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Articles

An analysis of water scarcity in a drought prone city: The case of Ensenada, Baja California, Mexico

Un análisis de la escasez de agua en una ciudad sujeta a sequías: el caso de la ciudad de Ensenada, Baja California, México

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Abstract

The city of Ensenada depends on groundwater, particularly from the Maneadero and Guadalupe aquifer for water supply for agricultural irrigation, urban use, and to support a range of ecosystem functions. Due to intensive extraction, the aquifers' water levels are decreasing and there is water scarcity in the area. Among the solutions implemented by the state of Baja California government is the construction of a desalination plant in Ensenada to meet urban demand, the construction of a new aqueduct to transport water from the Colorado River-Tijuana and the implementation of water reuse for irrigation and aquifer's infiltration. This paper aims to analyze the potential alternatives to mitigate water scarcity in Ensenada region, Baja California, by comparing the costs of water management alternatives and discussing possible solutions. It was found that the use of treated wastewater for irrigation and aquifer's injection could restore aquifers overused at the long term and is more cost-effective from an environmental and economic point of view. Transporting water from Colorado River-Tijuana-aqueduct Ensenada and the construction of a seawater desalination plant are important steps towards provisioning water to Ensenada yet are less desirable due to their environmental impact and the dependency on an already highly impacted watershed.

Keywords: Water management, Ensenada, Baja California, water scarcity.

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Resumen

La ciudad de Ensenada depende de agua subterránea, en particular de los acuíferos de Maneadero y Guadalupe como fuente de agua para irrigación agrícola, uso urbano y como soporte para un rango de funciones ecosistémicas. Debido a su alta tasa de extracción, los niveles de los acuíferos han disminuido y existe escasez de agua en la región. Entre las soluciones implementadas por el gobierno del estado de Baja California está la construcción de una planta desaladora en Ensenada, para suplir agua para uso urbano; la construcción de un nuevo acueducto para traer agua del sistema río Colorado-Tijuana, y la implementación de reúso de agua para irrigación e infiltración de acuíferos. El objetivo de este estudio es analizar tales alternativas para mitigar la escasez de agua en la región de Ensenada, al comparar sus costos y discutir posibles soluciones. Se encontró que el reúso de agua residual tratada para irrigación e infiltración de acuíferos podría restaurar los efectos de la sobreexplotación de los acuíferos a largo plazo y es la más costo-efectiva desde los puntos de vista económico y ambiental. La construcción de una planta desaladora y transportar agua desde el acueducto Río Colorado-Tijuana son importantes pasos para proveer agua a Ensenada, pero son menos adecuados por el impacto ambiental que pudiera causar y su dependencia a una cuenca altamente impactada.

Palabras clave: manejo del agua, Ensenada, Baja California, escasez del agua.

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Introduction

Water scarcity is growing worldwide, affecting more than 40% of people globally (WHO & UNICEF, 2015). Salinization and pollution of watercourses and bodies, and degradation of water-related ecosystems are rising (FAO & Earthscan, 2011). Water scarcity hinders the sustainability of natural resources as well as economic and social development (United Nations, 2015). More than 700 million people worldwide still lack access to reliable and safe drinking water sources. Moreover, climate change over the 21st century is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions, intensifying competition for water among sectors leading to drought, water scarcity, sea-level rise and storm surges (Treidel, Martin-Bordes, & Gurdak, 2012). Sustainable groundwater management in the future requires groundwater to be used in a manner that can be maintained for an indefinite time without having unacceptable environmental, economic or social consequences (Kløve *et al*., 2014).

According to FAO and Earthscan (2011), water scarcity has three dimensions: physical (when the available supply does not satisfy the demand), infrastructural (when the infrastructure in place does not meet water demand for all users) and institutional (when institutions and legislations fail to ensure reliable, secure and equitable supply of water to users). Only a careful analysis of the cost-effectiveness of each options allows for better identifying the most promising sources or gains in water demand management (FAO, 2012). To Ward and Michelsen (2002), the nature of problems involving water is typically one of conflict among alternatives stemming from economic scarcity rather than physical shortages.

Groundwater extraction supports a range of agricultural, industrial and household water uses around the world. Conversely, non-extracted groundwater stocks can provide services such as acting as a barrier against seawater intrusion or supporting natural flows critical to the functioning of ecological communities, and can have an option value for future uses such as buffering periodic shortages in surface water supplies (Qureshi, Reeson, Reinelt, Brozović, & Whitten, 2012). Groundwater is a finite resource as aquifers have limited capacity and natural recharge is often lower than extraction rates. A common failure in many groundwater management approaches is to view an aquifer

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merely as a source of groundwater; in other words the provision of water is regarded as the sole benefit derived from the aquifer. Failure to recognize the variability and range of these physical limits and the range of services that groundwater and aquifers provide result in ineffective management responses (FAO, 2003).

While the demand for irrigation continues to increase in many regions, demand for municipal and industrial uses is increasing many times faster. When water uses approach or exceed renewable supplies or developing new water resources becomes increasingly expensive, an increasingly common response to water shortages has been reallocation of water from irrigated agriculture —by far the largest water user— to non-agricultural water uses, particularly in urban areas. Such reallocations pose potentially adverse consequences for equity, environmental sustainability, and the livelihoods of the rural poor (Meinzen-Dick & Ringler, 2008).

As freshwater sources become scarcer, reclaimed water (wastewater receiving some form of treatment) reuse is becoming an attractive option for conserving and expanding available water supplies. Reclaimed water can have many applications, including irrigating farmland, aquaculture, landscape irrigation, urban and industrial uses, recreation, environmental uses and groundwater recharge. However, appropriate treatment or alternative safety precautions are necessary to prevent adverse health and environmental impacts (Ganoulis, 2012; Baghapour, Nasseri, & Djahed, 2013).

The use of reclaimed wastewater in agriculture is an option that is increasingly being investigated and taken up in arid and semi-arid regions with water scarcity, growing urban populations and growing demand for irrigation water, for instance: Israel, Palestine, India, Pakistan, China and several other countries (Winpenny, Heinz, & Koo-Oshima, 2010). Benefits of agricultural reuse of wastewater are expressed when agricultural production is maintained while water sources and environmental quality are preserved. In this way, negative effects on surface and groundwater are decreased (Haruvy, 1998). Worldwide, it is estimated that more than 330 km^3 per year of municipal wastewater are produced which would be enough to irrigate and fertilize millions of hectares of crops (Hernández-Sancho, Lamizana-Diallo, Mateo-Sagasta, & Qadir, 2015). Only about 20% of generated wastewater undergoes treatment in Latin-American countries and in Mexico an estimated 70 000 ha are irrigated with treated wastewater and 190 000 with untreated wastewater (Sato, Qadir, Yamamoto, Endo, & Zahoor, 2013).

