Estimating the future hydric needs of Baja California, Mexico. Assessment of scenarios to stop being a region with water scarcity
A. Cortés-Ruiz and I. Azuz-Adeath

ABSTRACT

This paper shows the actual conditions of freshwater availability in Baja California (BC), Mexico. It aims to estimate the water needs by 2030, and propose scenarios to move out of the scarce water region classification defined by international organizations. A population of 4.1 million people was defined for year 2030 as a target to provide at least 1,000 m³ of water per capita. As agriculture is the main water consumer in the region, empirical decomposition and optimization methods were used to define the trend line of the principal crops production and to establish the optimum conditions for planted surface reduction and water gain. The results show that by 2030, BC will need a total of 4,105 hm³ of water to be classified as a non-water scarcity region; in 2018, BC had 3,045 hm³ of renewable water per year, therefore 1,060 m³ will be needed. The best option in economic terms to attain this goal was the reduction of croplands in Mexicali with a cost of around 82 million US dollars. Although this option is the best quantitatively, the political and social implications of it are enormous; however, the correct management of the resource in critical conditions will require difficult decisions.

Key words | agriculture water consumption, Baja California, forecast, México, water scarcity

HIGHLIGHTS

- In Baja California, 87% of the water supply is used in agricultural activities.
- In 2017, Baja California had a water availability of 849 cubic meters per capita per year, this classifies it as a region with water scarcity.
- By 2030, Baja California will need to obtain by actually unknown sources 1,060 cubic hectometres of water to be re-classified as a non-water scarcity region.
- In the short-term, the installed capacity of wastewater treatment and desalination plants in Baja California will not be enough to satisfy the future water demand.
- Technically speaking, the only feasible option to eliminate the water deficit is the reduction of 35,558 ha of croplands, but this action would have a huge political and social impact.

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The global population in 2019 was 7.7 billion people; in the next 30 years it is expected to increase by 2 billion, reaching 9.7 billion in 2050 (United Nations 2019). Water use has been incrementing by about 1% yearly since the 1980s, mainly due to population growth, socio-economic development and evolving consumption (UN-Water 2019). The increase of population and water consumption (overall and per capita) has led to the rise of water shortages. In the present, there are numerous countries that are entering a period of severe water scarcity. Water scarcity, either physical or economic, is a multi-faceted problem that not only involves water availability but also water quality and access to safe drinking water (du Plessis 2017). Also, there are several countries that have been experiencing high levels of ‘water stress’, defined as the proportion of water withdrawal in relation to the available water resources.

The world’s average water stress level is 13% and it affects at least 2 billion people around the world (FAO & UN-Water 2018); there has been a 55% drop in globally available freshwater per capita since 1960; by 2030, global demand of water is expected to grow by 50%; water scarcity currently affects more than 40% of the global population; and worldwide, the total cost of water insecurity to the global economy is estimated at 500 billion US dollars (UNU-INWEH 2017). In short, there is no denying the occurrence of a global water crisis and, if not taken in to account accordingly, it will hasten the arrival of the impending ‘day zero’ for many countries.

At a national level, Mexico doesn’t seem to be experiencing extreme levels of water scarcity and stress. In 2014, FAO & UN-Water (2018) determined, based on the country’s total renewable freshwater, total water withdrawal and the environmental flow requirements, that Mexico has 26% of water stress. Even so, there is an alarming water crisis in Mexico which is manifesting at state and local level. The national water balance does not represent the real panorama nor the water issues that some of the federal entities have been experiencing (Otazo-Sánchez et al. 2020). In 2017, 11 states in the country registered less than 1,700 cubic meters per capita (m³ capita⁻¹) and 9 out of those states registered less than 1,000 m³ capita⁻¹ (EAM 2018). In accordance to the indicators of the FAO (2014), this means that from the 32 states in Mexico, 9 are identified as suffering from water scarcity and 2 from water stress (Figure 1).

