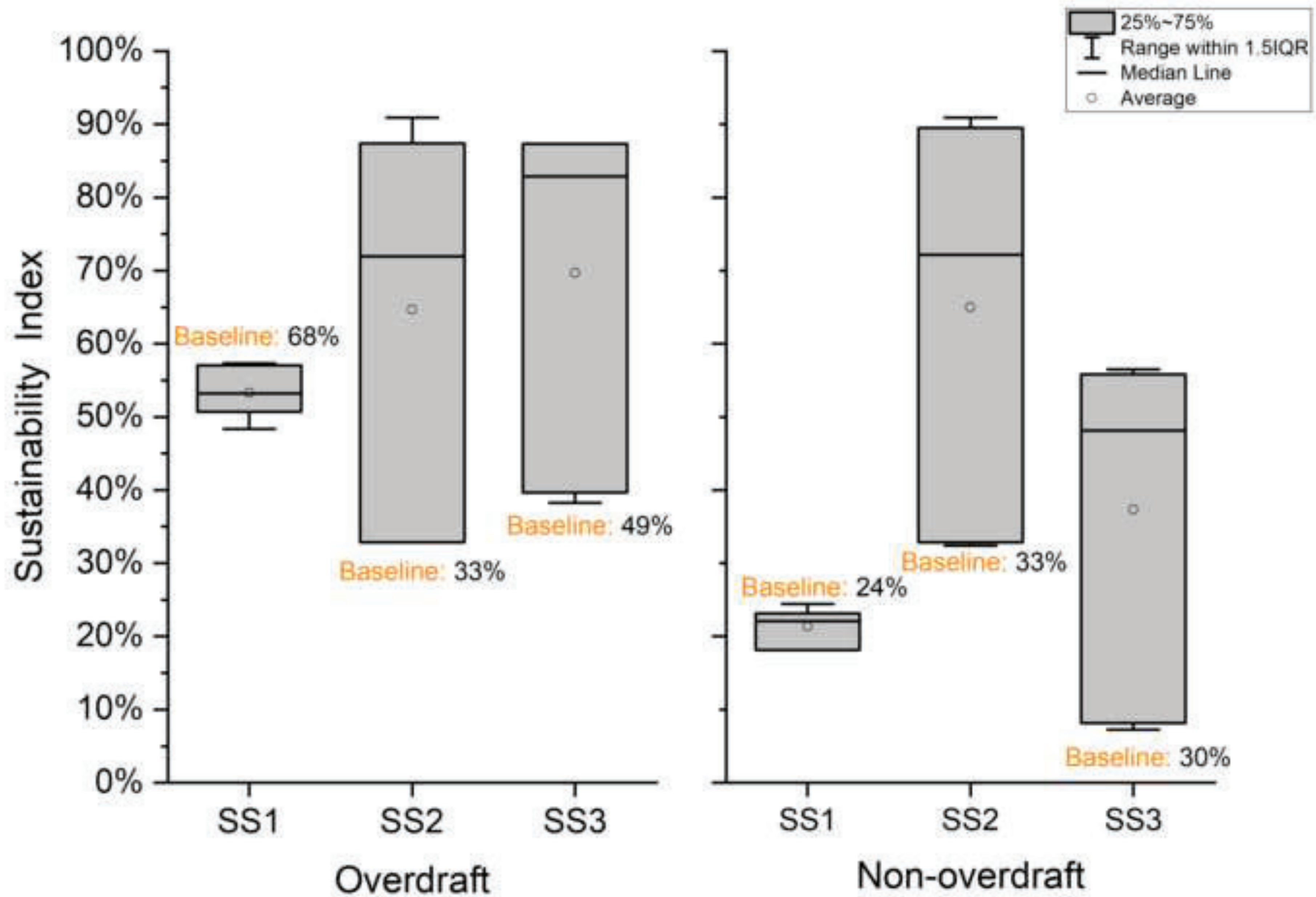

Data
Water Resources Data
Water Demands
Water Allocation to Mexico
Groundwater Data
Infraestructure
Inputs
Planning Model
Baja California-WAM
Water Strategies
Surface and Groundwater Balance
Infraestructure and operating rules
Water Allocation System
Outputs:
-Water Supply
-Deficit
-Aquifer storage
Evaluation
Performance Criteria:
Reliability
Resilience
Vulnerability
Maximun Deficit
Sustainability Index
-By User
-By Subsystem