Water management in Mexico

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Common characteristics of Mexico, and most Latin American countries, are an extremely limited formal institutional capacity to manage water resources; moreover, effective implementation of existing management instruments is not very high on political agendas. Such limitations cause problems that include inefficient public administration, widespread informality, weak regulatory institutions, low levels of participation, coordination, transparency, credibility and accountability, unstable and insufficient financing, corruption, fragmented and outdated water legislation, lack of technical capacity, implementation agencies and service providers with politicized and weak governance, and insufficient information (Barkin, 2011).

Mexico has very uneven water availability, with an arid northern half that is seriously water constrained, and a southern half that is less constrained but with problems such as pollution and inefficient use of water (Conagua-OECD-IMTA, 2010). The legal framework for managing water resources emanates from the country's Constitution which establishes that the federal government is the owner of all water resources in Mexico, while local governments are responsible for delivering water and sanitation services. The National Water Law further implements this framework through a federal agency —the National Water Commission (Conagua, for its acronym in Spanish)— with responsibility for leading and coordinating water resource management. Any use of national water resources (both extraction and discharge) requires a permit from Conagua. As a result, water policy is *de facto*

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dictated from the federal government, top-down approach, through federal programs that transfer resources to states, and water tariffs rarely covers operation and maintenance costs (OECD, 2013).

Federal and state regulations, although adequate on paper, are not easily enforced. The implementation of national and state-level policies at the local or grass-root level is inefficient (Pombo, Breceda, & Aragón, 2008). Reducing overexploitation of aquifers requires consensus across sector and water users or accompanying measures to manage tradeoffs. Without consensus, progress cannot be achieved and this has not been reached effectively in Mexico (Durham, Rinck-Pfeiffer, & Guendert, 2003; OECD, 2013).

To Pombo *et al*. (2008), the unequal distribution of water among the various productive sectors, low water use efficiency, and the lack of local public policies are factors that affect the sustainable use of this resource. According to Asad and Garduño (2005), the roots of water resource problems in Mexico are over concession, unsustainable patterns of extraction, and lack of measurement, regulation and actions to enforce the concession titles.

In Mexico, local groundwater management user groups or Comité Técnico de Aguas Subterráneas (Cotas), have existed for more than 18 years. The fundamental goal of the Cotas (as conceived) is to provide the social foundation to promote measures to slow down, and eventually eliminate, aquifer depletion. They have been able to promote awareness-raising activities and also, to some extent, water-saving investments, yet there are very few Cotas that have as yet decided to restrict total water use of the aquifer or take active steps towards its stabilization (Kemper, 2007; Foster, Kemper, & Garduño, 2004). Moreover, it is clear from the experience to date that the Cotas cannot achieve this goal alone, but neither could the 'water administration' achieve it without the Cotas (Kemper, 2007).

If institutional mechanisms within governments and other governance structures continue to follow narrow objectives along sector-specific mandates, fundamental disconnects will continue to occur (UNESCO, 2015). The failure from local (municipal), state and federal governments in the implementation of actions to protect these natural resources has caused water shortages in many places in Mexico, including the Ensenada region.

Water management decisions for the city of Ensenada, Baja California, have not been entirely based on technical or scientific data. The focus of the present study is to analyze the potential alternatives to mitigate water scarcity in the city of Ensenada, based on the cost of each alternative which include seawater desalination, transporting water from the Colorado River-Tijuana aqueduct and reuse of treated wastewater for irrigation and aquifer's infiltration. It is expected that by providing an analysis and comparison of the costs of the various water management alternatives for the region it will positively influence policy decision-makers on the management of the resource.

Study area

The city of Ensenada and the agricultural valleys of Maneadero and Guadalupe are located northwest on the state of Baja California, Mexico. The area has a Mediterranean climate, dry summers and winter rainfall. The annual rainfall is 248 mm (Daesslé *et al*., 2005). Within the Guadalupe valley two small towns are located, El Porvenir and Francisco Zarco with an overall population of 7 867 habitants (hab) in 2010 (OIEDRUS, 2015). Francisco Zarco has a small wastewater treatment plant yet only 1% of the population is connected. The vast majority has latrines at home. Ten wells have been historically used by the Comisión Estatal de Servicios Públicos de Ensenada (CESPE) to provide a maximum of 200 l/s for urban demand of Ensenada City (personal communication with Mr. Fernando Domínguez, Technical Operations, CESPE) However, since 2013 only approximately 40 l/s have been used for this purpose and since the beginning of the year 2017, they have completely stopped supplying the city of Ensenada altogether.

On the other hand, the Maneadero valley (officially named Rodolfo Sanchez Taboada) is 10 km south of the city of Ensenada. Its population in 2010 was 30 656 hab. (OIEDRUS, 2015). It has a wastewater treatment plant operated by CESPE and only 12.7% of the population is connected to the sewerage system. The Maneadero aquifer supplies approximately 190 l/s to the city of Ensenada for urban use (Figure 1).