In Mexico, all the matters related to water resources regulation and management belong mostly to the federal administration and are directed by the National Water Commission (CONAGUA, by its Spanish acronym), through 13 Basin Organisms (Organismos de Cuenca in Spanish) whose scope is the management of 13 hydrological-administrative regions (RHA in Spanish) which include all 32 states of the country (AAM 2018).

Mexico has an average of 451,585 cubic hectometres per year (hm³ year⁻¹) of renewable water, 67% of this water is located in the South and Southeast regions of the country, while the remaining 33% is in the north and northeast.
sides (CONAGUA 2018). Surface and groundwater resources are the main sources of water supply in Mexico and they both play a major role in the country’s hydrologic cycle. The surface water resources are divided into 1,471 river systems, 731 basins are managed for hydrological balances and are grouped in 37 hydrological units, three are shared with the United States (Tijuana, Colorado and Bravo), four with Guatemala (Grijalva-Usumacinta, Suchiate, Coatan and Candelaria), and one with Belize and Guatemala (Río Hondo) (Guerrero 2019). Regarding groundwater resources, Mexico has 653 aquifers from which 115 are over-exploited, 32 have brackish water and 18 have saline intrusion (SINA 2018).

Baja California state (BC) is located in the Northwest part of Mexico (Figure 2). It limits the North with the state of California on the Mexico-United States border. It has a territorial extension of 70,113 km² and occupies the Northern part of the Baja California peninsula, a piece of land surrounded by the Pacific Ocean to the West and the Sea of Cortes to the East. Baja California has 1,380 km of coastline, of which 740 km corresponds to the Pacific coast and 640 km to the Cortes Sea. The climate in BC is mostly very dry (68%), dry and semi-dry (24%), and temperate sub-humid (7%). Considering the yearly information from 1980 to 2018 (SMN 2019), the average maximum atmospheric temperature was 26.8 ± 0.89 °C and the minimum 11.7 ± 1.48 °C, with an average yearly accumulated rain of 200 mm. In 2017, BC had a precipitation of 131.8 mm and a total renewable water of 3,045 hm³ year⁻¹ from which 2,093 hm³ were surface water and 952 hm³ were groundwater (EAM 2018). Permanent rivers are scarce and the two most important watersheds are binational basins shared with the United States (Colorado and Tijuana rivers). The major source of clean water in the state comes from the Colorado River, it has a total natural surface runoff of 1,922 hm³ year⁻¹ from which 1,850 hm³ are delivered to Mexico due to an international treaty signed in 1944 (AAM 2018). The remaining 72 hm³ are on Mexican territory. Water extraction from aquifers is also compromised, from 48 aquifers registered in BC, in 15 there is no water availability, 11 are overexploited, 7 have saline intrusion and in 3 the water is brackish (SINA 2018).
Concerning hydraulic infrastructure, Baja California had a 95.43% drinking water coverage and 96.01% sewer access, both in year 2015 (SINA 2015). It has 3 main water dams: Rodriguez, El Carrizo and Emilio Lopez Zapata, which in 2018 accounted for a total of 282.11 hm³ of water. Likewise, the state holds another source of freshwater besides rivers and aquifers, although on a smaller scale: treated water. In 2015, BC had 31 water treatment plants with an installed capacity of 12,146 litres per second (L s⁻¹) and a treated water flow of approximately 6,984.3 L s⁻¹ (CONAGUA 2015). For the same year, 114 wastewater treatment plants were registered, 71 are industrial with a combined capacity of 613 L s⁻¹ and a treated water flow of 615 L s⁻¹ (EAM 2018), and 43 are municipal with a total capacity of 7,775 L s⁻¹ and a treated water flow of 5,480 L s⁻¹ (CONAGUA 2015). The total installed capacity for wastewater treatment was 8,388 hm³ year⁻¹ and the wastewater treated amounted to 6,095 hm³ year⁻¹.

Figure 2 | Mexico in the world and Baja California state in grey colour.