Figure_3



25%~75%
Range within 1.5IQR
Median Line
Average
Sustainability Index
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Baseline: 68%
Baseline: 33%
Baseline: 49%
Baseline: 24%
Baseline: 33%
Baseline: 30%
SS1
SS2
SS3
Overdraft
SS1
SS2
SS3
Non-overdraft

Figure_4

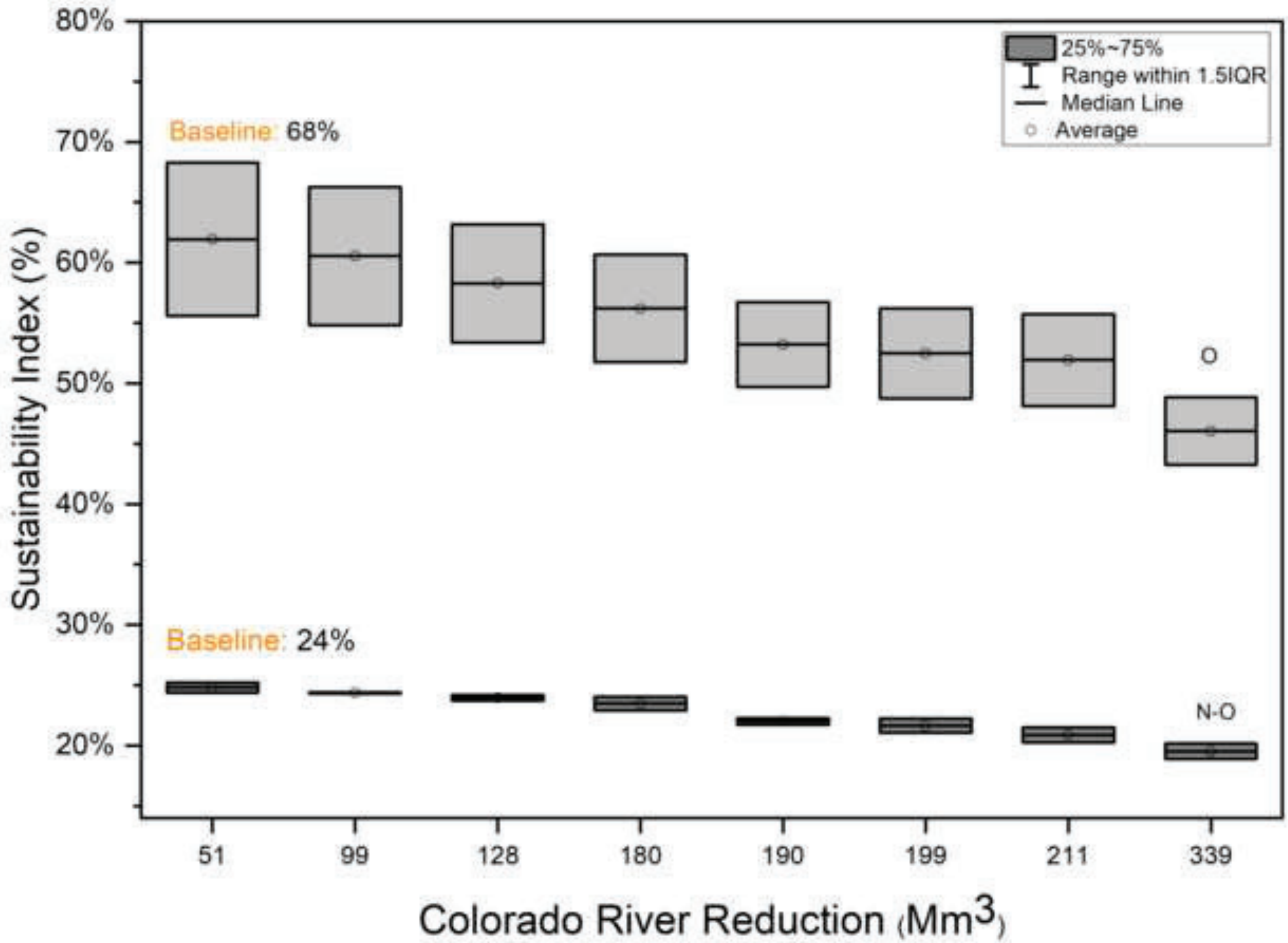

25%~75%
Range within 1.5IQR
Median Line
Average
Baseline: 68%
Baseline: 24%
O
N-O
80%
70%
60%
50%
40%
30%
20%
Sustainability Index (%)
51
99
128
180
190
199
211
339
Colorado River Reduction (Mm3)