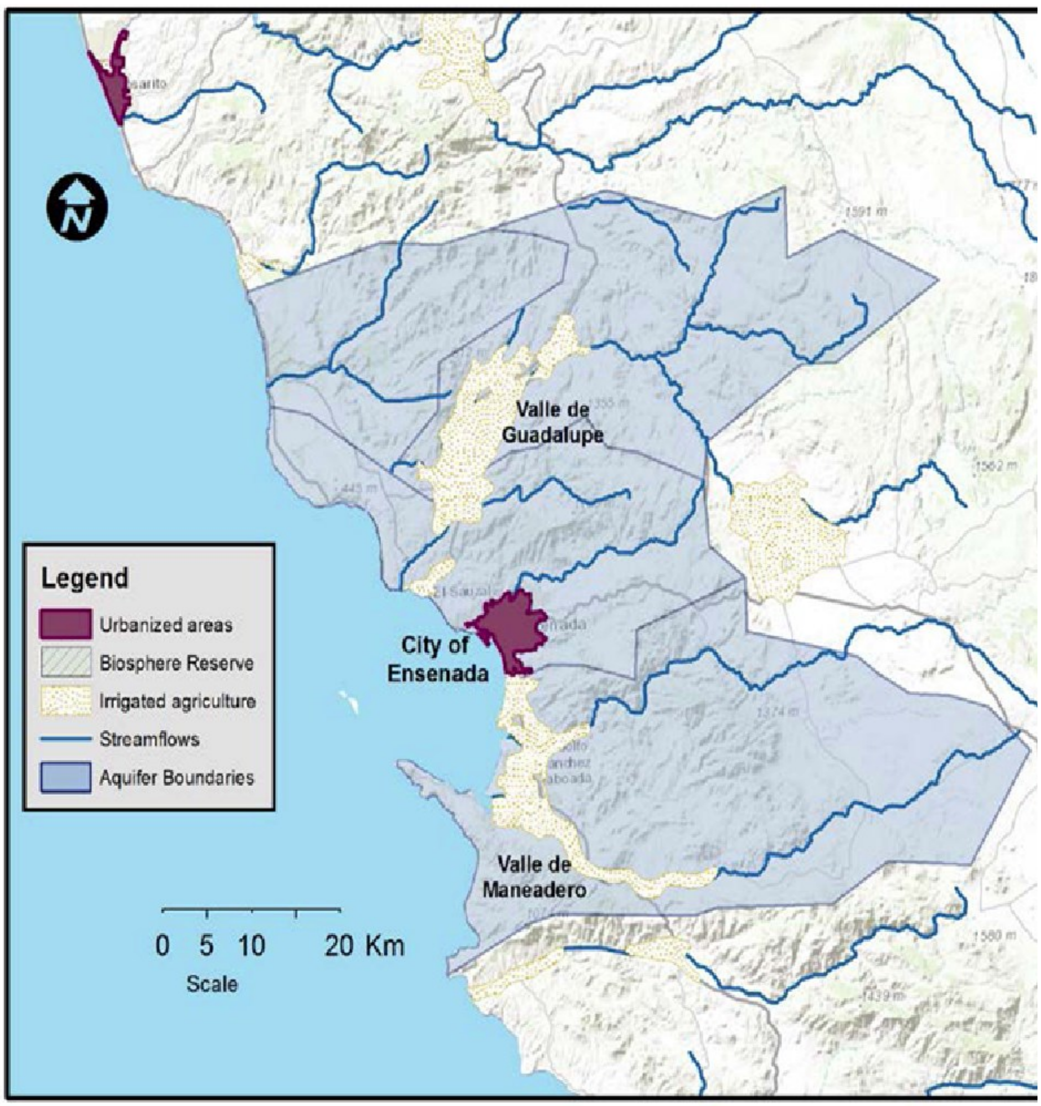

Figure 1. City of Ensenada and the valleys of Guadalupe and

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Maneadero, Baja California, Mexico. Source: Medellín-Azuara *et al*. (2013).

The water demand for the city of Ensenada is expected to increase in the following years as the population growth also increases (Figure 2).

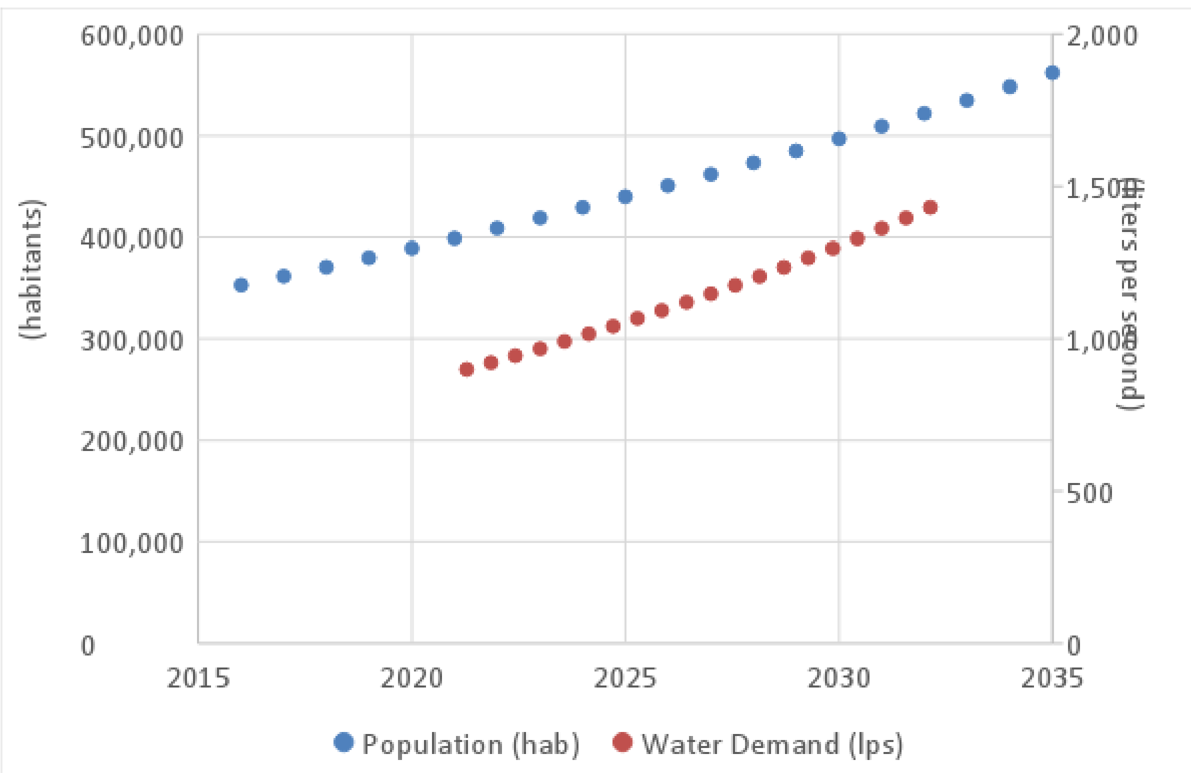

Figure 2. Population and water demand for the city of Ensenada, Baja California, Mexico, 2015-2035. Source: Built with information from CEA (2017).

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Guadalupe Valley is the main producer of grapes for wine production in Mexico. According to the Agriculture Secretary of Baja California (OIEDRUS, 2015), perennial agriculture in 2015 was 2 368 ha of which 81.9% (1 940 ha) were grapes and 18.1% (428 ha) are other crops such as olives, oranges and lemons and alfalfa.