Due to its geographical location and economic development, BC is one of the states with the highest population growth rate in the country. Administratively, BC comprises five counties: Ensenada, Mexicali, Playas de Rosarito, Tecate and Tijuana. The population is mostly settled in few cities located in the northern portion of the state, outside these urban centres the population is scattered throughout its vast territory. In 2015, 3.3 million inhabitants were registered and by the year 2030, 4.1 million are expected (INEGI 2019a). Baja California has historically contributed approximately 3% of the Mexican economy, and the internal Gross Domestic Product (GDP) in Baja California depends on primary activities (3%), secondary activities (40%) and tertiary activities (57%). Of these, the manufacturing industry (electronic, automotive, aerospace and medical equipment) is the one that generates the most employment and economic resources (15% of the internal GDP).

Baja California is among the top 10 most developed states in Mexico. As Table 1 shows, BC is above the national median in several positive defined socioeconomic indicators like GDP (D1) or social security affiliations as an indicator of formal employment (D2), and below the national median in those indicators that express bad conditions like poverty (D3, D4, D10, D11, D12), education (D5 and D6) or lack of primary services and facilities (D7, D8, D9). To maintain the historical regional economic development growth rate and maintain and increase the quality of life of its inhabitants, proper water management is essential for the state.
The main water users in BC are agriculture, public services (supply to residences and various industries), thermolectric plants (combined cycle, carbon, turbogas, internal combustion and others) and self-supplied industries (EAM 2018). Primary activities include agriculture, which despite its low contribution to the GDP is the main water user, accounting for 85% of BC water consumption; following, with 6% each, are public services and thermolectric plants, and self-supplied industries (secondary activities) account for the remaining 5% of the water consumption in the state (SINA 2018). In addition, water for agriculture purposes is highly subsidized in Mexico, which generates, in many cases, an inefficient use of the resource. As examples, mention may be made of the energy subsidy for pumping agricultural irrigation water (between 72% and 86% discount of the regular price) and the price paid by the farmers for the surpassed water from volumes granted to irrigation districts, which is 500 times less than the cost of the domestic urban waters (according with the Mexican Law of Rights of 2020, the cost of 100 cubic meters of irrigation waters is approximately 1 American dollar).

There has been a decrease of precipitation in the last years and an increase in temperatures, possibly associated with climate change. The condition of the aquifers is worsening both in quantity and quality along with the fact that the aquifers with water availability above 1 hm³ are located at great distances from the main cities (273 km on average). According to SIGAGIS (2019), the Colorado River is the main source of water in BC but subject to international treaties, and to top it all there are no long-term strategies to solve or counteract this issue.

All these together create an alarming problem in BC concerning water. According with the National Water Commission of Mexico (EAM 2018), the water availability per capita in BC in 2017 was 849 m³ year⁻¹, which allows it to be classified, using FAO (2014) indicators, as a ‘water scarcity’ region, and several areas inside BC as ‘extremely high water risk’ (WRI-AQUEDUCT 2019).

In order to reduce the levels of water scarcity by 2030 based on the indicators of FAO (2014), the renewable water available needed, supposing some level of water stress (1,000 hm³ capita⁻¹ year⁻¹), is 4,105 hm³ year⁻¹. Facing the best case scenario where there is no water stress (1,700 hm³ capita⁻¹ year⁻¹ and above) the renewable water needed is 6,979 hm³ year⁻¹. Knowing that the available renewable water in 2017 in BC was 3,045 hm³ with an agricultural consumption of 2,582 hm³ (SINA 2018), the dimension of the problem is clear, a water deficit of at

Table 1 | General social and economic conditions of Baja California state in the context of Mexico