Figure_5

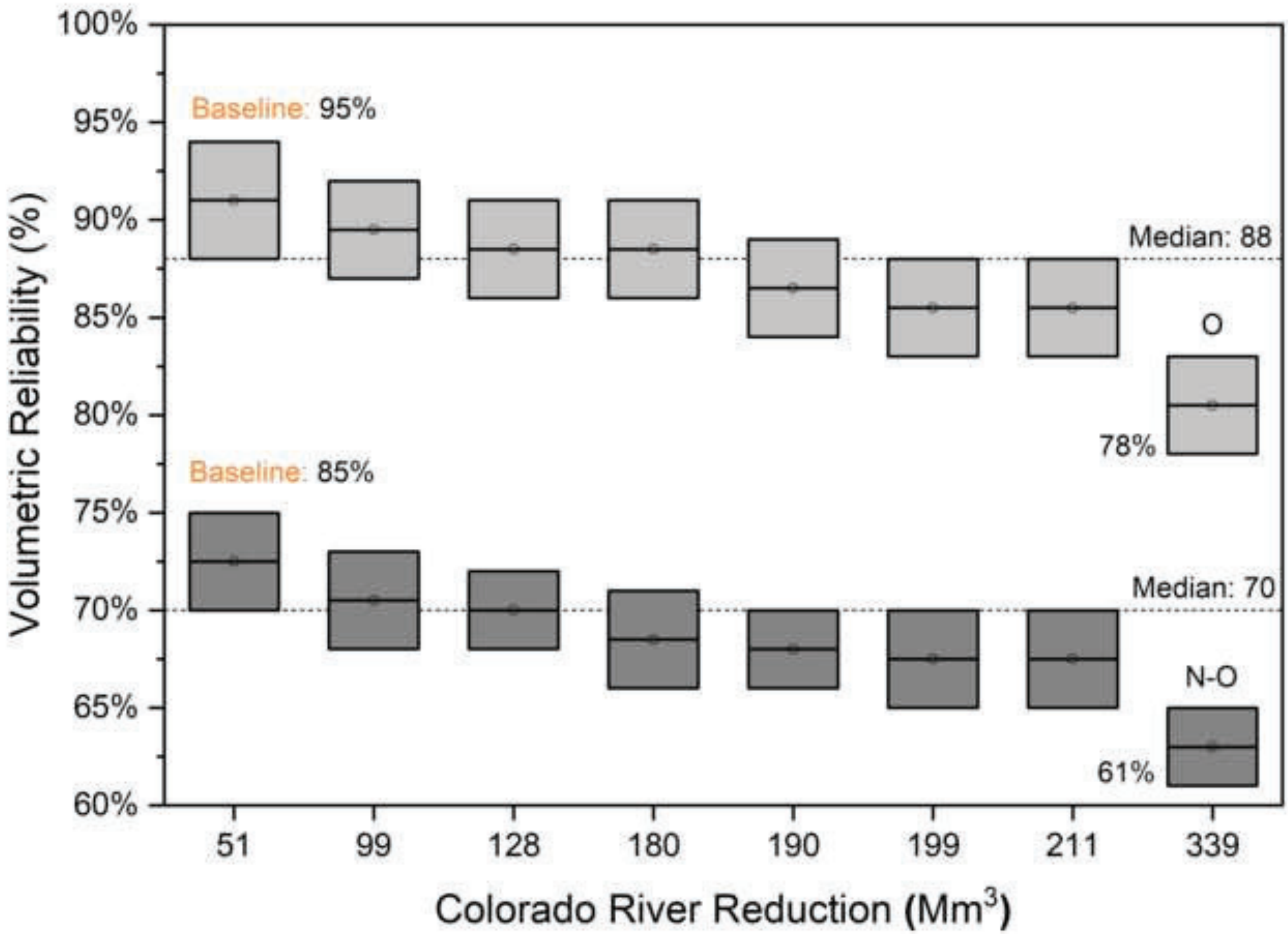