On the other hand, according to data from the Agriculture Secretary of Baja California (OIEDRUS, 2015), in 2015 in the Maneadero valley the total surface cultivated was 3 756 ha from a historically maximum of 9 000 ha just 15 years ago. This implies a drastic decrease in the agriculture in the area of Maneadero due to poor water quality (salinization). In Maneadero the main crops cultivated are fodder, flowers, cucumber and zucchini.

Currently the city of Ensenada has an urban demand of 920 l/s, yet supply is only 745 l/s (personal communication with Mr. Fernando Domínguez, Technical Operations; CESPE). By 2030 demand will grow to 1 266 l/s so assuming that current water availability remains constant, the deficit will increase to 418 l/s. Currently, the Guadalupe and Maneadero aquifers are already overexploited. Future water supply in this region is uncertain due to low rainfall, aquifer overdraft, and aquifer saline intrusion (Medellín-Azuara, Mendoza-Espinosa, Pells, & Lund, 2013; Mendoza-Espinosa, Acosta-Zamorano, De la Barca, & Cabello-Pasini, 2015).

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Within the area of study there are six wastewater treatment plants (WWTP) operated CESPE: El Naranjo, El Sauzal, El Gallo, Maneadero, Noreste and Francisco Zarco. Total wastewater produced by all plants is estimated at 22 043 664 m^3 per year (personal communication with Mr. Fernando Domínguez, Technical Operations; CESPE). In Maneadero, approximately 120 l/s of reclaimed water from El Naranjo WWTP is reused for irrigation of 200 ha of flowers and fodder (Mendoza-Espinosa & Daesslé, 2018).

In 2018, a seawater desalination plant initiated operation to produce 250 l/s of water for urban use, with plans to expand to 500 l/s by 2024.

Methodology

The costs estimated for the alternatives recommended were calculated based on literature review of different case studies worldwide and Mexico. The digital databases at the Autonomous University of Baja California (UABC) were used for information gathering. The following databases were consulted: Bio One, Elsevier, Asss Science, Scopus, Springer, Google Scholar, World Bank and Cepal. Prices were adjusted from 2016 prices using the average Mexican peso United States Dollar conversion for 2016, which was 18.68 pesos per US dollar. For data from 2017, the conversion rate used was 18.84 pesos per US dollar.

A set of 10 interviews were carried out between May and July 2016 with public servants of the federal water agency (Conagua), the local water utility in charge of drinking water and sanitation (CESPE), the federal agricultural agency (Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación, Sagarpa), the state of Baja California agricultural agency (Secretaría de Desarrollo Agropecuario, Sedagro), as well as with Maneadero´s and Guadalupe´s Cotas and farmers with water concessions. Also, the engineer in charge of building the seawater desalination plant in Ensenada was interviewed. The main focus of the interviews was to know their perception on water management for the city of Ensenada. The questions were open and related to water resource management in the area, challenges, alternatives to mitigate water scarcity (for instance, transporting water from the Colorado River Tijuana aqueduct to Ensenada through an hypothetical aqueduct, seawater desalination and the use of reclaimed water for irrigation and aquifer recharge). Their opinion about the role of the authority responsible for managing the resource, the policy of subsidies to electricity and the value of groundwater were also sought for. Each interview took approximately 45 to 60 minutes and the results are presented anonymously. The information on water markets was obtained from interviews with farmers and information recorded and collected by Cotas in both valleys. The questions were oriented to issues related to water scarcity in the area, whether there are other alternatives to irrigate their crops and how much they paid for water. Results from these interviews are also anonymous. Table 1 presents the water management options that were considered for the valleys of Maneadero and Guadalupe.

Table 1. Water management options evaluated in the current study.

Place	**Management options**	**Water sources**
Guadalupe valley	Aquifer infiltration	Reclaimed water from El Sauzal wastewater treatment plant (WWTP), Noreste WWTP, El Gallo WWTP and El Naranjo WWTP is sent to Guadalupe valley for aquifer infiltration
	Agriculture irrigation	Reclaimed water from El Sauzal WWTP, Noreste WWTP, El Gallo WWTP and El Naranjo WWTP is sent to Guadalupe valley for crop irrigation
	Colorado River Tijuana Aqueduct (CRTA)-Ensenada	Water from the Colorado River Tijuana Aqueduct is sent to Ensenada for urban use
	Seawater desalination	A seawater desalination plant is built in Ensenada for urban use
Maneadero valley	Aquifer infiltration	Reclaimed water from El Naranjo WWTP, El Gallo WWTP and Maneadero WWTP is sent to

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		Maneadero valley for aquifer infiltration
	Agriculture irrigation	Reclaimed water from El Naranjo WWTP, El Gallo WWTP and Maneadero WWTP is sent to Maneadero valley for crop irrigation
	CRTA-Ensenada	Water from the Colorado River Tijuana Aqueduct is sent to Ensenada for urban use
	Seawater desalination	A seawater desalination plant is built in Ensenada for urban use

WWTP = Wastewater treatment plant.

The costs per cubic meter considered for the study were obtained from the literature and the interviews with public servants, officials and company managers. In most cases the cost includes capital and operational costs.

Results

Table 2 presents the costs used for all calculation.

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Table 2. Cost of water for irrigation, aquifer infiltration, transportation and desalination.

Activity	Cost US$/m^3	Source
Reclaimed water for aquifer infiltration from El Sauzal, Noreste and El Gallo WWTP to Guadalupe (treatment + transportation)	0.445329	CEA, Conagua (2017)
Reclaimed water for irrigation from El Sauzal, Noreste and El Gallo WWTP to Guadalupe (treatment + transportation)	0.445329	CEA, Conagua (2017)
Reclaimed water for aquifer infiltration from El Naranjo, El Gallo and Maneadero WWTP to Maneadero (treatment + transportation)	0.156581	CEA, Conagua (2017)
Reclaimed water for irrigation from El Naranjo, El Gallo and Maneadero WWTP to Maneadero (treatment + transportation)	0.061040	CEA, Conagua (2017)
Seawater desalination	0.766985	CEA, Conagua and CESPE (2017)
Water from Río Colorado Tijuana Aqueduct to Ensenada	1.028662	CEA, Conagua (2017) CEA-CESPE-IMTA (2011)

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WWTP = Wastewater treatment plant.