<table>
<thead>
<tr>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
<th>D6</th>
<th>D7</th>
<th>D8</th>
<th>D9</th>
<th>D10</th>
<th>D11</th>
<th>D12</th>
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<tbody>
<tr>
<td>Baja California State</td>
<td>3.00</td>
<td>4.34</td>
<td>2.88</td>
<td>22.75</td>
<td>1.96</td>
<td>10.46</td>
<td>0.26</td>
<td>0.47</td>
<td>2.82</td>
<td>23.03</td>
<td>1.15</td>
</tr>
<tr>
<td>National median</td>
<td>2.17</td>
<td>2.14</td>
<td>3.56</td>
<td>39.00</td>
<td>4.30</td>
<td>15.17</td>
<td>1.75</td>
<td>0.77</td>
<td>3.25</td>
<td>27.34</td>
<td>2.53</td>
</tr>
<tr>
<td>Higher state value</td>
<td>16.78</td>
<td>17.35</td>
<td>7.00</td>
<td>76.75</td>
<td>14.98</td>
<td>31.71</td>
<td>13.03</td>
<td>2.87</td>
<td>15.64</td>
<td>44.46</td>
<td>14.86</td>
</tr>
<tr>
<td>Lower state value</td>
<td>0.53</td>
<td>0.50</td>
<td>1.62</td>
<td>14.35</td>
<td>1.49</td>
<td>6.62</td>
<td>0.04</td>
<td>0.04</td>
<td>0.81</td>
<td>19.19</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Variable/indicator description

D1 = Percentage of the National Gross Domestic Product (2017). Source: INEGI (2019b)


least 1,055 hm³ can be predicted or expected for the near future.

With limited natural sources of water (rain, rivers and aquifers), a high population growth rate and two agricultural irrigation districts (Mexicali Valley and Ensenada Region) which use 85% of the water, with entirely different efficiencies (e.g. Ensenada/Mexicali ratio is 5.6 times in terms of production value in Mexican pesos per hm³ of water), the only options to supply the future water demand in BC are: (a) reduction of water consumption in agriculture activities through the optimization of the irrigation district and reduction of cropland, this implies the reduction of food for human consumption and the income coming from this activity but an increase in water availability; (b) production of water from wastewater cleaning processes, this strategy is better implemented in addition to the strategy mentioned above since the amount of treated water generated is small in comparison, even if all the wastewater generated in the state is treated; (c) production of water through marine desalination processes, which involves an increase in water availability but also of electric power generation (sustainable practices can be implemented to reduce environmental impacts) and is also recommended to implement it in addition to the other solutions.

The main objective of this research is to estimate water needs for Baja California in the year 2030 in a scenario in which the region is not subjected to water scarcity conditions and assess the best options to satisfy those needs. In the next section will be discussed the methodology used to determine the best strategies to solve the problem addressed and the results obtained from each of them.

### METHODOLOGY

The assessment of the current water availability conditions (2017 and 2018) in Baja California state was done reviewing the official information and databases from the main federal and state water-related bodies of Mexico. The estimations of total population in 2030 were done using a sigmoidal Boltzmann nonlinear model (Azuz et al. 2019) and the official results from the Mexican Council of Population (CONAPO is the Spanish acronym), based on decadal information since 1930 and every five years for 1995, 2005 and 2015. The agricultural information was obtained from official records of the Mexican Ministry of Agriculture (SIACON 2019) on a yearly basis for 7 crops in the irrigation district of Mexicali for the period 1980–2018, these 7 crops (alfalfa, cotton, oats, onion, asparagus, sorghum and wheat) represent 89% of the planted surface, 82% of the production and 80% of the production value. Confidence intervals, a nonlinear regression model and empirical decomposition methods were used in the estimations of agricultural production, production value and planted surface in 2030 for every individual selected crop.

To evaluate the water supply options, the following cases were analyzed (Table 2) where: (a) reduction of agricultural lands in Mexicali: one or more crops and, (b) Increase in wastewater treatment: number of facilities or efficiency increase.