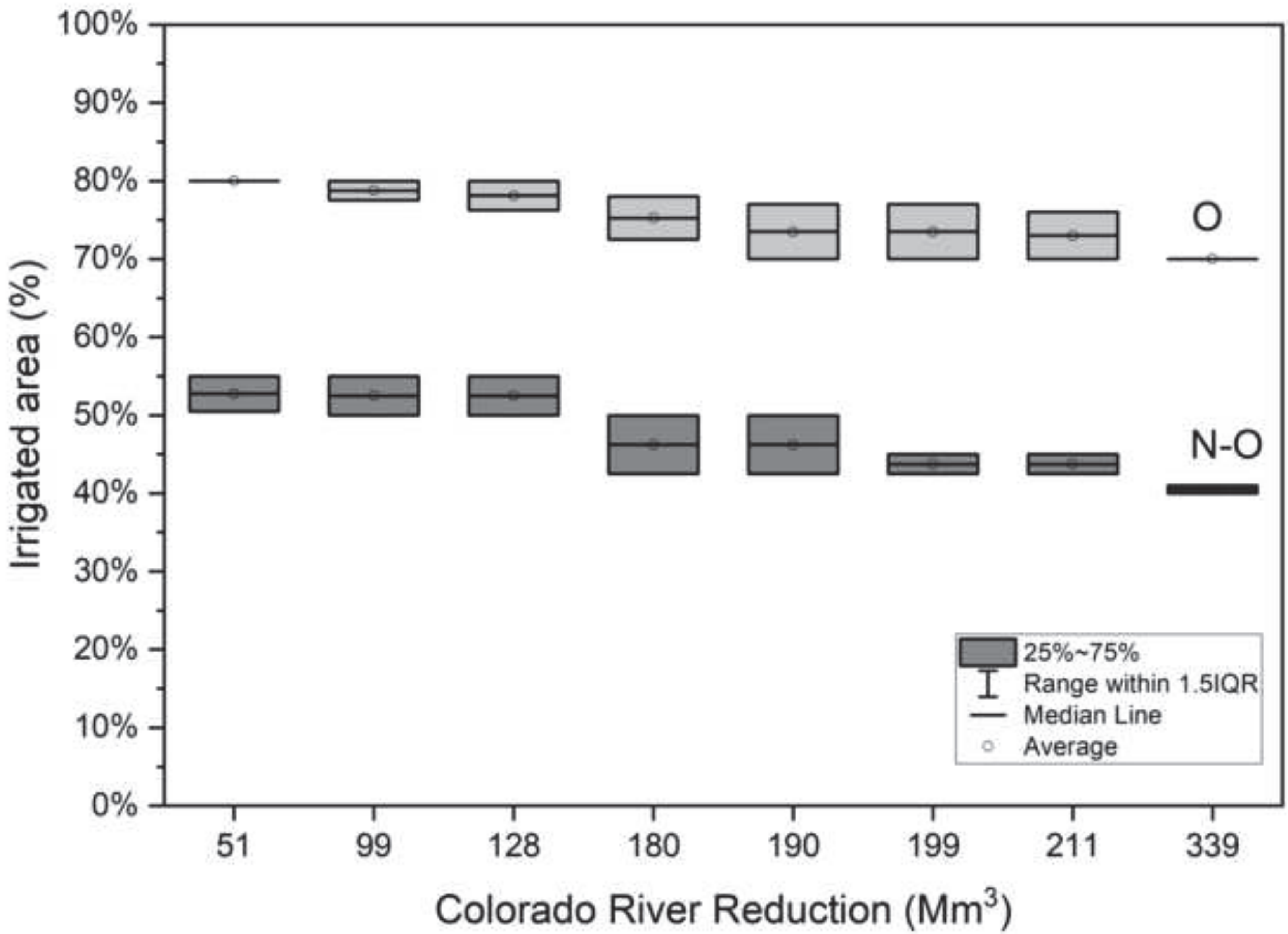
