D2.7 Feasibility study and pilot design for Maneadero Valley, Mexico

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Executive Summary

Maneadero Valley is a 35 km² coastal alluvial plain in Baja California, Mexico, producing high value crops such as tomatoes and cucumbers for local and export markets. Food production is under pressure because of a shortage of freshwater for irrigation. Over pumping of the aquifer has induced a strong intrusion of saltwater from the coast into the central valley. Due to the increasing salinization of the groundwater, already 1000 hectares of agricultural land have been taken out of production.

Farmers and (water) authorities are urgently looking for solutions to sustain freshwater supply, food production and thus the economy of the valley. In 2009, the Baja California State Government built a 20 km pipeline to distribute municipal reuse water from the city of Ensenada to the south of Maneadero Valley. Farmers, however, are hesitant to using this water, as they are concerned about the microbiological risks when irrigating (food) crops with reuse water. Also, the current (aboveground) storage capacity for this water is limited. Despite its substantial availability, reuse water in the valley is only used to irrigate 100 ha in an ongoing field pilot.

In 2014-2015, a SWS quick scan has been performed by ARCADIS and KWR, together with Mexican partners and stakeholders in Maneadero Valley. Together, they have drafted a potential SWS solution for the valley: (1) storage of large volumes of reuse water in the saline subsurface, (2) thereby creating a barrier against further saltwater intrusion, securing the freshwater wells land inwards, and (3) removal of pathogens from the reuse water by soil aquifer passage to secure microbiological safe irrigation water. All partners (including water authority COTAS, farmers, and the water and wastewater facility CESPE) are dedicated to upgrade the current reuse pilot to an SWS pilot in 2017 – 2018.

In order to assess the implementation potential of SWS in Maneadero Valley, a feasibility study and a site-specific hydrogeological model were performed. The feasibility study proved that Reclaimed Water is a possible water source for infiltration as it exists in sufficient amounts and there is a specific regulation that dictates the parameters required for infiltration of RW (NOM 014 CONAGUA). Also, the implementation of SWS would address several problems in agricultural, social, economic and sustainable fronts. Exact economic impacts are hard to quantify and therefore were performed specifically for tomato production. Results of the analysis over the 2010-2014 period (considered the drought period) showed accumulated losses of $155MUSD plus 7,062 jobs lost and 9,164 non-used trucks. All the above-mentioned factors will have an important impact over the competitiveness level of the state. An advantage for the project implementation is the current change of mind set of the government which has several plans in favor of water sustainability. One of the main challenges is the social acceptance to using RW for crop irrigation. Aquifer passage promotes the removal of pathogens creating a microbiologically safe water for irrigation, yet the true capacity of the Maneadero aquifer to remove pathogens or other potentially hazardous substances from the reclaimed water has not been quantified. A participatory Technology Assessment (pTA) is scheduled in September 2017 to discuss these and other challenges with all relevant stakeholders in Maneadero Valley.

The current insights obtained from hydrological modelling and (worst-case) scenario analysis, indicate that freshwater production from a combined (existing) infiltration pond and Freshkeeper is limited but not unviable. A detailed quantification and optimization based on a detailed characterization and small-scale pilot is required for further assessment of the feasibility.

A field pilot design for Maneadero was drafted. Important issues to be addressed in the pilot include obtaining a better insight in the (local) hydrogeology and geology, more details on the salinity distribution close to the pond, an assessment and improvement of the infiltration rates, and of the chemical and microbiological water quality changes during infiltration and aquifer passage. The pilot design and objectives will be discussed with relevant stakeholders in June 2017.

1 Introduction

Coastal areas are the most productive and economically dominant regions of the world. The high water demand in these regions, however, puts tremendous pressure on their freshwater resources and ecosystems. This leads to problems like seasonal water shortage, saltwater intrusion, and disappearance of wetlands. Building on national, regional and European research and innovation programs, in the past five years, a set of innovative, practical concepts have been developed for protection, enlargement and utilization of freshwater resources in coastal areas. These subsurface water solutions (SWS) combine innovations in water well design and configuration, allowing for advanced groundwater management, and maximum control over freshwater resources. SWS.

Subsurface Water Solutions (SWS) have proven to be effective and sustainable techniques to address saline intrusion problems and secure water availability in diverse areas. However, the implementation success of these techniques is highly related to the local environmental, hydrogeological and societal conditions. Therefore, analyzing the implementation feasibility of SWS in other target markets of the SUBSOL project is highly important to increase the confidence in these techniques and to develop a successful commercialization plan.

This report addresses the case of Maneadero Valley, Mexico where the implementation of SWS has the potential to abate salinization and, at the same time, promote the sustainability of the aquifers currently used for irrigation purposes.

Maneadero valley's main economic activity is agriculture and it is considered one of the major agricultural regions in Mexico due to its large crop production primarily used for exportation purposes (OEIDRUS, 2012). However, this region has been catalogued in the last years as a place suffering severe to extreme drought (NADM 2015). Furthermore, the region's main water supply depends on subsurface aquifers that, besides being overexploited, present saline intrusion and are becoming unsuitable for agricultural irrigation (CONAGUA, 2014). Frequently used techniques for desalination, such as Reverse Osmosis, are not sustainable solutions for Maneadero as brackish groundwater abstraction still promotes the intrusion of seawater and further salinization of the aquifer. Also, due to the economic level of the valley, RO doesn't represent an economically feasible solution.

Subsurface Water Solutions (SWS) is a technology created to maximize fresh water availability in coastal areas through an optimization of the subsoil capacity to contain fresh water. This is achieved through a combination of horizontal and vertical wells that extract brackish water and inject fresh water simultaneously; creating a barrier that protects the fresh water supply. This innovative water storage systems can prevent saline intrusion in a sustainable, cost-efficient manner. Due to the water scarcity in the area, the initiative to implement SWS in Maneadero valley contemplates the injection of reclaimed water from the neighboring city of Ensenada into the aquifer. This solution has several benefits for the area but *is the implementation of SWS economically, socially and technically feasible?*

1.1 Research objective

Development of a feasibility study combining expertise from Mexico and Europe to evaluate SWS potential to abate salinization and increase reuse water usage for crop irrigation in Maneadero Valley.

Development of a detailed hydrological model to evaluate SWS applicability and design in the Maneadero aquifer. The model will be used for a more thorough SWS feasibility check and will be a valuable tool for future analysis of SWS designs and implementation studies in similar systems elsewhere.

1.2 Research approach

To accomplish the research objective, the following activities were performed:

- Gain insights of the current situation of the study area
    - Background research
    - Contact and perform meetings with international and Mexican organizations in order to deepen the acquired knowledge and gather further information
- Creation of a water balance in the area to understand current water uses and assess source availability
- Mapping of the stakeholders involved in the project and potential future funding sources
- Assessment of the involved regulatory framework and the required activities to comply with it
- Impact quantification of SWS implementation in the area
- Development of site specific hydrogeological model using hydrological and geophysical data already obtained by CICESE institute (Ensenada, Mexico)
- Understanding of the advantages for implementation
- Understanding of the challenges for implementation
- Emission of recommendations

2 Background information - Maneadero Valley

Maneadero valley is a 35 km^2 coastal alluvial plain located 15 km south of the Town of Ensenada. (Figure 1). The local weather is a Mediterranean-like dry climate, with a yearly precipitation between 100 and 450 mm and occasional higher events influenced by El Niño Southern Oscillation (ENSO).

Figure 1 Location of Maneadero

The area main economic activity is agriculture focused on production of high quality and value crops mainly for exportation. This generates over 2,500 direct jobs and a large number of indirect jobs through the whole supply chain (transport, packaging, accountants, technical advisory and marketing). The primary source of irrigation water is Maneadero aquifer which is currently in overexploited conditions.

2.1 Geology and hydrology

Maneadero Valley is part of a larger 1,975 km2 basin (catchment), limited by Ensenada's basins up north, Ojos Negros and Real del Castillo, Santo Tomás to the south, Laguna Salada and San Vicente to the east, and with the Pacific Ocean to the west. The valley (study area) itself is a 35 km2 coastal alluvial plain, consisting of Quaternary alluvial and fluvial deposits, limited to the south by the Agua Blanca fault, to the east and north by volcanic rocks, and to the west by the Punta Banda Estuary and the Pacific Ocean (Figure 1). Two creeks drain the valley in the rainy season: San Carlos Creek in the north and Las Ánimas in the south. The aquifer consists of alternating sandy and gravel-sand-clay deposits, down to the granitic basement that dips from 400 m in the north to between 580 and 1,000 m in the south near the Agua Blanca fault. It is recharged in the rainy season by the precipitation surplus and, especially, by the runoff water infiltrating from the creeks. This natural recharge, however, is not sufficient to keep up with the exploitation concessions, which exceed the aquifer recharge by 17.6Mm^3/y (Table 1), leading to an aquifer in overexploited conditions.

Table 1 Maneadero Exploitation (Amounts in Mm^3/y) (OFD, 2015)

Aquifer	Medium annual recharge	Natural Compromised Discharge	Concessioned Volume	Extraction volume according to technical studies	Meduim annual availavility of water	DEFICIT
Maneadero	20.8	0	38.377	30.6	0	-17.577

The over pumping of the aquifer has resulted in an average water table drop of 1.6 m (2001-2009), with local extremes of 6 to 10 m. As a result, water tables are commonly at or below sea level, which has led to rapid increase in saltwater intrusion from the coast line to the central valley since the 1970s (Figure 2). Due to the increase of salinity levels, several exploitation wells have become unsuitable for irrigation leading to more than 1,000ha taken out of production in Maneadero Valley.

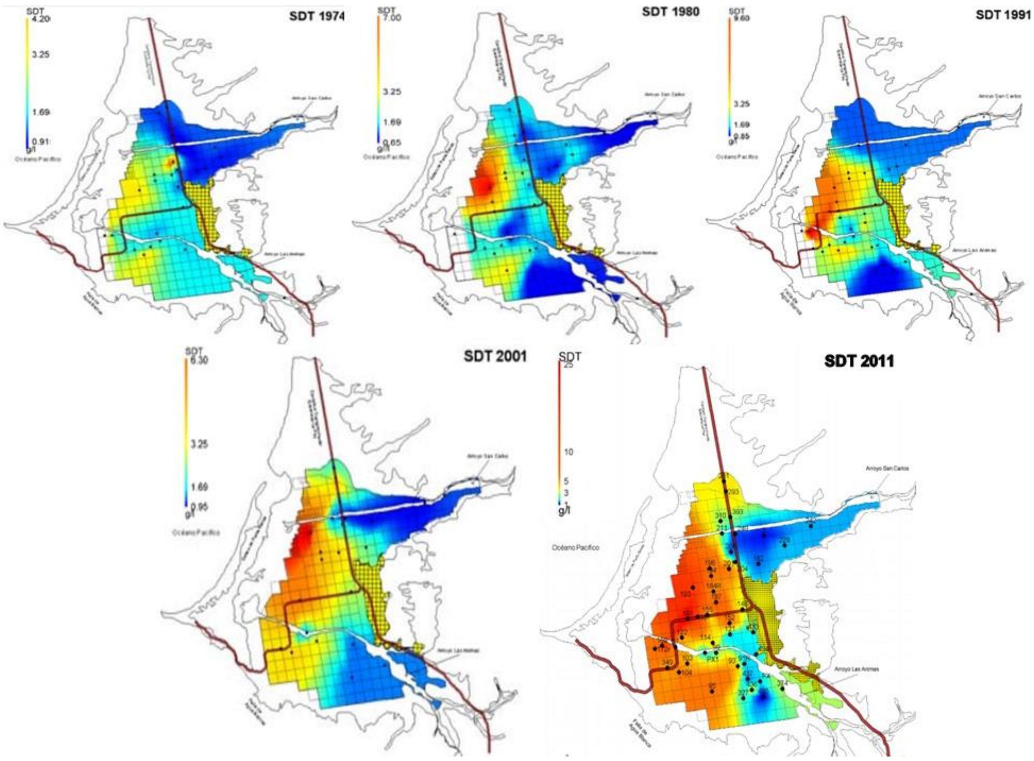


Figure 2 TDS concentration change over time1974-2011. (UABC data)

2.2 SWS and Maneadero Valley

In response to the severe salinization of the aquifer, farmers are looking for alternative water supply options. Some farmers near the coast have switched to desalination (reverse osmosis, RO), using brackish groundwater as the source water and disposing the RO concentrate via a pipeline into the Pacific Ocean. The switch to desalination shows the desperate need of famers and their willingness to invest in their freshwater supply. However, desalination is not a sustainable solution for Maneadero, as brackish groundwater abstraction still promotes the intrusion of seawater and further salinization of the aquifer.

To address the irrigation water scarcity, Baja California state government built a 20 km pipeline to distribute reclaimed water (RW) from the El Naranjo wastewater treatment plant, located south of Ensenada, to the south of Maneadero Valley where it is stored in two reservoir ponds (20m x 50m) exclusively for the irrigation of flowers and animal feed crops. With this action 100 ha have been put back to production.

The creation of the reservoir ponds was also expected to have an impact on the infiltration of water into the aquifer however, geophysical investigations by CICESE (Center for Scientific Research and Higher Education at Ensenada) indicate that the water hardly infiltrates, most probably due to buoyancy effects that prevent the infiltration of low-TDS reclaimed water in a high-TDS (thus denser) aquifer. Similar problems were encountered in the Netherlands with subsurface storage of harvested rainwater in brackish aquifers, forming the starting point of the development of SWT's ASR-Coastal and Freshmaker.

Additionally, reservoir ponds have limitations regarding the space availability, as available land is preferred to be used as agricultural land, the high evaporation rates in the area, which lead to higher TDS in the infiltration water, and farmer's hesitation to use reclaimed water in the irrigation of crops. The latter develops mainly after possible negative reactions of crop importers towards the new irrigation method.