<table>
<thead>
<tr>
<th>Case</th>
<th>Solution type</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>‘a’</td>
<td>(a) Reduction of agricultural lands in Mexicali: one or more crops.</td>
</tr>
<tr>
<td>2</td>
<td>‘a’ and ‘b’</td>
<td>(a) Reduction of agricultural lands in Mexicali: one or more crops and, (b) Increase in wastewater treatment: number of facilities or efficiency increase.</td>
</tr>
<tr>
<td>3</td>
<td>‘a’ and ‘c-1’</td>
<td>(a) Reduction of agricultural lands in Mexicali: one or more crops and, (b) Installation of desalination plants: production of water from salinized aquifers.</td>
</tr>
<tr>
<td>4</td>
<td>‘a’ and ‘c-2’</td>
<td>(a) Reduction of agricultural lands in Mexicali: one or more crops and, (b) Installation of desalination plants: production of water from coastal waters.</td>
</tr>
<tr>
<td>5</td>
<td>‘a’, ‘b’ and ‘c-1’</td>
<td>(a) Reduction of agricultural lands in Mexicali: one or more crops, (b) Increase in wastewater treatment: number of facilities or efficiency increase and, (c) Installation of desalination plants: production of water from salinized aquifers.</td>
</tr>
<tr>
<td>6</td>
<td>‘a’, ‘b’ and ‘c-2’</td>
<td>(a) Reduction of agricultural lands in Mexicali: one or more crops, (b) Increase in wastewater treatment: number of facilities or efficiency increase and, (c) Installation of desalination plants: production of water from coastal waters.</td>
</tr>
</tbody>
</table>
planted surface for individual crops and combinations of crops; (b) increase of wastewater treatment using the same number of plants more efficiently or by the installation of new plants; (c) installation of desalination facilities that produce clean water from salinized aquifers or directly from the coast waters. Linear and nonlinear optimization processes were used to obtain the best options in terms of these variables alone or combined among cases and between cases. Economic valuation of each case was used as a selection criterion for the possible scenarios.

Improvements in irrigation technology in Mexicali Valley cannot be evaluated and incorporated into the scenarios due to the lack of local information (e.g. number of farmers by crop, losses by irrigation channel), as well the level of implementation of local government efficiency plans (CEABC 2013, 2016).

RESULTS

Possible scenarios and solutions for the year 2030

Reduction of water consumption in agricultural activities

By 2030, the state needs a total of 4,105 hm$^3$ of renewable water to be classified as a non-water scarcity region (1,000 m$^3$ per capita or more). According to EAM (2018), BC has 3,045 hm$^3$ of renewable water per year, therefore 1,060 m$^3$ are still needed to achieve the goal.

Before reducing the planted surface, the irrigation district of Mexicali needs to optimize its water use; as mentioned before, the Ensenada/Mexicali ratio is 5.6 times in terms of production value in Mexican pesos per hm$^3$ of water. To simulate the results of this optimization, the main products grown in the region were defined, and consequently, the water needed to harvest these products was determined (Table 3). Knowing the total number of planted hectares and the water needed for each product, the optimal water use for agricultural land in Mexicali in 2017 was determined to be 1,371.55 hm$^3$ for the 7 products, and overall the water use in the state’s capital should be approximately 1,655 hm$^3$ according to the State Water Plan of Baja California (PHEBC, by its Spanish acronym), which indicates that the capital is to be given said amount of water for agricultural purposes from the Colorado River basin; however, the real water volume delivered in 2017 was 2,147 hm$^3$. By optimizing the irrigation district the water gain is around 512 hm$^3$, thus decreasing the water needed to reach the goal to 548 hm$^3$.

To define the optimal results for cropland reduction, the issue was approached taking into account four variables: (1) number of hectares reduced from total cropland; (3) total hectares of cropland after surface reduction; (3) crop production value losses in Mexican pesos; (4) total water gain. The first step was to reduce cropland in values of 5% to the main products of the region starting from greatest to lowest number of hectares planted. Once the surface of all 7 products was reduced separately, the results were subjected to a comparative analysis to define the best option, offering the highest water gain, lowest production value losses and/or minimal reduction of cropland.