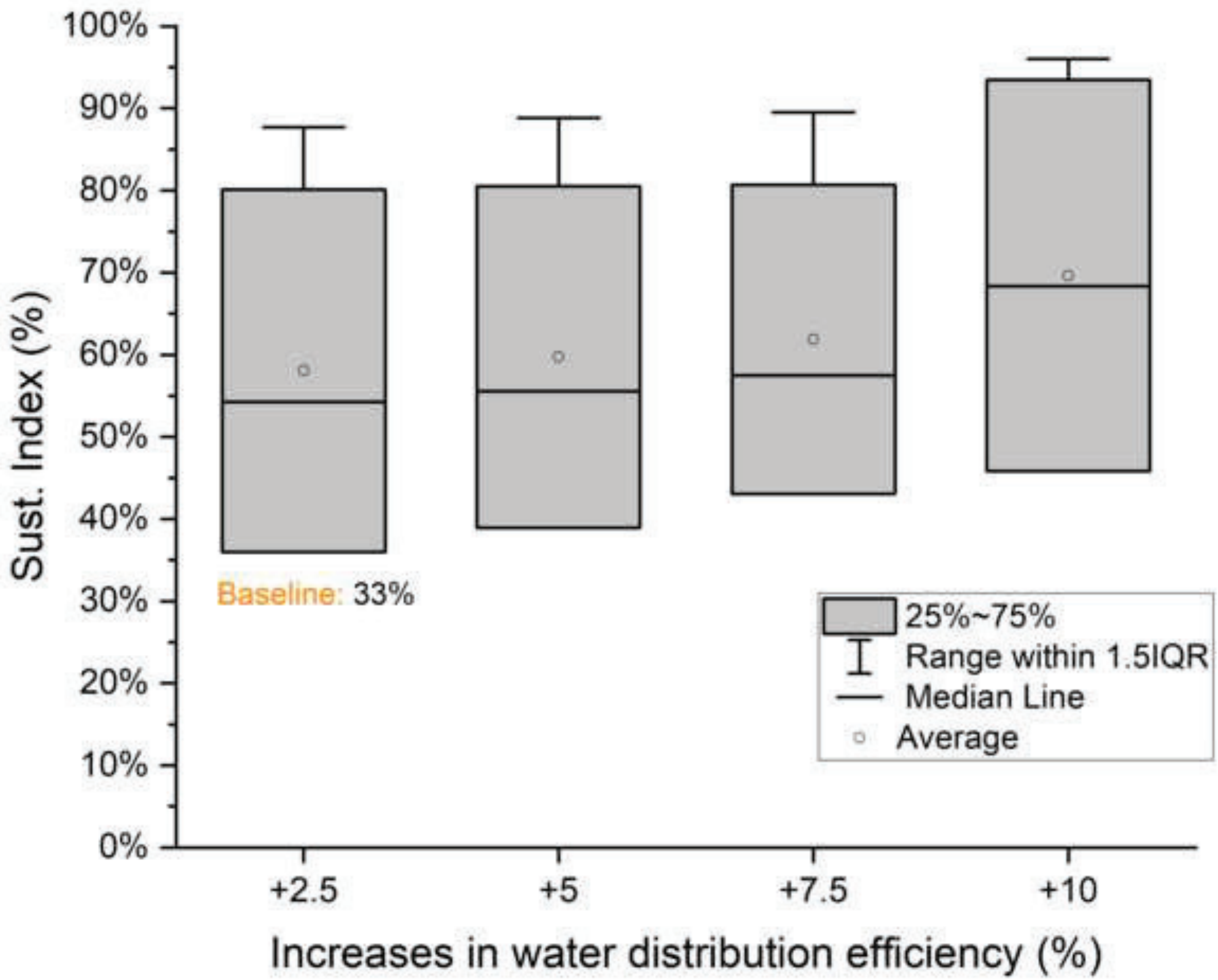