In 2014-2015, a SWS quick scan was performed by ARCADIS and KWR, together with Mexican partners and stakeholders in Maneadero Valley. Results from this scan showed that Subsurface Water Solutions represent a better alternative for water reuse and storage in the area. The application of SWS in Maneadero valley will allow farmers to store large volumes of reclaimed water in the subsurface and will also create a natural barrier against saltwater intrusion securing the freshwater land inwards. The use of the soil as an infiltration medium will remove all the pathogens from the reclaimed water and provide a microbiologically safe water for irrigation.

All partners (including water authority COTAS, farmers, and the water and wastewater facility CESPE) are dedicated to upgrade the current reuse pilot to an SWS pilot in 2017 – 2018.

3 Reclaimed water availability

Five WWTP's operated by CESPE (Ensenada Estate Commission of Public Services) are located nearby Maneadero Valley. Table 2 shows a summary of their designed and operation capacity and treatment procedures.

WWTP	Installed capacity [lps]	Operation capacity [lps]	Performance %	Treatment procedure	Disinfection Method
El gallo	200	168	84	Activated sludge	chlorine
El naranjo[1]	500	371	74	Oxidation ditch	chlorine
El sauzal	120	35	29	Oxidation ditch	chlorine
Noreste	26	32	123	Activated sludge	UV
Maneadero	30	4	13	Activated sludge and UF polishing step	UV

Table 2 Ensenada WWTPs operation (CESPE data)

Due to the distance between Maneadero Valley and other WWTPs, CESPE's functionaries consider El Naranjo WWTP to be the only feasible source of RW for the region. Figure 3 gives an overview of the location of the WWTPs in the area where Maneadero Valley is represented by the name of Rodolfo Sánchez Taboada (official name of the community).

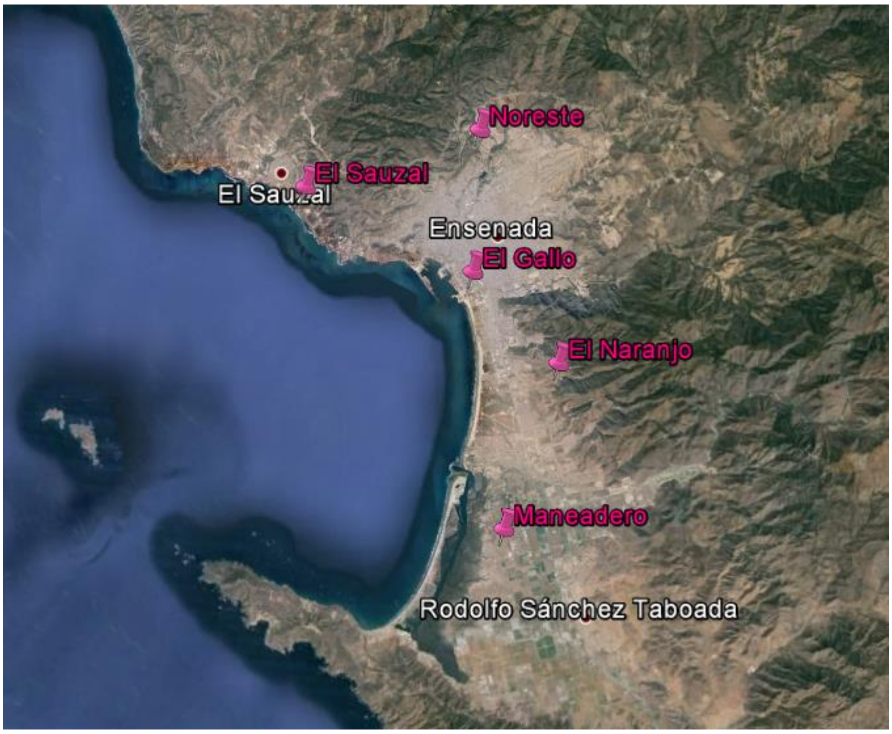


Figure 3 Location of WWTPs

3.1 Reclaimed water uses

Due to the unavailability of updated data regarding the compromised RW effluents, an approximation of the current situation was performed based on data published in the program of preventive and mitigation measures for drought (SEMARNAT, CONAGUA, 2014). Reused effluent from El Naranjo WWTP was increased considering the 50lps that are being used by Maneadero valley since 2014. The WWTP-El Naranjo operation scheme is characterized as follows:

- Process: Biological activated sludge with extended aeration
- Oxidation ditch: carrousel type with aeration plates (fine bubble). Residence time 20.3hrs
- Rapid sand filtration: only 6 of 12 RSF are in are in operation as the "quality is sufficient according to NOM-001-SEMARNAT-96." NOM-001-SEMARNAT-96 regulates water discharged by WWTPs
- Disinfection: chlorine gas with a residual concentration of 0.2-0.4mg/l
- DBO5: in 400mg/l, out- 30mg/l (design parameter)
- TSS: in 350mg/l out – 30mg/l (design parameter)

Table 3 WWTP effluents and reuses –

WWTP	Operation capacity [Mm^3/y]	Reuse* [Mm^3/y]	Reuse purpouse				Discharge to ocean	
			Green area* [Mm^3/y]	Compactactation* [Mm^3/y]	Agriculture* [Mm^3/y]	Industrial* [Mm^3/y]	[Mm^3/y]	%
El gallo	5.30	0.049	0.003	0.046	-	-	5.25	99.1
El naranjo[1]	11.70	1.653	0.041	0.017	1.593	0.002	10.05	85.9
El sauzal	1.10	0.022	-	0.022	-	-	1.08	98.0
Noreste	1.01	-	-	-	-	-	1.01	100.0
Maneadero	0.13	0.137	-	-	0.137	-	-	-

*Asuming original quantities in thousands of m3

[1] Agriculture value updated adding 50lps that are currently distributed to maneadero Valley

The entire effluent of El Naranjo WWTP is already being transported to Maneadero Valley however, due to the small amount used for the irrigation of flowers and crops for animal feed and the limited storage capacity of the reservoir ponds, almost 86% is still discharged to the ocean.

Ongoing activities in Maneadero Valley suppose an increase of the area irrigated with RW to 400ha (currently 100ha, see Figure 4). This change would lead to an increase in the consumption of RW (from 50lps to 200lps) and therefore, a reduction of the available RW from 10.05Mm^3/y to 5.32 Mm^3/y (COTAS, 2015). The implementation of these activities will require the construction of additional reservoir ponds. However, these ponds are expected to be provided with geomembranes to avoid infiltration and therefore don't suppose an advantage to this project.

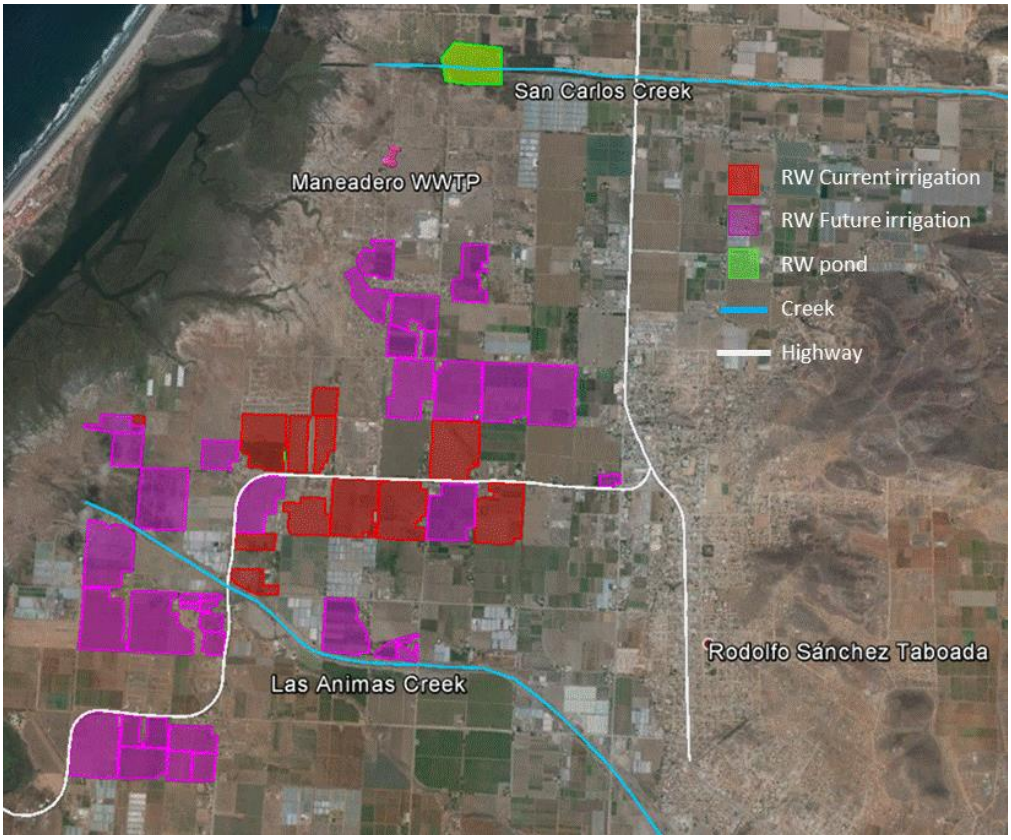


Figure 4 Mapping of Maneadero Area

A schematized version of the water balance in the area can be consulted in Figure 5.

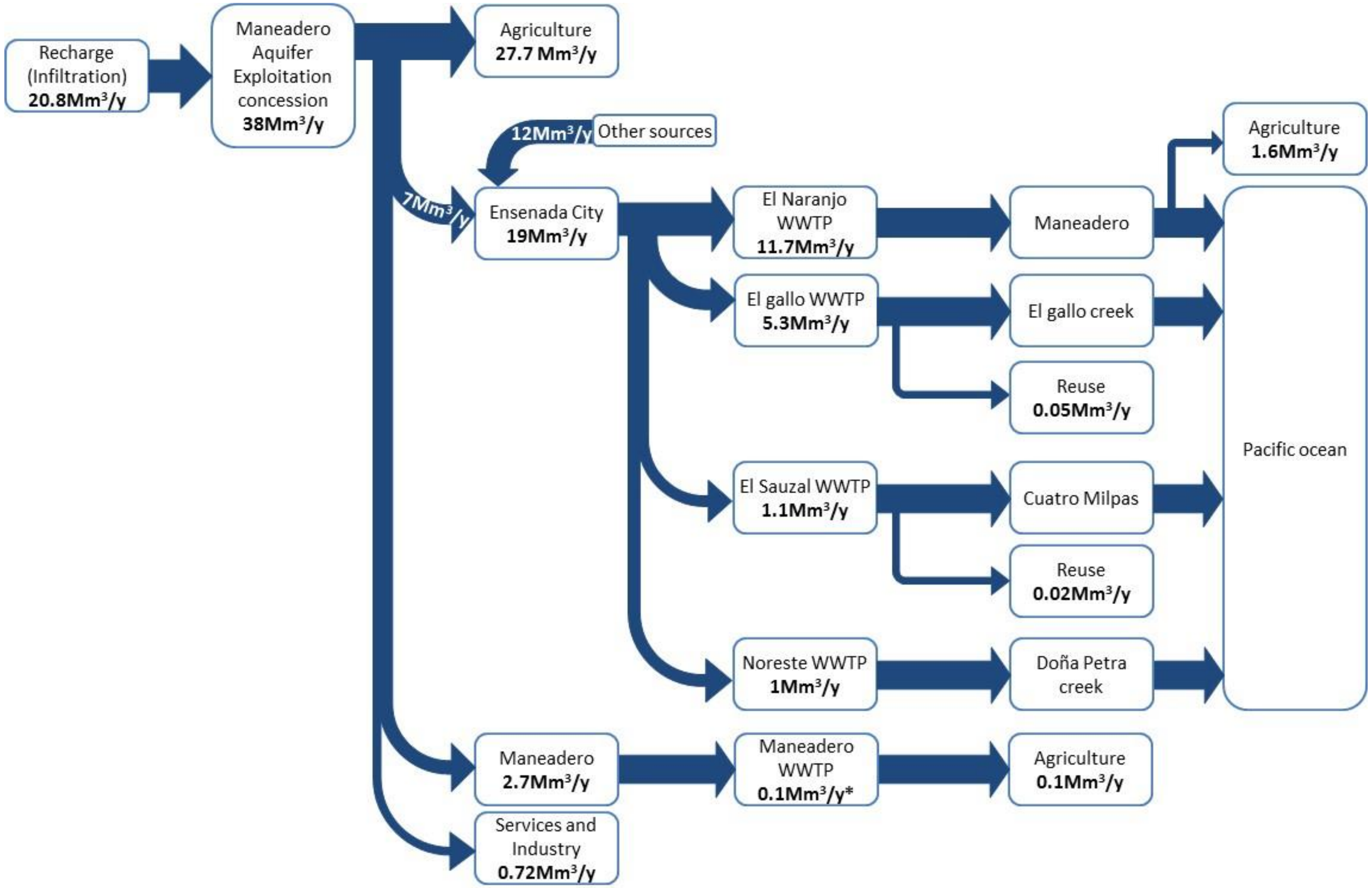


Figure 5 Water Balance of Maneadero Aquifer

4 Stakeholder mapping

As a first step a simple mapping of the main stakeholders in the area was performed. Table 4 and Table 5 show a brief description of the stake holders and the possible funding sources respectively. Complete stakeholder mapping is given in Figure 6.