With the costs presented in Table 2 and the scenarios described in Table 1, the following results for Guadalupe and Maneadero are presented (Table 3).

Table 3. Total cost of reclaimed water for irrigation in Guadalupe and Maneadero valley per year.

Description	Guadalupe Valley		Maneadero Valley	
	Volume (m^3)	Cost (US$)	Volume (m^3)	Cost (US$)
El Sauzal, Noreste and El Gallo WWTP	9 776 160	$4,353,608		
El Gallo, El Naranjo and Maneadero WWTP			16 020 288	$977,883

WWTP = Wastewater treatment plant.

The amount of reclaimed water sent to Guadalupe would be 9 776 160 m^3 per year at a cost of US$4,353,608. The amount of reclaimed water for irrigation at Maneadero would be 16 020 288 m^3 per year at a cost of US$977,883 per year. Assuming an application rate of 5 000 m^3

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of reclaimed water per hectare per year, it would be possible to irrigate 1 955 ha in Guadalupe and 3 204 ha in Maneadero.

Aquifer infiltration

The costs for aquifer infiltration are presented in the Table 4.

Table 4. Total cost of reclaimed water for aquifer infiltration in Guadalupe and Maneadero valley per year.

Description	Guadalupe Valley		Maneadero Valley	
	Volume (m^3)	Cost (US$)	Volume (m^3)	Cost (US$)
El Sauzal, Noreste and El Gallo WWTP	9 776 160	$4,353,608		
El Gallo, El Naranjo and Maneadero WWTP			12 866 688	$2,014,688

WWTP = Wastewater treatment plant.

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As Maneadero is closer than Guadalupe to the wastewater treatment plants of the city of Ensenada, the cost for aquifer infiltration is less in the former.

Seawater desalination

The cost estimated by CEA-Conagua-CESPE (2017), which is US$0.766985/m^3 was used for the present study, as it is the cost considered at the local level for Ensenada. These are costs for a reverse osmosis membrane system.

Colorado River Aqueduct

The transportation cost for the Colorado River-Tijuana-aqueduct to Ensenada considered by CEA-Conagua-CESPE (2017) was US$1.028662/m^3 and this was used for all calculations.

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Guadalupe valley scenarios

The following results (Table 5) were obtained when running the scenarios and its different costs for Guadalupe valley.

Table 5. Guadalupe valley scenarios.

Alternative	Assumptions	Results
Agriculture irrigation	1) El Sauzal, Noreste and El Gallo are used for irrigation. 2) Guadalupe will not send groundwater to Ensenada for urban use.	Total reclaimed water available for irrigation would be 9 776 160 m^3/y at a cost of US$4,355,920/y A total of 1 955 new hectares would be irrigated with treated wastewater considering an annual allocation of 5 000 m^3 per year per hectare. This alternative will have a positive impact on the economy by boosting employment and production in the region and resulting in desirable outcomes for the aquifer
Aquifer infiltration	1) El Sauzal, Noreste and El Gallo are used for	Total reclaimed water for infiltration would be 9 776 160

	aquifer infiltration 2) Guadalupe will continue irrigation with groundwater 3) Guadalupe will not send groundwater to Ensenada for urban use	m^3/y at a cost of US$4,355,920/y The Guadalupe aquifer would have a reduction on its deficit from 12.2 Mm^3/y to 2.5 Mm^3/y Although the trade-offs are high, the results are promising for aquifer restoration Does not create dependency from the USA in terms of water resources and is sustainable
Río Colorado Aqueduct	1) Guadalupe will not send groundwater to Ensenada for urban use. 2) Guadalupe will continue to irrigate with groundwater. 3) No WWTP effluent would be used for irrigation nor aquifer recharge.	The reduction in the deficit of the aquifer would be approximately 1 Mm^3/y The cost of delivering 7 884 000 m^3 is US$8,114,281/y The water allocation to Mexico from the Colorado River will vary depending on the water levels of lakes Mead and Powell in the USA, creating an uncertain future scenario to Mexico regarding water's allocation. It is expected that the use of water from Colorado river decrease by 8% by 2035 due to climate change (CEA, 2017)

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The following results (Table 6) were obtained when running the scenarios and its different costs for Maneadero valley.

Table 6. Maneadero valley scenarios.

Alternative	Assumptions	Results
Agriculture irrigation	1) El Naranjo, El Gallo and Maneadero will be used for irrigation 2) Maneadero will continue to send 190 l/s of water for urban use to Ensenada	A total of 16 020 288 m^3/y of reclaimed water would be available for irrigation at a cost of US$977,883/y Approximately 3 204 hectares would be irrigated at an annual application rate of 5 000 m^3 per hectare The aquifer's deficit could be reduced from 17.5 Mm^3 to 1.5 Mm^3 per year Other benefits include increases in the value of the land, land use conservation, conservation of the aquifer and provision of water for present and future generation
Aquifer infiltration	1) El Naranjo, El Gallo and Maneadero will be used for Maneadero's aquifer infiltration 2) Maneadero will	Maneadero aquifer would reduce its deficit from 17.5 million m^3 to 4.9 million m^3/y at a cost of US$2,014,688/y 2 573 hectares would be irrigated

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	continue irrigating with groundwater 3) Maneadero will still be sending 190 l/s to Ensenada for urban use	at an application rate of 5 000 m^3 per hectare This alternative would help reduce aquifer overexploitation and saline intrusion, promoting aquifer restoration
Seawater desalination	1) Seawater desalination plant would produce 250 l/s (21 600 m^3/day) of water for urban use at Ensenada 2) Maneadero's aquifer will still be sending 190 l/s of water for urban use to Ensenada	A total of 7 884 000 m^3/y of desalinated seawater would be at a cost of US$5,858,598/y Maneadero's aquifer extractions would remain the same as the desalination plant would not be enough to meet Ensenada´s urban demand

The use of treated wastewater for irrigation and aquifer infiltration seem cost-effective alternatives from the environmental economic standpoint of view in Ensenada. Assuming that all the reclaimed water is used in Maneadero for irrigation and assuming Maneadero's aquifer will still be sending 190 l/s per year (5 599 840 m^3) of groundwater to Ensenada and 30 l/s (946 080 m^3 per year) for urban use at Maneadero, 16 020 288 m^3 per year of groundwater would be saved. This amount of reclaimed water for irrigation should result in cost saving of US$6,075,162 per year (by not pumping groundwater at a non-subsidized cost of US$0.3386 per kWh assuming 0.9 kWh needed for

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every m^3 of groundwater). Meanwhile, the cost of infiltration for Maneadero is calculated at US$2,014,688 and would cause a reduction in Maneadero's aquifer deficit from 17.5 Mm^3/year to 4.9 Mm^3/year. This alternative would stop aquifer overexploitation and help stop saline intrusion. Both irrigation and infiltration represent great benefits.