After calculating the efficiency of the production value in 2017 (57.92 thousand Mexican pesos per cultivated hectare), the analysis demonstrated that the most convenient strategy was the reduction of alfalfa, followed by cotton and then wheat (which could be an option but the monetary loss is more prominent), the rest of the products show small values of gained water, thus their surface reduction is negligible. To accurately meet the water necessities of 548 hm$^3$ by only using the approach of planted surface reduction, the entire surface of alfalfa would need to be removed, as well as 27% of the cotton surface. This reduction accounts for 35,558 ha of reduced surface (80% alfalfa, 20% cotton); that is, 23% of the initial hectares, a total of 118,702 ha of planted surface after the reduction, a monetary loss of 2,059,506 thousand of Mexican pesos (MXN) and a water gain of 548 hm$^3$. Alfalfa production in the region is intended for the feeding of livestock from private producers, and cotton is destined for industrial use for the production of clothing by transnational companies; in this sense, the reduction of its cultivated area does not affect the production of food for human consumption. Making a decision of this type raises the need to privilege the common good (water availability) over the private one, with the associated political and social consequences.
Production of water from wastewater cleaning processes

In 2017, the total wastewater generation in BC was approximately 193 hm$^3$; however, for this study, only the wastewater generation and plants from Tijuana and Mexicali are taken into account. According to the Hydric Program of the state of Baja California (2016) or PHEBC, by its Spanish acronym, Mexicali had a population of 998,447 inhabitants, a wastewater generation of 75.30 hm$^3$ and a volume of 75.42 m$^3$ per capita (CEABC 2019). For Tijuana, the population was 1,657,289 inhabitants, 87.46 hm$^3$ of wastewater was generated and a total water volume of 52.77 m$^3$ per capita (CEABC 2019). Considering the approximate values of wastewater per capita in both municipalities and their projected population for 2030, an estimation of the wastewater generation for the same year can be made. For Mexicali, the projected population for 2030 is 1,234,931 inhabitants, therefore the wastewater generation is estimated to be 93 hm$^3$; continuing with Tijuana, the population will be approximately 2,023,931 with a volume of wastewater of 107 hm$^3$. This amounts to an estimation of 200 hm$^3$ of wastewater generated. Assuming that the entire volume of wastewater generated in both Mexicali and Tijuana in 2030 will be treated, the total expenses sum up to 907,729 thousand MXN, considering a treatment cost of 4.54 pesos/m$^3$.

While the amount of water coming from wastewater treatment plants is significant, it is not enough to fulfill the goal of 548 hm$^3$ by 2030 on its own, thus the best way to implement this solution is by doing it in alignment with cropland reduction. The alternative is to avoid the reduction of the entire cultivated surface of alfalfa and any reduction of cotton surface by providing Mexicali with the 200 hm$^3$ of reusable water (while Mexicali yields 200 hm$^3$ of clean water coming from the Colorado River to the rest of the municipalities). Based on this, the water needed from cropland reduction is 348 hm$^3$, which represents the water needed for 76% of alfalfa surface; that is, 21,746 ha removed
(14% of overall croplands), a total surface of 132,514 ha after reduction and a loss of 1,259,499 thousand MXN. Knowing the cost of both the reduction of 14% of cropland and the treatment of 200 hm³, the overall expenses of implementing solution b) along with solution a) are 2,167,229 Mexican pesos (107,723 thousand MXN more expensive than implementing solution ‘a’ alone).

Production of water through desalination processes

Baja California has 1,380 km of coastline, of which 740 km correspond to the Pacific coast and 640 km to the Gulf of California (INAFED 2019). This opens a new window of opportunity for obtaining clean water through marine desalination methods. According to the Federal Water Commission of Baja California (2013 and 2016), or CEABC by its Spanish acronym, the state has two desalination plants in operation, both in the municipality of Ensenada. The first one, located in the main city, has an installed capacity of 7.88 hm³ per year, while the remaining one is located in Isla de Cedros with a capacity of 0.15 hm³ per year. Likewise, the CEABC proposed the construction of three more desalination plants, which by 2018 were either in the planning phase or starting construction.

In Table 4, the desalination projects in the state are shown; three of the plants will be located in Ensenada while the other two are in Playas de Rosarito, all five of these plants will operate or are operating with reverse osmosis, the installed capacity will be 93.18 hm³ and all of the water is meant for public supply. Now, if this volume of water is directed to the irrigation district of Mexicali under the same conditions as in the case of wastewater reuse, this means that 93 hm³ of freshwater coming from the Colorado River basin can be used for different purposes and be distributed between Mexicali and the other municipalities.