Table 4 Main stakeholders and identified motivations to support SWS implementation in Maneadero

Category	Entities	Motivation
Public	SEMARNAT (Secretary of Environment and natural resources)	Ensure water bodies protection. Promote the sustainable exploitation of water sources.
	CONAGUA (National Water Comission) and its subsidiaries COTAS (Technical council for underground water) CEA (State water comission)	
	SAGARPA (Secretary of Agriculture, livestock, rural development, fishery and feeding)	
Private	Industries in the area	Possible affectations to the water quality in the surrounding area
	Importers	Sanitary risks from the use of reclaimed water
Local community	Agricultural associations	Water availability for crop production
	Land Owners	
	Urban water users	Possible water quality affectations. Slow the need of large infrastructure investments that can be translated to increased fees
Academic	UNAM (Mexico National Autonomous University)	Water balance. Aquifer recharge studies. Saline intrusion studies. Soil impacts of the use of reclaimed water.
	UABC (Baja California Autonomous university)	
	CICESE (Ensenada Center for Scientific Research and Higher Education)	

Table 5 Possible additional funding sources identified

Category	Organization	Goal
NGO	Pro Natura	Conservation of the flora, fauna and ecosytems in Mexico by promoting a harmonic nature-society development
	Terra Peninsular	Civil Association that promotes the conservation and protection of natural ecosystems and wild life in Baja California
	FEMSA Foundation	Social investment that promotes sustainable use and conservation of water
Public	CONAGUA	Universal access to waterservices. Clean water supply. Stop aquifer overexploitation
	SAGARPA	Ensureand promote agricultural production in the area
	SEFOA (Secretary for agricultural development)	
	SEDESOL (Secretary of social development)	Social development for poverty minimization
	SEDECO (Secretary of Economy)	Economic and social development in the area
	Ensenada's economical development council	
International Lenders	NADbank (North American Development)	Support border communities funding infrastructure projects that promote sustainable development and enhace life quality in the border region. Special focus in water and wastewater projects
	BECC (Border Environment Cooperation Commission)	
	IDB (Interamerican Development Bank)	Support the economic and social development in Latin America. Invests in projects and activities that amplify the low income population economic opportunities. Promotes projects oriented to climate change and water supply and treatment
	World Bank	Partnership to reduce poverty and support development. Provides low-interest loans, zero to low-interest credits, and grants to developing countries Special interest in food safety

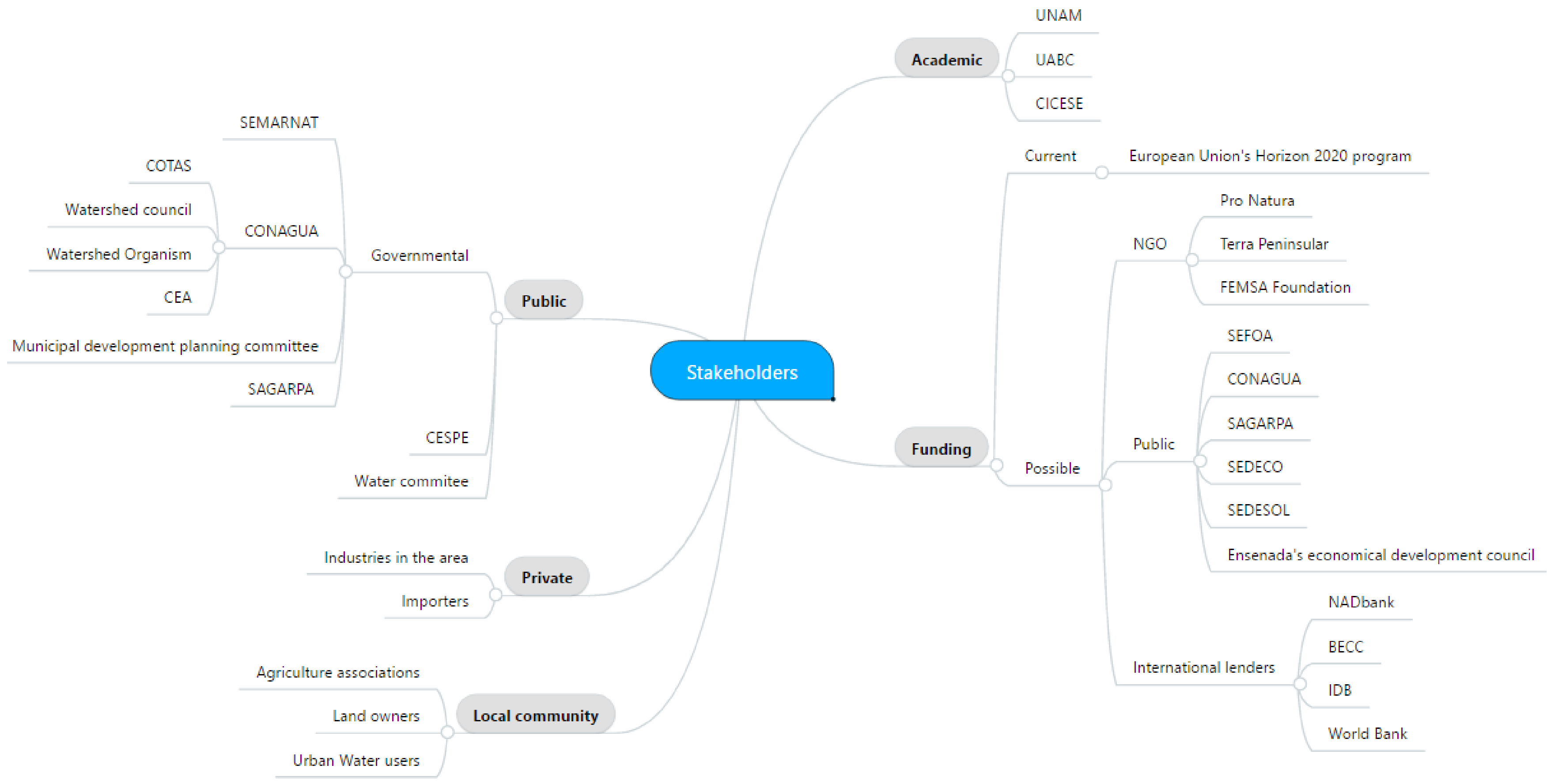


Figure 6 Stakeholder Mapping

5 Regulatory framework

The implementation of SWS has an applicable environmental legal framework that follows the hierarchy observed Figure 7.

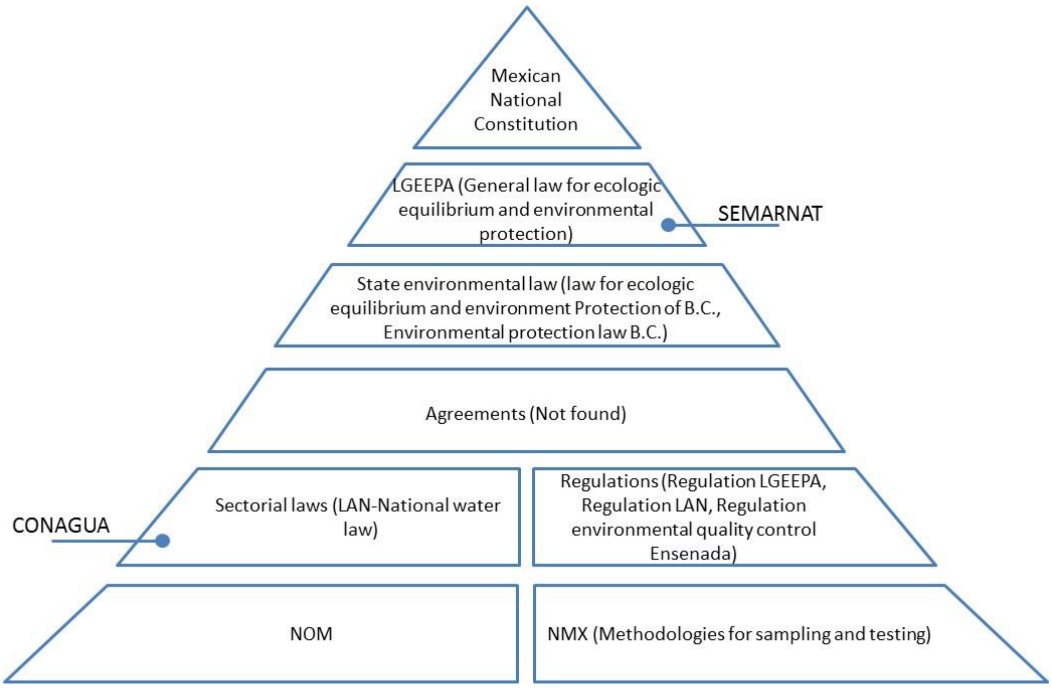


Figure 7 Regulatory law Hierarchy

5.1 Mexican national constitution

The Mexican constitution states that all waters that exist in the country's territory belong to the nation. Their exploitation can be performed only through a concession given by the "federal executive" represented, in this case, by the national water commission (CONAGUA).

5.2 LGEEPA (General Law for Ecologic Equilibrium and Environmental Protection)

This law is considered the main standard for environmental regulation, the concerning authority is the Secretary of Environment and Natural Resources (SEMARNAT) who will issue all the permissions and will enforce the law compliance through its subsidiary PROFEPA (Federal attorney for environmental protection).

Figure 8 shows a summary of the law process to determine the related activities and in which cases an Environmental Impact Manifestation (EIM) should be submitted. It also indicates the secretary response times (in working days) or the meaning, according to the law, of the absence of response.

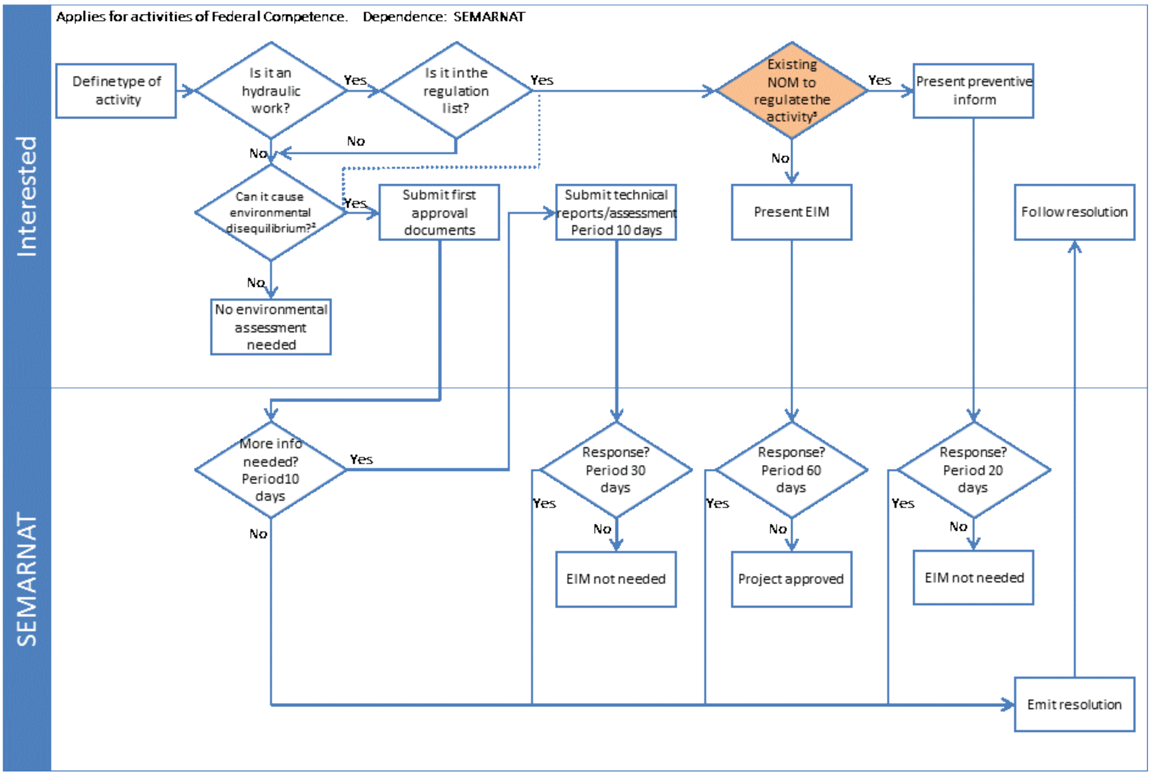


Figure 8 LGEEPA application flow chart

The "submission for first approval" can be performed with a simple letter specifying the activity to be performed

²Considering the environmental impact assessment a preventive tool, this activity will be considered as a threat for possible sabotage and health risks

³NOM 014 doesn't specify in its objective that it is "for environmental protection", might be rejected for exemption

The environmental impact assessment is catalogued as a preventive tool. Therefore, aquifer recharge with RW is expected to be classified as an environmental risk activity and most likely further documentation and possible an entire EIM study will be required. The existence of a NOM that regulates aquifer recharge might not suffice an exemption given that the NOM objective doesn't state that the required limits are for "environmental protection purposes".

5.3 State environmental law

Even though aquifer recharge is considered as Federal competence, the proposed soil passage might be considered to concern state or municipal authorities. To determine which permissions are required, it necessary consult an expert or to submit a review request to the local authorities.

Law for ecologic equilibrium and environment Protection of Baja California

Dictates that any works that can cause damage to the environment need previous authorization from the state's general direction of ecology. Also, all activities that are not stated in article 62 (aquifer recharge is not included) must submit a preventive inform before the start of any work.

Environmental protection law of Baja California

This law concerns the State's secretary of environmental protection. It states that an environmental impact manifestation must be presented and authorized before the start of any activity that can be considered a risk for the environment.

Works that don't produce significant negative environmental impacts or that have existing NOM to regulate them will just present a preventive inform. After this, the secretary has a reply period of 10 days, if no response is given the EIM is considered not necessary.

5.4 Sectorial law: National Water Law (LAN)

The compliance of this law concerns to CONAGUA (National water commission).

It states that every water exploitation requires a concession given directly by CONAGUA or through the basin organisms. Once the request is submitted, the maximum response period is 60 days (working times).

It also indicates that infiltration of reclaimed water requires CONAGUA's permit and to comply with the specified NOM (NOM 014 CONAGUA).

5.5 Regulation

The LGEEPA and LAN regulations explain further the considerations for applying the law. These aspects were already covered in the respective law explanation and therefore won't be mentioned again.