Desalination is still the most expensive option. The investment cost of the desalination plant alone is approximately US$27.4 million-plus the operating cost of desalinated seawater is US$6 million per year. In contrast, the operational cost of transporting water from Colorado River-Tijuana aqueduct Ensenada is approximately US$8 million plus the cost of building the aqueduct US$81.2 million. Total investment costs of these alternatives add up to US$122.6 million. The desalination plant is expected to produce 250 l/s seawater desalinated at its first stage with an extended capacity of 500 l/s (CEA, 2017). In contrast, the sum of the costs of using treated wastewater for irrigation and aquifer recharge is approximately US$2.9 million for Maneadero and US$8.7 million for Guadalupe. This adds up to US$11.6 million, which is less than desalination and a new aqueduct.

Therefore, the best alternatives after considering costs, environmental concern to restore the aquifers and the ecosystem and how sustainable the alternative could be at the long run to Ensenada are aquifer infiltration and agriculture irrigation with reclaimed water.

Regarding subsidies to electricity to pump groundwater, this has been designed to increase farmers income and to make their products competitive in the international market; however, it has had a high opportunity cost in terms of aquifers' depletion and will eventually reduce the amount of groundwater available for future agricultural and domestic use.

In the present study, after consulting official documents and farmers, the following calculations were obtained regarding subsidies to electricity. The total electricity subsidies for pumping water for irrigation in the state of Baja California during the year 2015 was US$153,571,124 while the electric energy consumption was 491 219 013 kW. For the study area, as the Table 7 indicates, in Ensenada 1 030 agricultural producers benefited from 1 070 wells, for which the total subsidy for 2015 was US$70,970,679 and the energy consumption was 227 009 778 kW.

Table 7. Electricity subsidies for pumping groundwater in Baja California, 2015.*

Region	Producers Receiving benefits	Wells benefited	Energy consumption (kW)	Amount subsidized (US$)
Ensenada	1 030	1 070	227 009 778	70,949,454
San Quintin	519	636	253 537 926	79,240,540
Tijuana	53	61	5 207 742	1,627,623
Tecate	65	48	5 463 566	1,707,577

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Total	1 667	1 815	491 219 013	153,525,195

*Note: Cost of kWh without subsidy $6.43 ($ 0.3412 USD) and with subsidy $0.54 ($0.0286 USD). Energy cost at subsidized cost $227,009,778*$0.3412 = $77,455,736 USD. Energy cost without subsidy $227,009,778*$0.0286 = $6,492,479 USD. Therefore, total subsidy is 91.6 %.

Source: Personal communication with Ing. Fernando Felipe Sánchez Galicia, Chief of the Department for the Development of Rural Districts SAGARPA, Rural District 01 Ensenada, Programa Especial de Energía Para el Campo en Materia de Uso Agrícola, Special Program of Energy for Rural Areas for Agriculture Use (Sagarpa, 2015).

Discussion

A cost comparison between seawater desalination, a new aqueduct and reclaimed water reuse for Ensenada undertaken by Waller-Barrera, Mendoza-Espinosa, Medellín-Azuara and Lund (2009) concluded that the most viable option was the latter and the least viable was desalination. However, the State and Federal governments favored the option of seawater desalination.

The positive environmental externality from desalinated seawater are the production of freshwater for urban use in Ensenada that could eventually cause the reduction of groundwater extraction in Maneadero and Guadalupe. However, there are also the negative externalities, which are the discharge of brine and chemicals used for the cleaning of RO membranes plus the CO_2 production associated to the energy required to operate the RO membranes. Seawater desalination typically yields a brine flow of 50-65% of the intake water flow, with about twice the initial concentration of salts and it may affect the local marine ecosystem (March, Saurí, & Rico-Amorós, 2014; Sarai-Atab, Smallbone, & Roskilly, 2016).

In the same context, in a study carried out in Alicante in Spain on the use of desalination as an alternative to water scarcity for urban and regional growth, it was found that although desalination increases security of supplies in times of drought and has several advantages regarding other options, it hardly represents the ultimate water source able to put an end to scarcity for all users. This management approach was strongly based in the enhancement of water supply sources rather than in the management of water demand (March *et al*., 2014). Water scarcity for urban areas could be overcome but water scarcity for irrigation won't disappear (March *et al*., 2014). Similarly, the National Research Council (NRC, 2008) stressed that the promise of desalination to rid the world of water scarcity that has been touted for nearly 50 years, remains largely unfulfilled.

Sarai-Atab *et al*. (2016) pointed out that the cost-effectiveness of production of desalination plants with RO is highly sensitive to changes in energy prices and policy decisions related to greenhouse gas emissions. According to Ghaffour, Missimer and Amy (2013), in a seawater RO desalination plant, the production of one cubic meter of freshwater from seawater uses 3-4 kWh of energy.

In Maneadero, electricity is used in water treatment processes like reverse osmosis (RO) used for irrigation is subsidized by the federal government through electricity tariffs 9 and 9M. According to the Federal Electricity Commission (CFE) to have access to this benefits, the farmers require authorization from Conagua that specify that the pumping plant will supply an RO plant for agricultural irrigation. This policy has the intention to be advantageous to farm producers as it allows them to use water and land that would be otherwise non-productive and, thereby, create jobs. The downside is that it causes water extraction from aquifers that are already experiencing depletion or freshwater and saltwater intrusion. This policy does not take into account other options to stimulate the agricultural sector and recover the aquifer at the same time.

Many studies carried out worldwide and in Mexico have proved that this policy has led to increase groundwater extraction and may have long-run environmental consequences such as the generation of negatives environmental externalities, for instance, stream depletion (surface-water groundwater interaction), salinization and land subsidence, the generation of CO_2 and also inequity among small farmers in terms of access to the subsidy (Scott, 2013; Sun, Sesmero, & Schoengold, 2016).