Baseline: 95%
Baseline: 85%
Median: 88
Median: 70
O
N-O
78%
61%
100%
95%
90%
85%
80%
75%
70%
65%
60%
Volumetric Reliability (%)
51
99
128
180
190
199
211
339
Colorado River Reduction (Mm3)

Figure_6



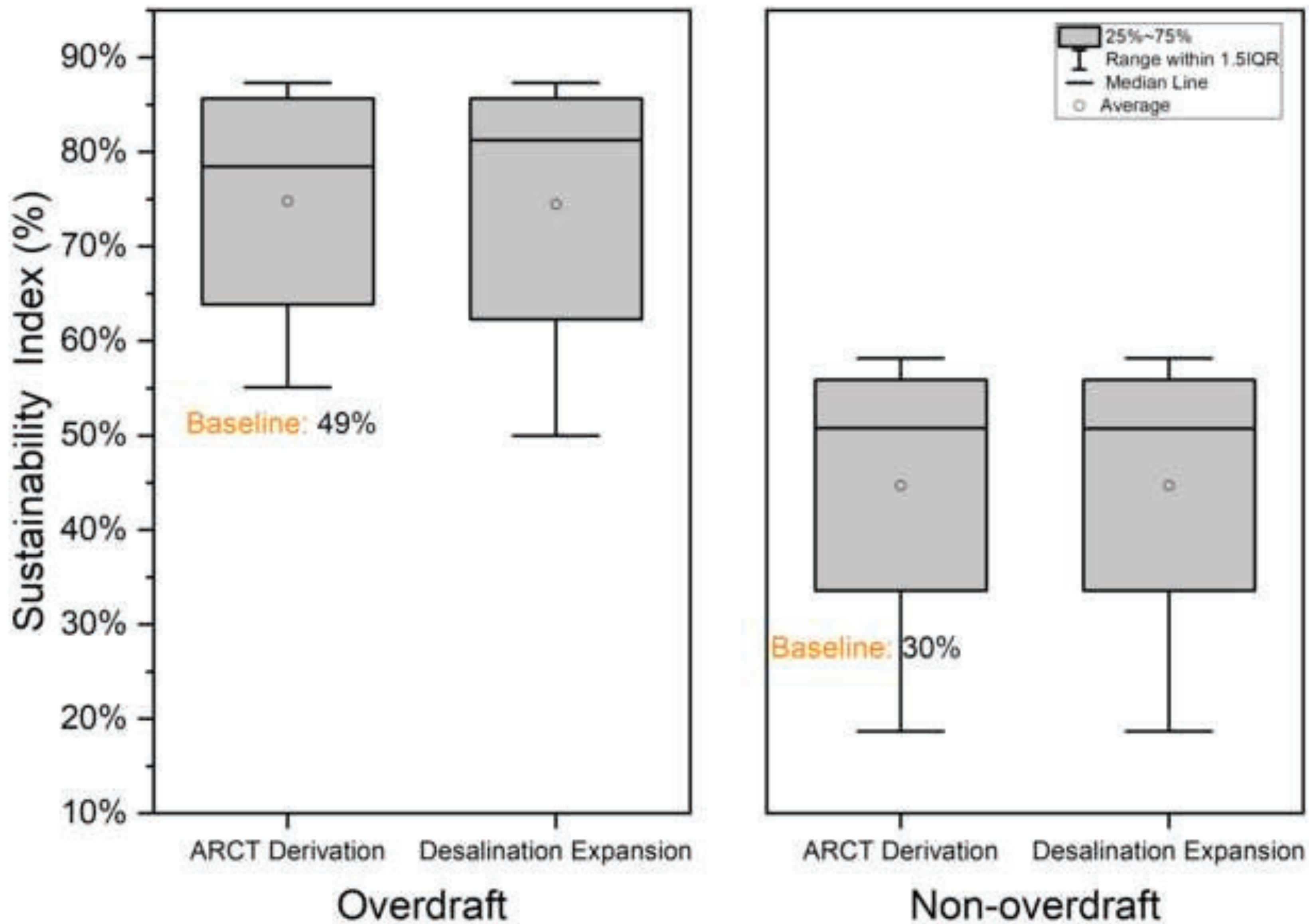
Irrigated area (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
O
N-O
25%~75%
Range within 1.5IQR
Median Line
Average
51
99
128
180
190
199
211
339
Colorado River Reduction (Mm3)

Figure_7



Sust. Index (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Baseline: 33%
25%~75%
Range within 1.5IQR
Median Line
Average
+2.5
+5
+7.5
+10
Increases in water distribution efficiency (%)

Figure_8


90%
80%
70%
60%
50%
40%
30%
20%
10%
Sustainability Index (%)
Baseline: 49%
Baseline: 30%
25%~75%
Range within 1.5IQR
Median Line
Average
ARCT Derivation
Desalination Expansion
ARCT Derivation
Desalination Expansion
Overdraft
Non-overdraft