Regulation for environmental quality control Ensenada

Activities that, even being reserved to the federation and the state, can be decentralized into favoring the municipality require an environmental license by the direction of urban development and ecology.

5.6 Mexican Official Norms (NOM)

NOM's objective is to regulate and ensure minimum and maximum values, quantities and characteristics in the design, production or operation of diverse activities. A brief description of their objective and applicability is mentioned below.

- NOM-001-SEMARNAT: maximum permissible pollutant discharge in national waters and holdings. Indicates diverse standards based on the type of final discharge water body. According to classification given in the Federal rights law, Maneadero aquifer is a type C body.
- NOM-003-SEMARNAT: maximum permissible pollutant discharge for reused water in public services. Regulates parameters for water that might lead to incidental contact. Irrigation of green areas or fields is prone to incidental contact therefore, the current irrigation with RW should comply with them.
- NOM-014-CONAGUA: aquifer artificial recharge with reclaimed water. This law indicates the procedures to follow to infiltrate reclaimed water. In the case of water quality, it states that the non-specified parameters should comply with NOM-127 SSA (Water for human use and consumption). Also, it states that the construction and maintenance of wells should comply with NOM-003-CONAGUA and NOM-004-CONAGUA respectively.

5.7 Mexican Norms (NMX)

The Mexican Norms give standards for sampling and testing procedures. Their application is considered mandatory only when a NOM specifies that they should be followed, otherwise they represent only a recommendation. As the NOMs specify that all samples are expected to be evaluated by a certified lab, these norms were not further evaluated.

6 Cost-benefit analyses

In order to create a stronger business case in favor of the implementation of SWS in Maneadero Valley, diverse impacts of the water shortage and aquifer overexploitation were quantified.

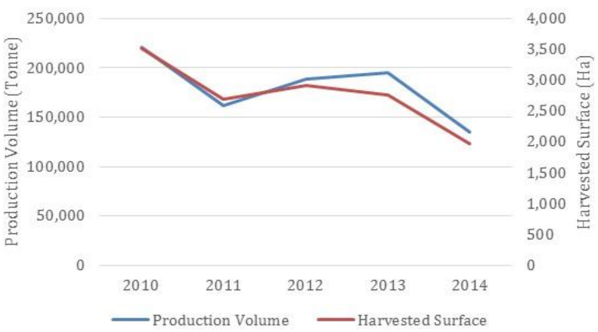
6.1 Agriculture impacts

Agricultural production represents the main consumption of water in the area, 75% of the water extracted from Maneadero aquifer (~25Mm^3/y) is used for this purpose.

Due to the drought and saline intrusion in wells, already 1,000 ha have been taken out of production. Tomato is one of the main crops produced in Maneadero therefore, the impact quantification over crop production was performed specifically for this case and for the period 2010-2014, as drought period is considered to start in late 2010. Over this period, the harvested surface decreased 44% and the production value 39%. Details of the data can be consulted in Table 6 and its corresponding graph. It is important to note that values for Maneadero's production weren't available and therefore data from Ensenada region was used for this analysis.

Table 6 Agricultural data of tomato harvesting over time for Ensenada. SIAP- SAGARPA

Year	Cultivated Surface (Ha)	Harvested Surface (Ha)	Production Volume (Tonne)	Yield (Tonne/Ha)
2010	3,535	3,525	220,754	62.63
2011	2,751	2,685	161,942	60.32
2012	2,933	2,914	188,970	64.85
2013	2,760	2,759	195,464	70.86
2014	1,998	1,976	135,030	68.35
	Decrease	**44%**	**39%**	



6.2 Social impacts

The agriculture sector in Maneadero generates over 2,500 direct jobs and a large number of indirect jobs through the whole supply chain (transport, packaging, accountants, technical advisory, and marketing).

Maneadero's agricultural work force is mainly composed from marginalized workers that emigrated from other states and municipalities in seek of better opportunities. Maneadero provides them with more profitable and dignifying jobs improving with this their life quality. The loss of agricultural jobs in the region will cause migration to the surrounding cities which, besides representing an increased abandonment of the agricultural lands, would lead to an intensification of the already existing water shortage problems that, over the last years, have caused big dissatisfaction towards the government and generated several strikes.

The drought in Maneadero's region has caused several affectations to human activities and therefore, according to FAO's definition, is considered not only as a meteorological event but as a socioeconomic drought (FAO, 2015).

6.3 Economic impacts

The amplitude of economic impacts a drought generate are often difficult to determine. Therefore, this case focus only on estimating the financial damages originated by the decrease of tomato production in Ensenada. The analyzed period comprehends from 2010 to 2014 (considered the drought period) and estimations are based on the yearly production decrease using 2010 production values as base line.

Accumulated losses generated by tomato production decrease were divided in direct and indirect impacts. Conclusive results are shown below and the complete calculation procedure can be consulted in Appendix A- Economic impact quantification.

- Direct.
    - Product sales $1,728MMXN ($132.6MUSD)
    - Considering an average requirement of 7.5 workers per cultivated hectare this translates into 7,062 jobs
- Indirect
    - Fertilizer sales $214MMXN ($16.5MUSD)
    - Pesticide sales $75.6MMXN ($5.8MUSD)
    - Non-used trucks 9,164

The above-mentioned losses represent a non-quantifiable impact over Baja California's national and international competitiveness levels.

Another economic impact of the drought and the overexploitation of fresh water sources in the area is the current requirement of large investments for Reverse Osmosis projects. These are planned to increase the water supply to the city and represent a high pressure in the economic sustainability of the state.

6.4 Environmental Sustainability impacts

The exploitation of Maneadero aquifer has not been done in a sustainable manner. Extraction concessions exceed natural recharge by 17.6 Mm^3/y. This has generated a 1.6 m drop of the water table of in less than 10 years. The location of water table below the sea level has led to a destabilization of the hydraulic pressures of fresh and salt water leading to saline intrusion problems. RO procedures offer a solution to saline sources but, besides representing a non-economically feasible procedure, their implementation promotes further salinization of the aquifer making it a non-sustainable solution.

As drought is expected to remain for a longer period and maybe increase its severity, it is important to find sustainable solutions that can ensure the water availability all year round.

7 Advantages for SWS implementation

An increasing tendency of the importance of water issues in the National plans has been observed over the last decade. On National scale, some examples are:

- The *National Development Plan 2013-2018* addresses two main issues as the most relevant water related topics: create a responsible water management and increase water supply and sanitation coverage
- The *Water Agenda 2030* main goals are: the development of a solid watershed governance oriented to an adequate water management and the improvement of responsibilities distribution of all government instances and levels in projects related to achieve better water supply and sanitation
- The federal authorities concern to promote wastewater reuse led to CONAGUA publishing of official guidelines for artificial groundwater recharge using reclaimed water (NOM-014-CONAGUA-2003).

Being drought considered as one of Baja California's main hazards, *Baja California state development Plan 2014-2019* was developed with a big focus on water sustainability. Related to this project implementation, mainly two plans can be addressed:

1. Infrastructure for competitiveness and development plan
2. Impulses the use of reclaimed water for agricultural irrigation and aquifer recharge
3. Considers Maneadero aquifer recharge as a strategic project for the state
4. Sustainable economic development plan
5. Aim to increase the sustainability of agricultural activities through the recovery and sustainable use of aquifers
6. Considers desalinization as a strategic project. SWS technology implementation provides a more sustainable and cost effective solution

Given the desperate need for freshwater in Maneadero Valley, stakeholders are very open to eco-innovation, such as SWS. All partners (including water authority COTAS, farmers, and the water and wastewater facility CESPE) are dedicated to upgrade the current reuse pilot to an SWS pilot in 2017 – 2018.

8 Social challenges for SWS implementation

The main challenge identified for the implementation of the project is the social acceptance to the use of reclaimed water.

Agriculture in Maneadero mainly consists of high value crops for exportation. This is a very competitive market and its sanitary regulations are highly strict. Therefore, farmers are concerned about the pathogens that might be present in the reclaimed water and their possible affectations to their crops value. Also, there’s a high uncertainty feeling on the acceptance of this new agriculture procedure by the vegetable importers. The before mentioned factors generate hesitation to the use of reclaimed water.

Aquifers are efficient in removing pathogens. As a rule of thumb, it is considered that a period of 60 to 90 days of aquifer passage is sufficient to remove pathogens from sewage water; yet the removal rate will vary depending on redox and geochemical conditions (e.g., Schijven et al, 2000; Van der Wielen et al., 2009). The NOM 014 CONAGUA, for infiltration with reclaimed water, establishes that the minimum residence time in the aquifer before extracting the water must be 6 months creating an additional barrier. The pathogen removal capacity (rate, residence time) of the Maneadero aquifer, however, has not been quantified up to date. This information is vital to be able to ensure microbiological safe irrigation water to the farmers. Until quantification and evaluation water should be used for the irrigation of flowers and crops for animal feed only, as is the practice in the current direct reuse pilots in Maneadero. Besides pathogens, organic (emerging) substances will likely be present in the reclaimed water, though data is lacking. This as well should be part of further research.

Another challenge that might arouse for the implementation is the agreement on cooperation levels between different actors. This has generated already some conflicts in the information gathering process. It is important to keep the main stakeholders interested and informed of the main activities of the project as they can help to enforce certain actions through their power stakes and relations.

A participatory Technology Assessment (pTA) is scheduled in September 2017 to discuss and reflect on the above challenges with all relevant stakeholders in Maneadero Valley.

9 Groundwater flow modeling

9.1 Aims and approach

To assess the SWS feasibility, a detailed hydrological model of the study area was developed. The aim of the model was to explore the impact of SWS on the local fresh-salt water interface and the freshwater infiltration from the recharge pond. The outcomes of this modeling study will guide the setup of a field pilot, including the (research) questions to be answered through the pilot.

SEAWAT Version 4 (Langevin, Thorne Jr et al. 2008) program was chosen as modelling code for this purpose because of its ability to simulate three-dimensional variable-density groundwater flow coupled with multi-species solute transport. This allows for accurate description of the groundwater flow movement taking into account the density differences between fresh and saline water (buoyancy effects and upconing).

Hydrological parameters of the study area, infiltrated and abstracted volumes in and close to the infiltration pond, distribution of the infiltrated treated water below the pond and information on the seawater intrusion in the coastal aquifer of Maneadero were based on studies performed by CICESE and COTAS. These parameters were used as initial conditions ('reference situation') in the model and were used to optimize other unknown parameters. Once the hydrological processes and salinity distribution in the area were satisfactorily described by the model, different scenarios and SWS designs were run to study the most optimal design.

In the following sections, the extension of the model, parameters used, boundary conditions and the different scenario runs are described.

9.2 Model domain and boundary conditions related to the hydrogeology of the study zone

Setting

The model area is located around the treated waste-water infiltration pond, located 15 km South of the city of Ensenada. The infiltration pond is located in a relatively flat sedimentary area where several rivers discharge to the ocean; more specifically the study area lies between las Ánimas Creek (South) and San Carlos creek (North). The sedimentary aquifer surface is around 75 km^2 and its volume is estimated to be 2,940 Mm3. The aquifer is confined in the bottom by a granitic basement that dips from 400 m in the north to between 580 m and 1,000 m in the southern aquifer, where the Agua Blanca fault is located. Elevated topography can be found to the East and South of the flat plain, resulting in a regional groundwater flow towards the Pacific Coast in the west (Gil Venegas 2010).

The local groundwater flow, is - despite the original regional groundwater flow towards the sea - highly dependent on the pumping rates. In fact, recent piezometric head development indicates reversal of the groundwater flow direction towards the inland due to severe water table drops (Figure 9). Therefore initial conditions of background groundwater flow towards the sea are neglected and background pumping is simulated by extra wells located further from the pond.

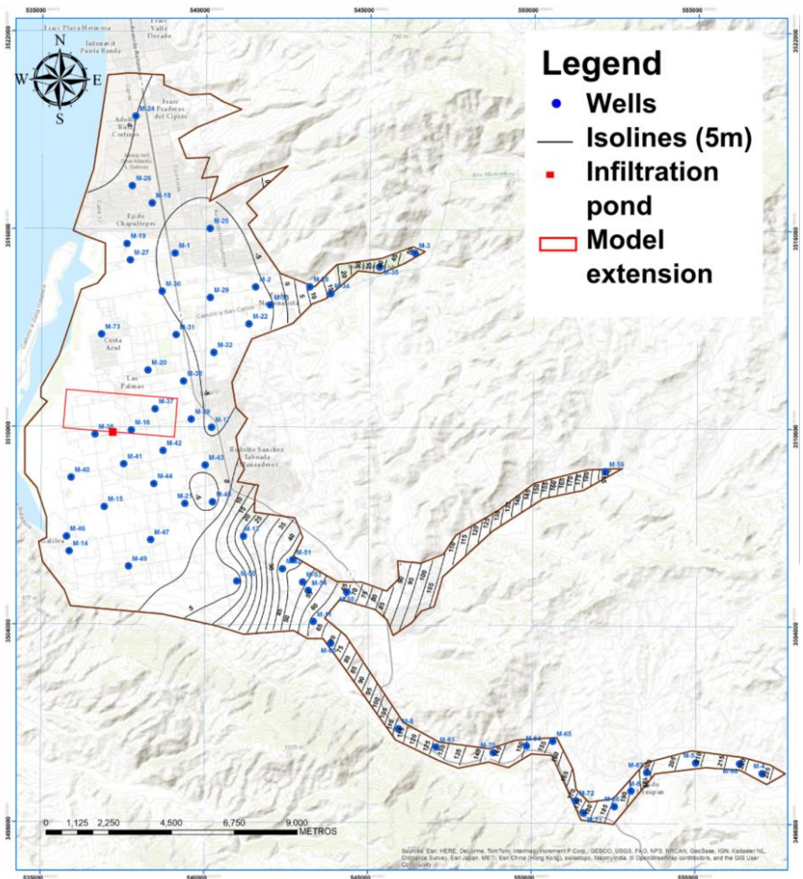


Figure 9 Water table depth with respect to sea level (isolines every 5m), location of the infiltration pond and extension of the model.