According to information in Table 7, farmers with concessions are receiving approximately 91.6 % of electricity subsidy for the pumping of groundwater for irrigation. This explains why agricultural policy should better reflect the scarcity of groundwater resources (Das, 2015) and its correlation with the subsidy policy. This could be reached by reforming this policy either by decreasing the subsidy or by pricing the resource according farmers' willingness to pay. The OECD (2010, 2013), recommended that Mexico needs to eliminate harmful subsidies because they have become disincentives toward the sustainable management of water resources.

Decision-makers

As in other places, some of the factors that are driving Ensenada to water scarcity are the increasing competition among the different water users, particularly agriculture and urban and mismanagement of water resources from the authority responsible resulting from procrastination and failure to take actions. Aquifers have often been marginalized in water management by not being considered in water planning efforts and management (Kemper, 2007). Without intervention, groundwater

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resources are misallocated by individual agents that do not internalize the extraction cost and the environmental externalities in their pumping decisions. In this context, government regulation can be a means to control water extraction to prevent market failure caused by these externalities (Esteban & Albiac, 2012).

In Mexico, the Cotas are intended to function as forums for water users of different sectors to participate in the bottom-up process for the development of integrated water management plans and the oversight and management of aquifer resources (The World Bank, 2009). The two existing Cotas in the study area (Guadalupe and Maneadero) are supposed to work on capacity building measures to strengthen the participation of concessioners on the sustainable management of the aquifers. However, both auxiliary organisms face financial and human constraints to achieve their tasks. In the case of Guadalupe there is no engagement with concessioners to develop a socially sustainable approach to water resources management and are concentrated on administrative duties rather than on the management of the aquifer. There is a consensus by the public servants interviewed in the present study that people at high level in water resources management agencies should be experts in water management and not public officials appointed by political parties with limited knowledge or interest on water resources management. The latter result in limited capacity of the institutions to manage water resource sustainable adequately (Barkin, 2011) and has led to inefficient public administration, widespread informality, weak regulatory institutions, low levels of participation, coordination, transparency, credibility and accountability, unstable and insufficient financing, corruption, fragmented and out-dated water legislation, lack of technical capacity, implementation agencies and service providers with politicized and weak governance, and insufficient information. For instance, according to the OECD (2013), in the irrigation sector, corruption is related to capital investments, failed operation and maintenance by irrigation officials, and falsified wells and concessions. Moreover, Barkin (2011) and OECD (2013) argue that some large enterprises benefit from privileged access to aquifers and they can obtain rights to drill wells or exploit water surfaces without control. According to the OECD (2013), corruption in water and sanitation services in Mexico is number 12 among 35 public services analyzed.

In the present study it was found that the local water utility (CESPE) and the state agency in charge of providing water for urban use (CEA) have been very slow to act. Although wastewater reuse was identified since 2004 as a viable option for Maneadero (Mendoza-Espinosa, Victoria-Orozco-Borbón, & Silva-Nava, 2004), a pilot project on using treated wastewater for irrigation in Maneadero's valley just started in 2015 (Mendoza-Espinosa & Daesslé, 2018). Likewise, in Guadalupe's valley, it took ten years to finish a small wastewater treatment plant with capacity of 15 l/s in the town of Francisco Zarco. It is desirable that government authorities, politicians and water resource managers take steps forward towards an efficient, equitable and

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sustainable management of water in Ensenada. If policy decision-makers do not take actions, it is likely that future sustainable development in the area will continue to be constrained by mismanagement of water. An effective water resources governance and management is central to avoiding overuse and depletion described by Harding's notion of the "tragedy of the commons" (Gray, Holley, & Rayfuse, 2016).

Wastewater reuse is the most attractive option in terms of costs and benefits for Ensenada. This has been proven in places such as Israel, in which treated wastewater has helped to maintain a healthy water balance of the country, by protecting conventional water resources and the socio-economic benefits associated with wastewater reuse. It has boost agriculture development that would not be possible without a constant and reliable supply of water that does not depend on rain, a reduction of the costs of sewage treatment in the urban sector and the availability of water for irrigation at a lower cost than the cost of importing conventional water from distant sources (Friedler, 2001).

Water prices, water subsidies and water markets

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When the price of water reflects its true cost, the resource will be put to its most valuable uses. Rogers, De Silva and Bhatia (2002) pointed out that price policy can help maintain the sustainability of the resource itself.

Concerning water right trading, after reviewing a Mexican case and five international cases (Australia, Wales, Chile, Spain and USA) there was not enough evidence to confirm that water right trading has contributed significantly to reduce water abstraction (Charalambous, 2016). In Mexico, for instance, groundwater continues to be overexploited even where water markets are available (Charalambous, 2016). For this market to work efficiently, Hearne and Donoso (2005), and Casado-Pérez (2014) suggest that government intervention (acting as a regulatory institution) should arbitrate the transactions. In Maneadero, saline intrusion has been historically a problem (Daesslé *et al*., 2005). This causes severe alterations in water quality which results in an informal water market based on water quality that does not reflect the value of water, neither the externality cost of the resource. In situations where prices are absent and markets are distorted, estimating the economic value of groundwater can be an essential component of valuation in the allocation of public welfare and other public policy options (Hanemman, 2006).

Another inefficiency from the institutional point of view that is distorting the value of water is the subsidy policy to groundwater extraction (Asad & Dinar, 2006). For instance, in 2004 in Maneadero

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and Guadalupe water extraction cost averaged US$0.14/m^3 that includes the cost of energy for pumping (Medellín-Azuara *et al*., 2009). According to five farmers from Maneadero Valley, for June 2016 they used on average between 0.9 and 1.2 kWh/m^3 of groundwater. This means that the real cost for farmers with no subsidy for electricity for pumping water, would be US$0.3070-$0.4094/m^3 considering a cost of 6.43 pesos per kWh (US$0.3412). In contrast, the farmers with subsidy will pay US$0.0257-$0.0343/m^3 considering a cost of 0.54 pesos per kWh (US$0.0286). Subsidies to electricity to pumping groundwater are leading to aquifer overexploitation as has been argued in many other studies (The World Bank, 2009; OECD, 2013; Sun *et al*., 2016). This is the most heavily subsidized use of electricity in Mexico, with the national average price equal to just 28% of the real cost compared to a subsidy of only a maximum of 10% in industry (Scott, 2009).