For 2030, the public sector will require approximately 256 hm³ of water, meaning that the water amount coming from desalination processes is not enough to satisfy the public demand in its entirety; nevertheless, it covers 36% of the demand, which gives the possibility of using the volume of freshwater coming from basins and aquifers that was replaced by this treated water to be used for human necessities, while at the same time it contributes to the 2030 goal (4,105 hm³) by 2.27%. The investment resulting from treating 93 hm³ is defined by the method of extraction of water, that is through (1) marine wells or (2) direct take. For the first case, the cost of extraction per cubic meter according to CEA Sonora (2016) is 8.20 MXN, while for the second method, the cost is 11.09 pesos per m³. This means that for marine wells the total investment is 764,053 thousand MXN, and for direct take is 1,033,335 thousand MXN.

Now, using the water treated from desalination processes for agriculture in Mexicali, means that the reduction of planted land would have to provide a volume of water of 455 hm³, which represents 28,433 ha of alfalfa planted (99.6% alfalfa), 125,827 ha of planted surface after reduction, a loss of 1646,839 thousand MXN and a water gain of 455 hm³. Knowing the total loss coming from surface reduction and the cost of water desalination in both cases, the total investment will be (1) 2,410,893 thousand MXN if marine wells are used; and (2) 2,680,175 thousand MXN in the case of direct take.

**Implementation of three possible solutions altogether**

Considering the case in which the three solutions are implemented altogether, where all desalinated water in the

<table>
<thead>
<tr>
<th>Municipality</th>
<th>Plant</th>
<th>Capacity (hm³/y)</th>
<th>Minimum annual treatment cost (Thousand MXN/m³)</th>
<th>Maximum annual treatment cost (Thousand MXN/m³)</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ensenada</td>
<td>Ensenada</td>
<td>7.88</td>
<td>64,648.80</td>
<td>87,433.56</td>
<td>In operation</td>
</tr>
<tr>
<td>Ensenada</td>
<td>Isla de Cedros</td>
<td>0.15</td>
<td>1,197.30</td>
<td>1,619.27</td>
<td>In operation</td>
</tr>
<tr>
<td>Ensenada</td>
<td>Valle de San Quintán</td>
<td>7.88</td>
<td>64,648.80</td>
<td>87,433.56</td>
<td>Planning</td>
</tr>
<tr>
<td>Playas de Rosarito</td>
<td>Playas de Rosarito</td>
<td>69.38</td>
<td>568,909.44</td>
<td>769,415.33</td>
<td>In construction</td>
</tr>
<tr>
<td>Playas de Rosarito</td>
<td>La Misión</td>
<td>7.88</td>
<td>64,648.80</td>
<td>87,433.56</td>
<td>Planning</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>93.18</strong></td>
<td><strong>764,053.14</strong></td>
<td><strong>1,033,335.28</strong></td>
<td></td>
</tr>
</tbody>
</table>
state and all wastewater treated in Tijuana and Mexicali are destined for agricultural use in Mexicali, the reduction of planted surface could be minimized once more. With a total volume of water of 293 hm³ coming from treatment processes, the amount of water needed to reach the 2030 goal would be 255 hm³. In terms of cropland reduction, this means the reduction of 56% of alfalfa; that is, a reduction of 15,953 ha, a total planted surface of 138,327 ha after reduction, a loss of 922,839 thousand MXN and a final water gain of 255 hm³. Now, knowing the cost of planted surface reduction, wastewater treatment and desalination treatment processes, the overall investment would be either 2,594,622 thousand MXN (marine wells) or 283,904 thousand MXN (salinized coastal aquifers).

**CONCLUSION**

The information of all cases addressed in this study is presented in Table 5, prepared by the authors based on information provided by the Agri-food Consultation Information System (2019) and the Federal Water Commission (2016), respectively, SIACON and CEA, by their Spanish acronyms. Solution (a) represents reduction of planted surface; solution (b) wastewater treatment; and solution (c) marine desalination processes, being c-1 marine wells and c-2 direct take from already salinized coastal aquifers.