Information on detailed hydrogeological parameters of the study area was provided by CICESE. The study of Sarmiento López (1996) contains the lithology encountered during several drillings. One of the drillings (PEZA 3: Figure 10), located 400m West of the infiltration pond, was used to schematize the geology of the model. Furthermore, pumping test data was available from four locations in the Maneadero aquifer (Figure 11).

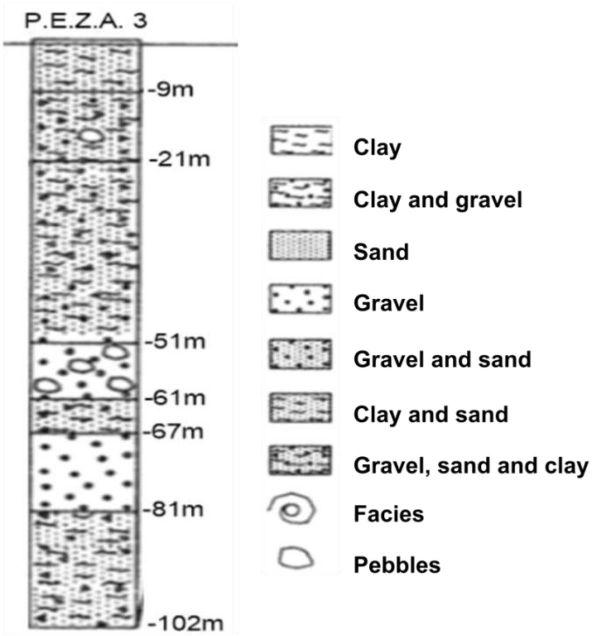


Figure 10 Geological description of drilling PEZA 3.

Well	X_UTM	X_UTM	Q (lps)	Depth (m)	Dejection T (m2/day)	Dejection K (m/day)	Recovery T (m2/day)	Recovery K (m/day)
311-P-CNA	539,537	3,508,650	29	57.91	1,310.07	42.94	467.88	15.33
E-154	544,418	3,501,941	22	60	307.83	6:25	267.57	5.43
P236-M12	541,607	3,513,635	10	72.07	39.53	0.9	93.01	2.12
Rancho El Capricho	537,418	3,508,215	27.3	45	719.41	27.94	2,539.09	98.61

Figure 11 Location of the pumping tests performed in the Maneadero Aquifer (yellow pins) and of the salt water infiltration measured through geophysical methods ((LUJÁN and Romo 2010))

The groundwater quality in the Maneadero aquifer has been monitored in the last years and it is concluded that water quality deteriorates resulting from extensive water extraction for agricultural and urban supply, salinization by seawater, and nitrate pollution derived from septic tanks in the town of Maneadero and fertilizer and manure input (Daesslé, Pérez-Flores et al. 2014). Daesslé et al. provide information on the TDS, Cl, Na, NO3 and F concentrations measured in different wells in the Maneadero aquifer, including wells 161 and 157, located close to the infiltration pond (Table 7, Figure 13 and Figure 14).

Also, the geophysical study performed by LUJÁN and Romo (2010) provides local information on soil conductivities very close to the infiltration pond (blue line in Figure 13). According to the resistivity distribution found, sea water intrusion is well beyond the infiltration pond.

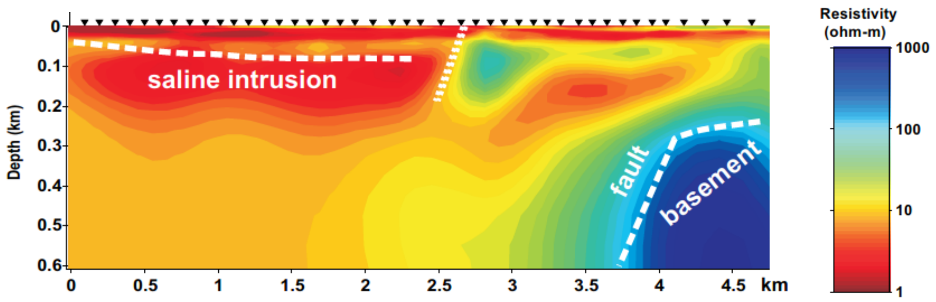


Figure 12 Resistivity measured by (LUJÁN and Romo 2010)along profile 3of their study. Resistivity is related to salinity of the water, the less resistant the more saline the groundwater is expected to be. The figure indicated the possible location of the salinization front in 2011.

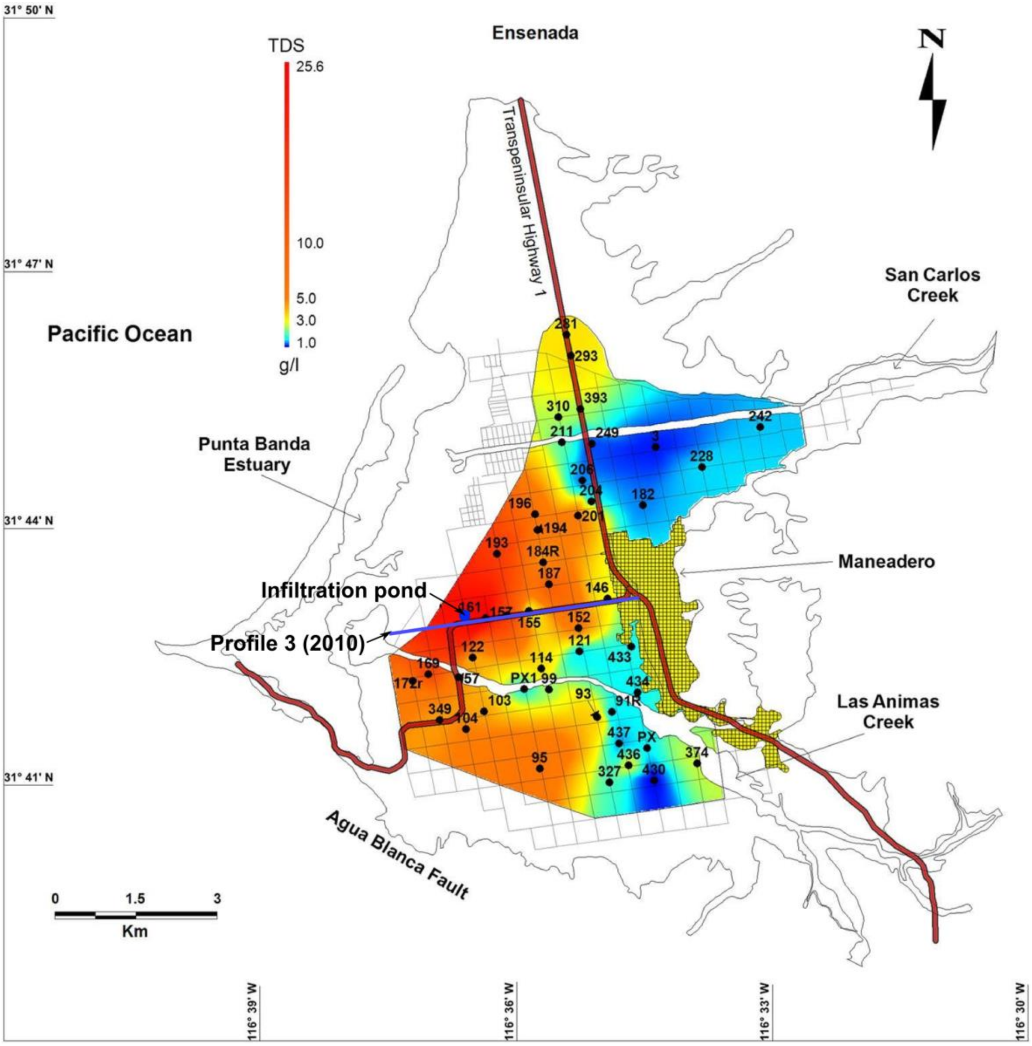


Figure 13 TDS distribution in 2011 based on geophysical studies by CICESE. The blue dot indicates the location of the infiltration pond and the blue line the location of the third geophysical profile performed by (LUJÁN and Romo 2010). Modified after (Daesslé, Pérez-Flores et al. 2014)

Recent information on the salinity concentrations (as TDS) measured in observation wells located close to the infiltration pond (Figure 14) is summarized in Table 7, together with the water quality measured in the infiltration pond by GARCIA, (2016).

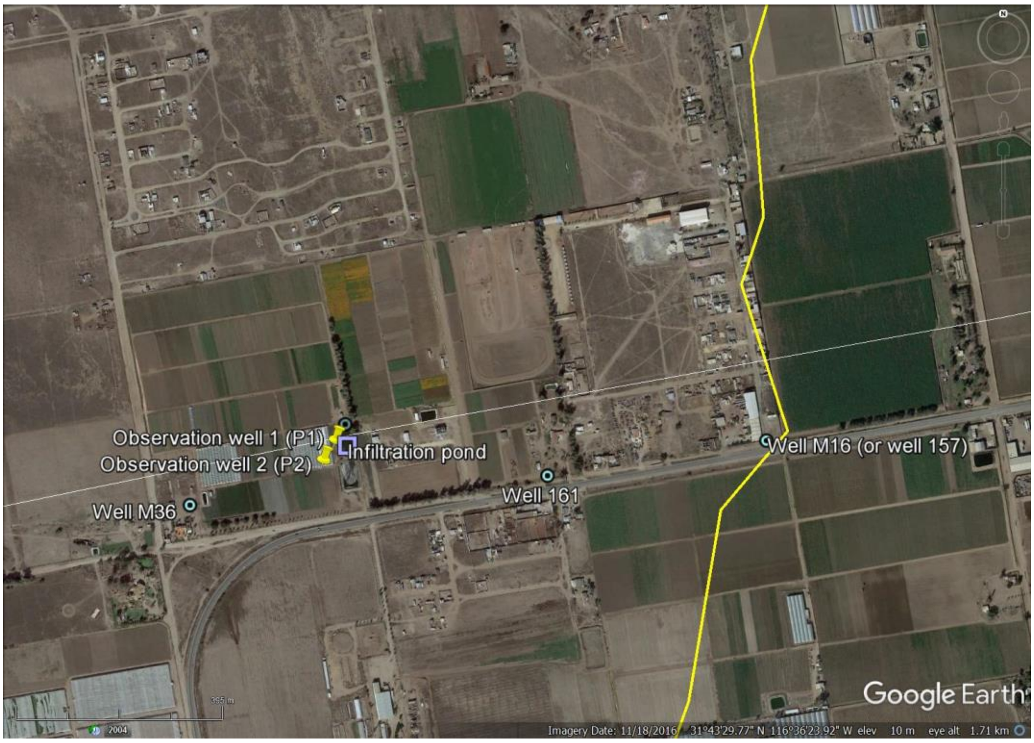


Figure 14 Location of the pumping and observation wells closest to the infiltration pond. The yellow line indicates the extension of the sea-water intrusion

Table 7. Coordinates, filter depth and TDS measured in the infiltration pond and surrounding wells

Well	Longitude	Latitude	Depth filter	Year TDS measurement	TDS
	N	E	m-surf		Ppm
M36	3509759.24	536636.83	60	2016	17000
M16/ 157	3506211.479	537744.916	48	2011	16000
161	3509818	537324	25	2011	25600
P1	3509863	536910	12	2017	3820
Pond	3509872	536939	2.5	2016	2100
Pond	3509872	536939	2.5	2014	2653
Pond	3509872	536939	2.5	2014	2776

The hydrogeological conditions found 1 km around the infiltration pond were replicated to set a model domain of 1.2km width, 4km length and 200m depth, designed to ensure enough distance to the boundaries and, therefore, less artificial impacts on the simulated fresh-salt water interface.

In order to reduce calculation times a half-domain type of model was used by which the groundwater behavior is mirrored in the other half that is not included in the model. One of the boundaries therefore passes through the infiltration pond and the two wells surrounding it (Figure 9).

The model was subdivided in 6 geological layers based on the geological description of drilling PEZA 3 and the pumping tests information. Model layer thicknesses were chosen to study the shallow subsurface in more detail. The top 6 m below surface level were assumed to be unsaturated and were not included in the model. Horizontal extent of the model cells near the wells and the infiltration pond was 10m by 10m. The porosity, horizontal and vertical conductivities (Khor/Kver), storage coefficients, and salinity are described in Table 8. These coefficients are based on the information of the pumping tests and on common values for the given lithology of drilling PEZA 3. Model dispersivity was set to 0.1m; the molecular diffusion to 8.64E-5 m^2/d. Reference density (ρ_f) was 1000 $kg/m^{3;}$ the volumetric concentration expansion gradient (β_C) was set to 0,7 (m^3/ppt salinity)

Table 8 Main parameters used in the model. The values between brackets correspond to the thickness of the model cells. BSL = below surface level

Geological Layer	Depth (m BSL)	Model Layers (thickness of cell in m)	Porosity (-)	Khor/Kver (m/d)	Storativity (-)	Salinity (ppm)
1	6 - 9	3 (1 m)	0.2	10. / 3.33	1·10-3	2,500 (2 m) 25,000 (1 m)
2	9 - 61	10 (1 m) 21 (2 m)	0.3	40. / 40.	1·10-6	25,000
3	61 - 67	3 (2 m)	0.2	10. / 3.33	1·10-4	16,000
4	67 - 81	1 (14 m)	0.3	40. / 40.	1·10-6	16,000
5	81 - 102	1 (21 m)	0.3	30. / 30.	1·10-6	16,000
6	102 - 200	2 (49 m)	0.3	30. / 30.	1·10-6	16,000

Boundary conditions were set as depicted by Figure15. The left-hand (west) side of the model was set as constant head of -6m (sea level = 6m below surface level) and constant concentration boundary, with a high salinity (TDS=25000 ppm) for simulating sea water intrusion. The right-hand (east) side of the model also was a constant head boundary. No head differences were imposed between the two boundaries since regional groundwater flow was counteracted by the surrounding pumping wells. The infiltration pond was simulated using Modflow's River Package with the parameter values included in Table 9; in which concentrations were assumed to be constant at TDS=2500ppm, i.e. the salinity of the reuse water currently fed to the pond. The pond was simulated to be 20m wide and 30m long (since we are only simulating half of the pond (real extent: 20m by 60m). To simulate the actual situation, it would have been required to model an unsaturated zone in the top 6m below surface level, while including the river package in the top few meters. However, model instabilities were encountered by the partial rewetting of model cells near the infiltration pond. It was therefore decided to simplify the model by excluding the top 6m (unsaturated zone) below surface level in the scenario studies, and to model the saturated zone only.