According to the OECD (2013), in 2010 in Mexico the subsidies to electricity for irrigation pumping accounted to more than 6.9 billion MX) or US$369 million, which is over nine times more than the US$41 million used for financing an efficient water infrastructure. Moreover, around 80% of electricity subsidies to irrigation water pumping accrue to only the richest 10% of farmers, making it a particularly regressive subsidy. The effects on the environment are catastrophic as over 100 major water aquifers in Mexico are now over-exploited. Also, between 2003 and 2015 there was an increase in the overexploitation of groundwater, which is one of the reasons the cost of depletion of this natural resource

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has been increasing at a nominal average rate of 0.7% per year, thus groundwater depletion results in an ecological costs of approximately 0.2 % of the GDP (INEGI, 2016).

In relation with water tariff and subsidies, a recent study carried out by Tellez-Foster, Rapoport and Dinar (2017) analyzed the theoretical effectiveness of three policy interventions: elimination, reduction, and decoupling—an innovative policy that substitutes the electricity subsidy for a cash transfer. The study demonstrated that changing the subsidy structure for groundwater extraction has significant effects on the extraction levels and consequent height of the water table of the aquifer. The elimination of the subsidy produced the strongest effect although it is not politically feasible. Reducing the subsidy produces a limited effect (less than one unit per period on average), and its implementation would face the same political difficulties. Decoupling the subsidy affects close to the one observed in the elimination condition without the adverse political difficulties. Therefore, they propose decoupling as an alternative policy intervention in overcoming the political obstruction. Moreover, in a study carried out in India by Badiani & Jessoe (2011) found that a 10% reduction in the average subsidy generates a 6.7% decrease in groundwater extraction. Overall, the consensus is that reducing subsidies can definitely reduce aquifer's overdraft (Scott, 2013; OECD, 2013; Sun *et al*., 2016).

Another way of controlling groundwater extractions is by monitoring extraction to determine water availability in aquifers and the sustainable level of groundwater extraction, in order to develop guidelines on groundwater use to inform and to engage farmers in the management of the aquifer (Jinno & Sato, 2011). In such study, the reduction in groundwater pumping was so drastic that it not only reversed the land subsidence process, but the recovery of the water table exceeded expectations.

Finally, another policy for managing groundwater use is voluntary agreements between farmers and government organizations. Participation in such control programs is encouraged through positive incentives (a restitution of taxes). Such programs try to convince farmers through education of the advantages of fine-tuned groundwater control. Voluntary agreements on controlling groundwater use are efficient, since they rely on specialized knowledge of participants about local conditions (Das, 2015). This means participation of farmers in planning and decision-making at the local level as stated for OECD (2010).

All of the policies mentioned could be recommended for both valleys Maneadero and Guadalupe. They could be more transparent, efficient and politically feasible potential solutions compared to a drastic elimination of electric subsidy, particularly when Cotas is actively engaged with the farmers' community.

Impediments

As mentioned earlier, in Mexico water scarcity for irrigation is not only attributed to mismanagement of the resource, but a lack of transparency. One of the largest challenges is to achieve good governance to guarantee a safe and reliable water supply to agriculture and all sectors in the economy (Transparency International, 2008). The extent of public sector corruption in government institutions is linked with the size of the informal sector, which in turn has a negative impact on all sectors and, particularly, the environment (OECD, 2015). Another common practice, according to Kemper (2007), is that water users falsify the registration of primary water rights by reporting less water extraction than their actual water use. In 2010 the Superior Auditor of Mexico published a report that shed light on the irregularities and illegal practices in the management of public financial resources and investment in the water sector. The report exposed Conagua's inability to provide trustworthy documentation to monitor how states manage their resources and insufficient information to allow for a comprehensive audit (OECD, 2013). All of the above may provide an explanation why water management decisions are frequently taken by reasons unrelated to scientific or technical data.

The need to invest in sustainable solutions to an efficient groundwater use and allocation is urgent. The possible solutions are endogenous to Ensenada's natural resources availability. The alternatives consisting in the use of treated wastewater for irrigation and aquifer infiltration have been highlighted for several years and they have not been fully implemented despite water scarcity condition in the area. The main reasons to select the alternatives described are that they could: 1) be potential solutions to mitigate water scarcity in the area and restore the aquifers; 2) are financially and environmental sustainable; 3) allow the maximization of the plain use of endogenous natural resources already available, reduce waste and minimize cost of fertilizer and other inputs required to irrigation crops in Ensenada; 4) are an option to climate change adaptation and mitigation by saving energy and reducing the cost of freshwater pumping, providing irrigation and reducing the water footprint of food production; 5) provide self-sustainability in groundwater resources management reducing dependency from the USA to control their future on water resources management in the area, and 6) help sustaining economic development by guaranteeing a permanent water supply to irrigation.

Conclusions

The reuse of reclaimed water for irrigation and aquifer infiltration are cost-effective alternatives from the environmental economic standpoint of view in Ensenada. The potential benefits of infiltration in Maneadero are similar to the irrigation option in terms of reducing groundwater pumping cost. It can be said that the total benefits of implementing these alternatives are greater than the costs of transporting and desalination seawater altogether. The cost of the Río Colorado Tijuana to Ensenada aqueduct is high. Moreover, there is an uncertain future scenario to Mexico regarding the allocation of transboundary water. The federal authority (Conagua) and the state government (CEA) should provide authority to Cotas and increase its financial, human and technological resources so that it can play a proactive role in the sustainable management of the aquifers of Maneadero and Guadalupe. The Cotas should have the autonomy to make decisions at the local level and not being constrained by top-down decision from the federal and state government so the resulting process would become more simple and transparent to farmers in the area. Cotas Guadalupe needs to engage concessioners through public participation and work closer together if its goal is to have a contribution towards the sustainable management of the aquifer. Despite the differences between water concessioners in both valleys, there is a common problem that they are sharing, which is water scarcity. This implies that both Cotas should collaborate, share information and work together and engage other Cotas in the region towards the same goal, which is to maintain and restore the services from the aquifers for the present and future generations. Water prices, as well as electricity prices for pumping groundwater do not reflect water scarcity. The opportunity cost of groundwater from the aquifer for irrigation is zero; the subsidy to electricity to extract water is above 80% and, as a result, the aquifers are depleted. The option decoupling subsidies would be more politically accepted than elimination and reduction of subsidies. Moreover, another potential option to reduce irrigation water could be through the combination of valuing the resource and the establishment of a sustainable level of groundwater management extraction, in which water users will be provided with the maximum allowable extraction rate as a function of the piezometric levels of the aquifers.

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