This synthesis of information facilitates the evaluation of all cases at once and shows that financially the best option is Case 1, which is the less expensive solution by at least 107,723 thousand MXN, followed by Case 2, then Case 3 and 5, and finally Cases 4 and 6. This indicates that the use of desalination processes increases the amount of investment significantly (Cases 3–6), therefore can be concluded that this is the most expensive solution in comparison to wastewater treatment and planted surface reduction, especially with a method of water extraction of direct take (Cases 4 and 6).

Besides the economic valuation of the scenarios, it is important to note that some options considered in this study (the proposed agricultural land decrease in Mexicali), could affect the socio-economic conditions of the region, through food production reduction or unemployment increase. However, as mentioned before, the most suitable crops to be reduced (alfalfa and cotton) are not for human consumption, the first crop is for cattle feeding and the second is for industrial use (clothes). The valuation of unemployment is more difficult to assess due to the lack of specific information about agriculture-related workers; however, using a gross approximation, considering the total planted surface and the total users of water, a mean value

**Table 5** | Summary of possible solutions for water scarcity in Baja California for the year 2030

<table>
<thead>
<tr>
<th>Case</th>
<th>Implemented solution(s)</th>
<th>Volume of water provided (hm³/y)</th>
<th>2030 goal coverage (%)</th>
<th>Investment by solution (thousand MXN)</th>
<th>Total investment (thousand MXN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solution a)</td>
<td>548</td>
<td>100</td>
<td>2,059,506</td>
<td>2,059,506</td>
</tr>
<tr>
<td>2</td>
<td>Solution a)</td>
<td>348</td>
<td>64</td>
<td>1,259,499</td>
<td>2,167,229</td>
</tr>
<tr>
<td></td>
<td>Solution b)</td>
<td>200</td>
<td>36</td>
<td>907,729</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Solution a)</td>
<td>455</td>
<td>83</td>
<td>1,646,839</td>
<td>2,410,893</td>
</tr>
<tr>
<td></td>
<td>Solution c-1</td>
<td>93</td>
<td>17</td>
<td>764,053</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Solution a)</td>
<td>455</td>
<td>83</td>
<td>1,646,839</td>
<td>2,680,175</td>
</tr>
<tr>
<td></td>
<td>Solution c-2</td>
<td>93</td>
<td>17</td>
<td>1,033,335</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Solution a)</td>
<td>255</td>
<td>47</td>
<td>922,839</td>
<td>2,594,622</td>
</tr>
<tr>
<td></td>
<td>Solution b)</td>
<td>200</td>
<td>36</td>
<td>907,729</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solution c-1</td>
<td>93</td>
<td>17</td>
<td>764,053</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Solution a)</td>
<td>255</td>
<td>47</td>
<td>922,839</td>
<td>2,863,904</td>
</tr>
<tr>
<td></td>
<td>Solution b)</td>
<td>200</td>
<td>36</td>
<td>907,729</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solution c-2</td>
<td>93</td>
<td>17</td>
<td>1,033,335</td>
<td></td>
</tr>
</tbody>
</table>
of 9.2 ha per user of water was estimated, which gives a potential unemployment number associated with the crop land reduction of 55,558 ha in Mexicali of 3,865 persons. This number represents only 0.9% of the total workers in Mexicali, and only for comparative purposes, a single maquiladora industry in Baja California that cannot operate due to lack of water could abruptly fire this number of employees. Considering the specific planted surface reduction proposed in the presented scenarios, the number of unemployed workers goes from 1,280 to 2,860, which could be easily incorporated in other economic activities in the region or subsidise by the local or federal government through – for example – by ‘payment for environmental services related with water conservation’ which is an already working governmental program in other Mexican zones.

Decision-making in the context of water scarcity zones is complex, but the authors consider that in order to achieve sustainable development in Baja California, in certain circumstances, the common good must be privileged over the private one, especially with a central resource like water.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES


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