The three pumping wells that are aligned with the pond: M36, 161 and 157 (or M16), are located as depicted in Figure15. They were simulated to be out of operation during the model runs and only used as observation points for salinity measurements to test whether freshening will occur.

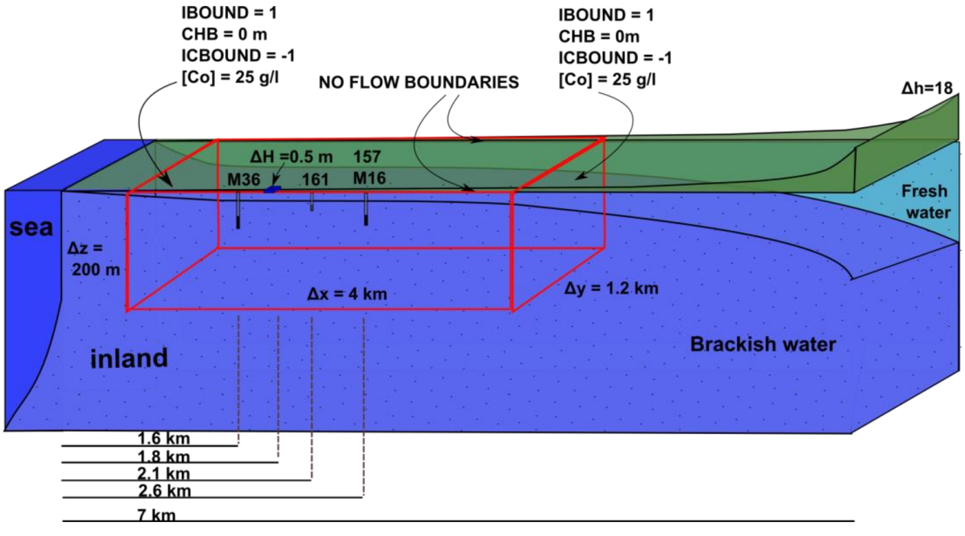


Figure15. Conceptual model of the area surrounding the infiltration pond. The red box indicates the extent of the model in a regional scheme of the area and the boundary conditions chosen

Table 9. River package parameters. Total conductance is the sum of the model cells' conductance values in m^2/day. BSL is below surface level (sea level = 6 m BSL).

Model Layer	Top (m BSL)	Bottom (m BSL)	Total conductance (m2/d)
1	5.5	7.0	30.0

9.3 Scenario modeling

The Freshkeeper (i.e. brackish water interception wells preventing salinization of (freshwater) abstraction wells) was selected as SWS solution, since the infiltration facility was already in place (the pond) and only built-up and recoverability of the infiltrated freshwater had to be provided. Several scenarios were run with different Freshkeeper configurations to acquire insight in potential freshwater production from the subsurface below the pond

9.4 Scenarios A: Freshkeeper wells at larger distance from the pond

The scenario runs involved using both Freshkeeper wells and the nearest existing abstraction wells (Figure 0-15). The idea was that Freshkeeper wells could bring the abstraction wells back to operation by increasing freshwater infiltration around the infiltration pond and deepening the fresh-salt water interface.

Different well configurations were studied:

1. Freshkeeper wells (marked red in Figure16) located just further away from the infiltration pond than the existing abstraction wells (25 m west of pumping well M36, 25m East of well M16, and 525m North of the infiltration pond scenario E1);
2. Freshkeeper wells located half-way between the existing abstraction wells and the infiltration pond, and 500m North from the infiltration pond (scenario E2);
3. Freshkeeper wells located immediately below the existing abstraction wells (Scenario E3).

These scenarios, however, rendered very poor improvement regarding freshwater infiltration, even when run for 20 years with Freshkeeper abstraction rates of 100 m^3/day. The Freshkeeper configurations proved to be too far from the infiltration pond with the given local conditions and discharge rates should be considerably higher to impact the current infiltration rate.

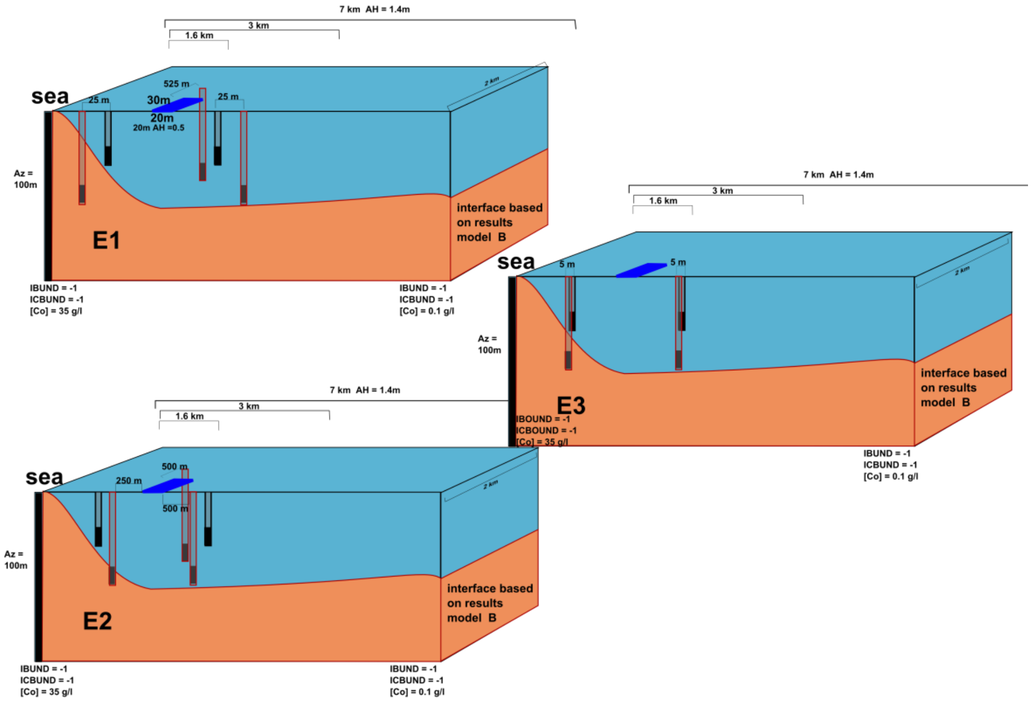


Figure16. Scenarios run with different Freshkeeper configurations related to the existing wells. The blue rectangle represents the infiltration pond, the orange part of the aquifer the brackish groundwater and the blue the expected fresh groundwater.

9.5 Scenarios B: Freshkeeper wells close to the pond

Implementation of Freshkeeper wells at a large distance from the pond did not (significantly) influence the infiltration rate at the infiltration pond and buildup of a freshwater lens. Therefore, a second Freshkeeper configuration was setup that would not employ the existing abstraction wells but would enlarge the present lens nearby the infiltration pond by abstracting deeper brackish groundwater in the vicinity of the pond. Because of the position of the wells close to the infiltration pond, it was chosen to refine the previous grid to 1m by 1m around the wells and the infiltration pond.

In total 8 scenarios (Table 9) were run. In all scenarios, saline water was abstracted by a total of four Freshkeeper wells at a distance of 20 m from the outer edges of the pond (West, North, East, and South; filter depth 41 – 51 mBSL). In half of the scenarios, shallower abstraction wells were used to recover the freshwater infiltrated from the infiltration pond (indicated by “withRecov”). The other half of the scenarios excluded direct recovery from the shallower wells (Freshkeeper wells only:

"noRecov"), and were used as a reference for the withRecov scenarios. Maximum well rates of the shallow recovery wells (filter depth: 10 to 15 m BSL) were 100 m^3/d. This freshwater recovery was automated, i.e. the wells were set to abstract only when TDS <3000 ppm. Note that this TDS is close to the salinity of the infiltrating water (2500 ppm), thus allowing for very little mixing of infiltrated water with ambient groundwater. The maximum (constant) well rates of the Freshkeeper wells were either 100 (FK100), 500 (FK500), or 1000 m^3/d (FK1000). After interpretation of these scenarios, it was chosen to include two additional scenarios with shallower Freshkeeper wells (at 25 – 35 m BSL). These shallow Freshkeeper wells were thought to improve the freshwater recovery of system. The starting salinity of the simulations is shown in Figure 17.

Table 10: Scenario runs. BSL = below surface level

Scenario name	Maximum well rate Recovery wells (m^3/d)	Freshkeeper well rate (m^3/d)	Depth of FK wells (m BSL)
1: FK100_noRecov_D	0	100	41 - 51
2: FK100_withRecov _D	100	100	41 - 51
3: FK500_noRecov_D	0	500	41 - 51
4: FK500_withRecov_D	100	500	41 - 51
5: FK1000_noRecov_D	0	1000	41 - 51
6: FK1000_withRecov_D	100	1000	41 - 51
7: FK100_noRecov_S	0	100	25 - 35
8: FK100_withRecov_S	100	100	25 - 35

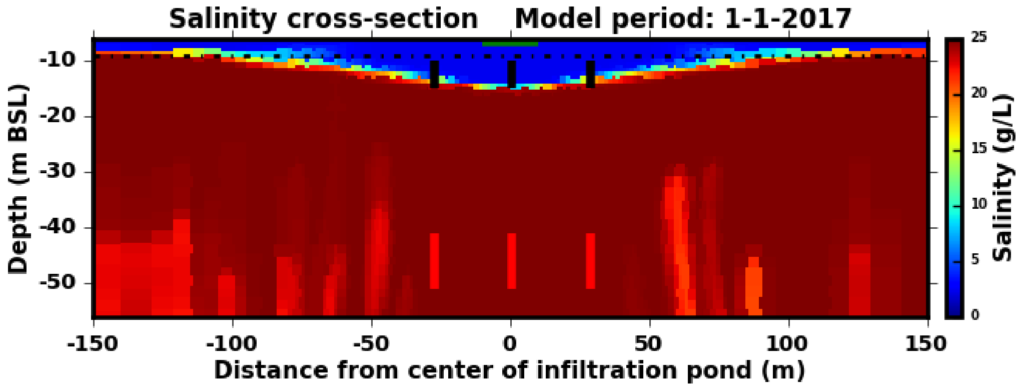


Figure 17. Reference situation after simulation of 2 years of Infiltration by the pond. The maximum depth occurrence of the lens is 15 m BSL (below surface level). The black and red markers indicate the location of the Recovery and Freshkeeper wells (studied in the "Deep" scenarios).

9.6 Scenarios B: results

The most significant model results are highlighted by using salinity cross-sections and the freshwater recovery, obtained directly from the model. For brevity, only the most distinctive model scenarios are discussed in this section. These included:

1. Scenario 1: FK100_noRecov_D
2. Scenario 2: FK100_withRecov_D
3. Scenario 6: FK1000_withRecov_D
4. Scenario 7: FK100_noRecov_S
5. Scenario 8: FK100_withRecov_S.

Scenarios 1 and 2: 100m^3/day Freshkeeper, without and with freshwater recovery

Salinity distributions (cross-sections) after 5 and 10 years of operation for scenarios 1 (FK100_noRecov_D) and 2 (FK100_withRecov_D) are presented in Figure 18 - Figure 21. The salinity distributions for both scenarios were the same, because in the FK100_withRecov_D scenario recovery of groundwater below 3000 ppm salinity was insignificant during the first 10 years of operation. The freshwater lens increased in thickness, due to the brackish water abstraction via the Freshkeeper wells, but the increase was marginal only (ca. 3 m). The lens widened as well, spanning a distance of 300m after 5 years of operation. Wide but thin lenses are difficult to manage, as indicated by the poor recoverability of the infiltrated freshwater. Both results (slight increase in thickness, widening of the lens) indicate that the buoyancy effects were hardly counteracted by the Freshkeeper abstraction. Over a period of ten years, the salinity below the freshwater lens decreased from 25000 to 16000 ppm, especially directly below the pond. This is a result both of infiltration water mixing with the ambient groundwater, as well as inflow of deeper, less saline groundwater.

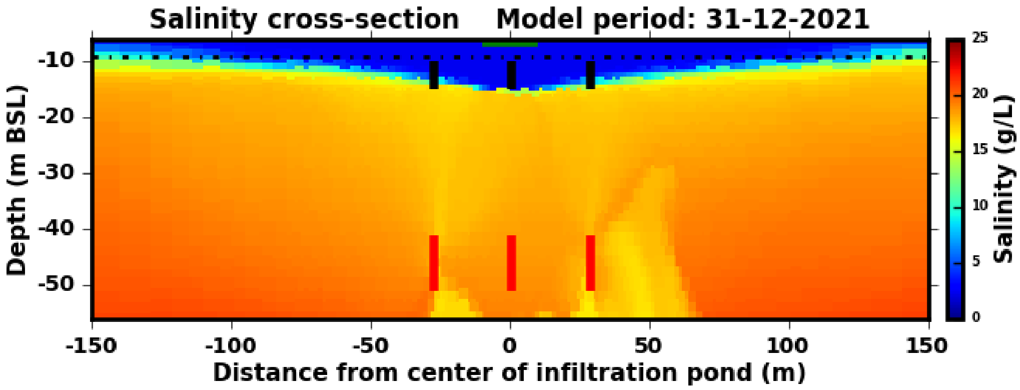


Figure 18. Salinity cross-section (W-E) through the center of the pond after 5 years of implementation of scenario 1: FK100_noRecov_D.

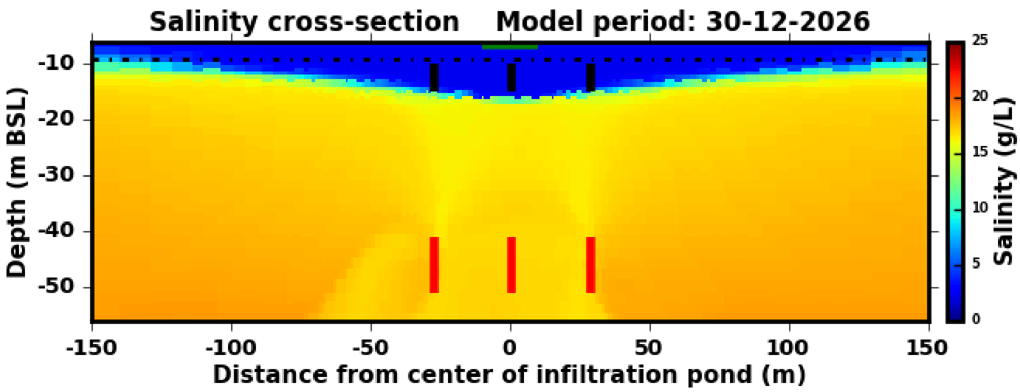


Figure 19. Salinity cross-section (W-E) through the center of the pond after 5 years of implementation of scenario 1: FK100_noRecov_D.

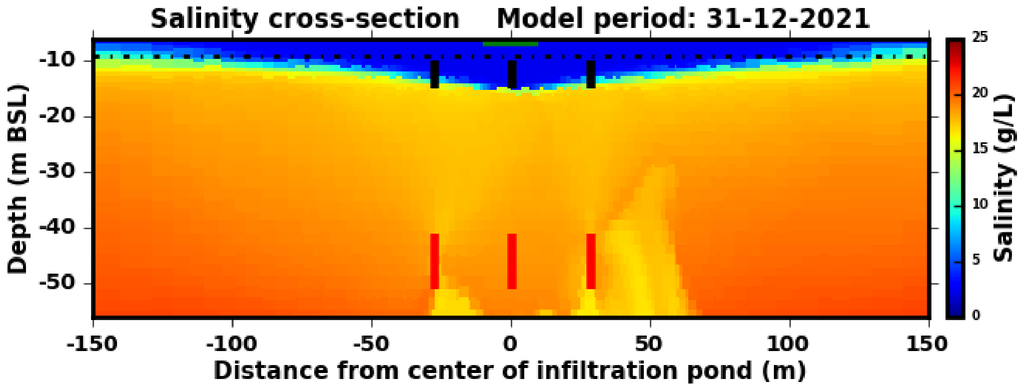


Figure 20. Salinity cross-section (W-E) through the center of the pond after 5 years of implementation of scenario 2: FK100_withRecov_D.

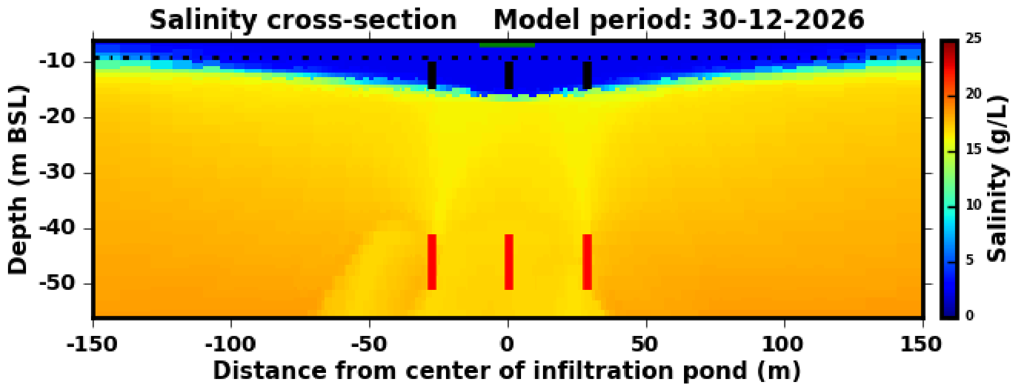


Figure 21. Salinity cross-section (W-E) through the center of the pond after 10 years of implementation of scenario 2: FK100_withRecov_D.

Scenario 6: 1000 m3/day Freshkeeper, with freshwater recovery

In scenario 6, the (brackish water) abstraction of the Freshkeeper well was set to a rate of 1000 m^3/day, to test whether a deeper freshwater lens could be formed in the Maneadero aquifer by increasing the Freshkeeper effect. Salinity distributions after 5 and 10 years of operation are shown in Figure XX and XX. The freshwater lens increased significantly in depth (below the pond up to 15 mBSL; below the Freshkeeper well up to 25 mBSL), and indeed was narrower than the previous scenarios, and centered around the infiltration pond. The high brackish water abstraction caused salinization at a distance from the pond (outside range of Figures), forming a steep fresh-salt water interface there. A significant proportion of the infiltrated freshwater was “consumed” by the deeper Freshkeeper wells, resulting in losses in otherwise recoverable freshwater. Similar to the previous scenarios, this mixing of infiltration water with the ambient groundwater and the inflow of less saline groundwater from deeper down, resulted in a decrease in salinity of the aquifer below the freshwater lens.

Despite the narrower and deeper freshwater lens, recoverability of the infiltrated freshwater was still low; the fresh-to-brackish water abstraction ratio was in the order of 4:100 only. Important causes for this low recoverability are the high salinity of the ambient groundwater (strong buoyancy effects) and the lack of confining and/or less conductive soil layers, promoting the upward from of (saline) groundwater when recovering freshwater.

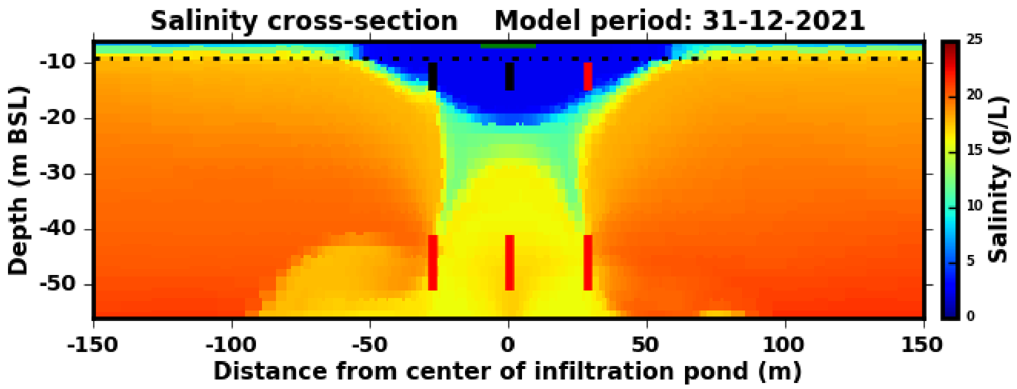


Figure 22. Salinity cross-section (W-E) through the center of the pond after 5 years of implementation of scenario 6: FK1000_withRecov_D.

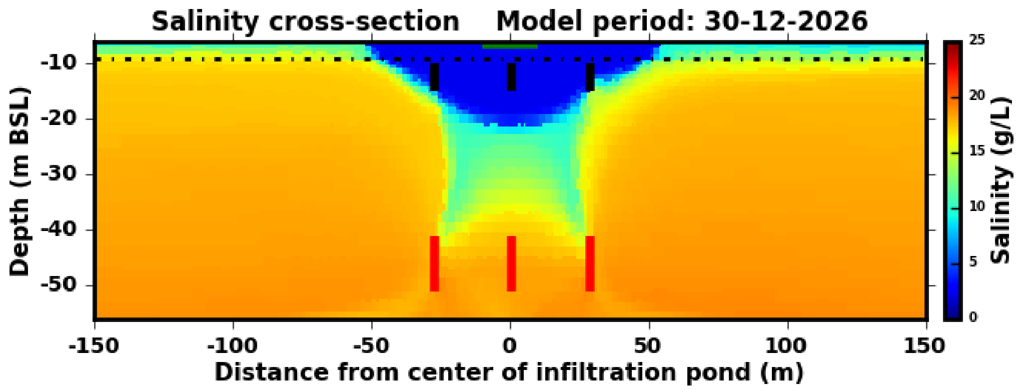


Figure 23. Salinity cross-section (W-E) through the center of the pond after 10 years of implementation of scenario 6: FK1000_withRecov_D.

Scenarios 7 and 8: shallow Freshkeeper wells

The previous scenarios all had Freshkeeper (brackish water abstraction) wells with a filter depth of 41 – 51 mBSL. A disadvantage of this relatively large filter depth was the large proportion of brackish water flowing to this well laterally and from below, making the well less efficient in counteracting the buoyancy effects and at stabilizing /

building the freshwater lens (hence the inefficient freshwater recovery). Scenarios 7 and 8 therefore included shallow Freshkeeper wells, with a filter depth of 25 – 35 mBSL. The brackish water abstraction rate of the shallow Freshkeeper well was set equal to the abstraction rate in scenarios 1 and 2, i.e. 100 m^3/day.

Salinity profiles of scenarios 7 and 8 are presented in Figures XX and XX. Similar to scenarios 1 and 2, a thin, wide freshwater lens was formed with time. Some of the infiltrated water was lost to the Freshkeeper wells and there still was a significant inflow of less saline groundwater from deeper down, but these effects were not as severe as in the previous (deep Freshkeeper) scenarios. In contrast to scenario 2, in scenario 8 (FK100_withRecov_S) it was possible frequently recover freshwater with the shallow recovery wells. The recovery efficiency was, however, still very limited: the fresh-to-brackish water abstraction ratio was in the order of 8:100 only, again stressing the challenges for efficient freshwater storage in the Maneadero aquifer.

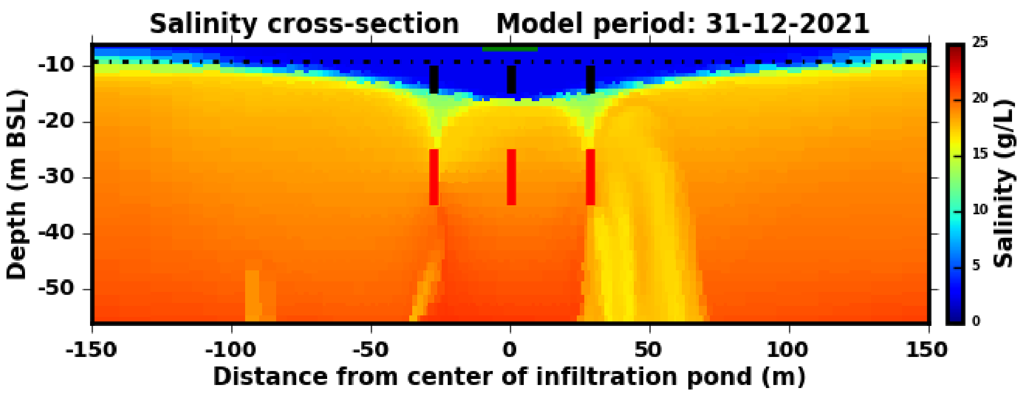


Figure 24. Salinity cross-section (W-E) through the center of the pond after 5 years of implementation of scenario 7: FK100_noRecov_S.

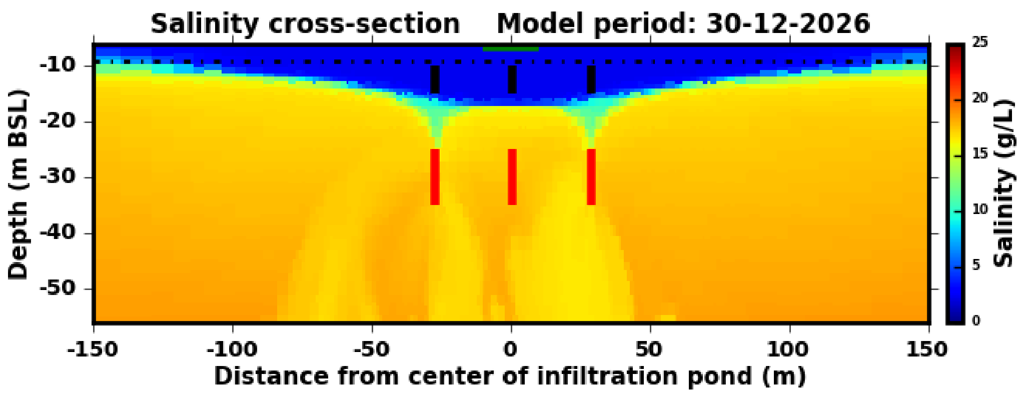


Figure 25. Salinity cross-section (W-E) through the center of the pond after 10 years of implementation of scenario 7: FK100_noRecov_S.

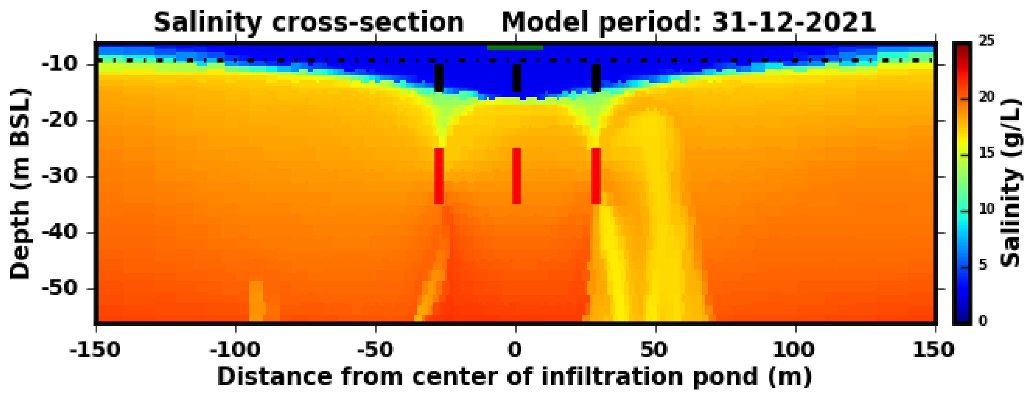


Figure 26. Salinity cross-section (W-E) through the center of the pond after 5 years of implementation of scenario 8: FK100_withRecov_S.

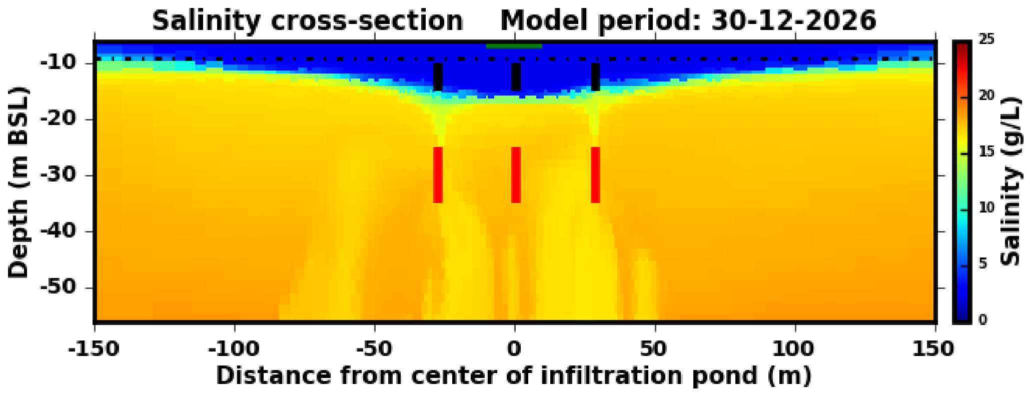


Figure 27. Salinity cross-section (W-E) through the center of the pond after 10 years of implementation of scenario 8: FK100_withRecov_S.

9.7 Lessons learned from groundwater flow modeling

The objective of the modeling study was to gain insight into the functioning of the Maneadero aquifer, the possibilities of storing and recovering freshwater in/from the aquifer, and to guide the pilot setup, including research questions to be addressed and answered. The most important lessons learned are:

1. The Maneadero aquifer as set up in the model is relatively thick and highly permeable, and seems to lack confining (or less conductive) clay layers. This is disadvantageous for realization of an effective Freshkeeper: a large proportion of the brackish water that is abstracted by a Freshkeeper well, originates from deeper down in the aquifer and it is hard to lower the hydraulic head below the pond to promote transport of freshwater to deeper parts of the aquifer. This negative effect is worse if the Freshkeeper wells are placed at a large depth below

the pond, hence the advice to place Freshkeeper wells at relatively shallow depth. Obtaining a better insight in the (local) hydrogeology and geology should be part of the pilot: often, clay layers are present but not properly detected during drilling or geophysical explorations. They can however have a strong impact on the attraction of deeper groundwater, and thereby the efficiency of the Freshkeeper.

2. In the model setup, the groundwater below the infiltration pond is highly saline, as a result of seawater intrusion. A large density difference between infiltration water and ambient groundwater can be disadvantageous for the build-up of a fresh water lens and the recoverability of the infiltrated water (strong buoyancy effects). In the simulations this was illustrated by (1) the thin, wide freshwater lenses that formed, except when Freshkeeper abstraction rates were set 1000 m^3/d, and (2) the rapid upconing of ambient, saline groundwater during recovery of the infiltrated water.

3. The salinity distributions as imposed in the model were derived from regional studies and model calibration. There is, as such, limited information on the “real” salinity distributions close to the infiltration pond, even though this significantly impacts the freshwater recovery. A pilot should provide more details on the salinity distribution close to the pond.

4. The infiltration rate was simulated and optimized using model calibration of river conductance, rather than from field observations or field test. Understanding (and controlling) the infiltration rate is crucial for design and operation of an efficient aquifer storage system in Maneadero. If infiltration rates are no longer limiting, a relatively thick freshwater lens can already be built-up because of the water level difference between pond and groundwater. Assessment and improvement of the infiltration rates should therefore be an important goal of a field pilot.

Altogether, it is concluded that based on the current worst-case insights, freshwater production from the combined infiltration pond and Freshkeeper is limited but not unviable. A detailed quantification and optimization based on a detailed characterization and small-scale pilot is required for further assessment of the feasibility.

10 Field pilot design

From the (worst-case) modelling study we concluded that freshwater production from the combined infiltration pond and Freshkeeper is not unviable, but that a detailed quantification and optimization of the model based on a detailed characterization and small-scale pilot is required for further assessment of the feasibility. Important issues to be addressed in the pilot include obtaining a better insight in the (local) hydrogeology and geology, more details on the salinity distribution close to the pond and an assessment and improvement of the infiltration rates. One of the main challenges identified for (large scale) use of reclaimed water in Maneadero Valley is the social acceptance and the farmers' concerns about pathogens that will be present in the reclaimed water. Aquifers are well capable of removing pathogens and other substances, however the removal capacity of the Maneadero aquifer has not (yet) been quantified A field pilot should thus address the Maneadero aquifer's capacity to remove pathogens and other hazardous substances from the reclaimed water, to ensure microbiological safe irrigation water.

10.1 Pilot objectives

1. Detailed characterization of the target aquifer at the reuse water pond:
   - Lithology, geochemistry
   - Hydrogeological properties / parameterization
   - Groundwater quality and potential stratification (reference situation)

2. Enlargement of freshwater lens below the reuse water pond:
   - Pull: enlargement of freshwater lens by applying the Freshkeeper concept
   - Push: enlargement of freshwater lens by improving the infiltration capacity of the pond (e.g., removing clogging material from pond floor to enhance infiltration)

3. Evaluation of chemical and microbial water quality upon aquifer passage for safe use in horticulture and compliance with regulations

10.2 Pilot design

Figure 28 shows the (preliminary) pilot setup, designed to fulfill the objectives. A Freshkeeper well is proposed just aside (approx. 5m) of the infiltration pond. This well will consist of a (brackish) water abstraction filter screen at approx. 26 – 30 mBSL, and additional piezometers (observation filters) in and below the (current) freshwater lens. In addition, a second (monitoring) well is proposed at approx. 25 m from the pond, equipped with piezometers at similar depths as those in the Freshkeeper well. The Freshkeeper well is to be used to impose different pumping scenarios that will render information on aquifer hydrogeology (objective 1) and the ability to enlarge the freshwater lens (objective 2). Piezometers in both wells enable detailed monitoring before, during and after the pilot of salinity, chemical and microbiological water quality (objective 3).

A more detailed description of this setup is provided in Table 11. Technical specifications of the Freshkeeper and additional monitoring wells are provided in Tables Table 12Table 13.

Pilot objectives, design, setup and permitting will be discussed with relevant stakeholders (COTAS, CICESE, CONAGUA) in Maneadero Valley in June 2017. In terms of permitting, the disposal of the abstracted brackish water is the main issue to be discussed, for which there are two possible options: (a) injection at distance and at a lower point in the aquifer, or (b) disposal to the ocean.

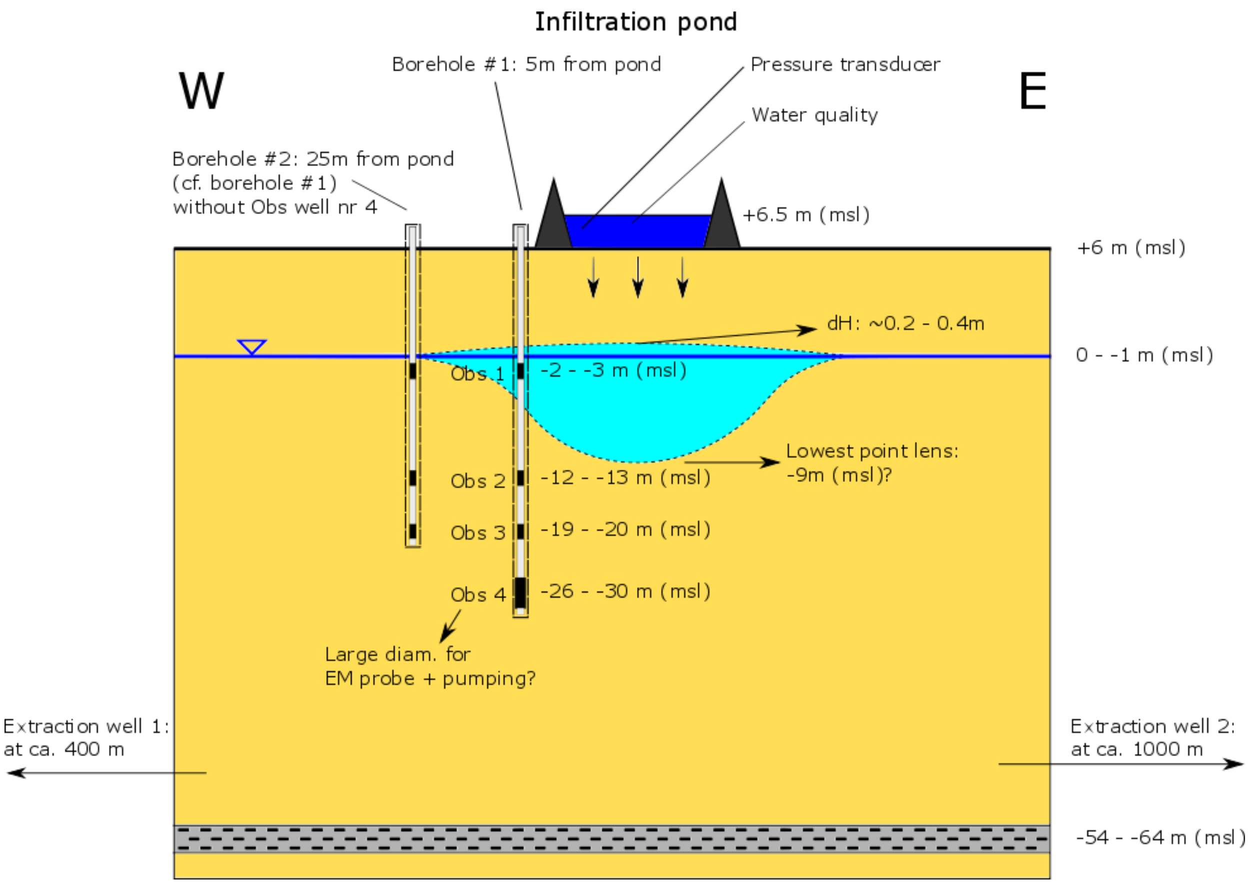


Figure 28. Sketch of set-up Pilot location Maneadero, including 2 borehole locations.

Table 11 Maneadero pilot description. Draft to be discussed with stakeholders in June 2017

1	**Detailed characterization**
1A	Drilling of two boreholes using reverse rotary drilling to • Obtain sediment samples for further lithological analysis (grain size, geochemistry) • Install monitoring wells (PVC, slotted) at various depths (separated by bentonite clay plugs) to sample the groundwater and measure the piezometric heads • Install one pumping well at approximately 35 mBSL to act as a Freshkeeper
1B	Measure water levels (piezometric heads) near basin: both manual and with sensor • Perform ‘pumping test’ with Freshkeeper and/or surrounding wells to parameterise the target aquifer
1C	Water quality stratification • Sampling for physical properties: EC, pH, temperature, turbidity, colour, smell • Sampling for chemical quality: Macrochemical composition and selection of trace elements • Geophysical (borehole/piezometer) logging (EM + natural gamma) + ERT (Electrical Resistivity Tomography)
1D	Assess the extension and thickness of a potential fouling layer at the base / floor of the pond
2	**Enlargement of freshwater lens**
2A	Action plan: • Strategy 1, ‘Pull’: Freshkeeper next to basin. Pump and dispose of the brackish-saline groundwater below the freshwater lens • Strategy 2, ‘Push’: Remove any clogging material from pond floor to enhance infiltration
2B	Monitoring during operation • Water levels (pressure transducers, hourly) • Sampling campaign and macrochemical water quality analyses (weekly) • Geophysical borehole logging / ERT • Monitoring of the pond level
3	**Microbial and chemical water quality evolution**
	• Tracing of infiltration water (optional) • Microbiological analyses on freshwater from monitoring wells and pond • Trace elements analyses on freshwater from monitoring wells and pond

Table 12: Technical specs Borehole #1

Drilling technique	**Reverse rotary**
Diameter monitoring wells	**2 inch**
Length well screen monitoring well	**1 m**
Depth monitoring wells	**-2.5, -12.5, -19.5 m-SL**
Diameter pumping well	**90 mm**
Length well screen pumping well	**4 m**
Depth well screen pumping well	**-26 to -30 m-SL**
Material	**High-class PVC (10 Ato)**
Slot size	**0.5 mm**
Grain size gravel pack	**1.1 – 1.6 mm**
Bentonite clay plugs	**Between all monitoring wells (1m)** **Seawater proof: e.g. Mikolit300 or better**

Table 13: Technical specs Borehole #2

Drilling technique	**Reverse rotary**
Diameter monitoring wells	**2.5 inch**
Length well screen monitoring well	**1 m**
Depth monitoring wells	**-2.5, -12.5, -19.5 m-SL**
Material	**High-class PVC (10 Ato)**
Slot size	**0.5 mm**
Grain size gravel pack	**1.1 – 1.6 mm**
Bentonite clay plugs	**Between all monitoring wells (1m)** **Seawater proof: e.g. Mikolit300 or better**

11 Conclusions

Drought is considered as a major risk concern globally. Nations affected by this phenomenon must change their response model from having reactive actions into creating preventive plans. In this view, Maneadero aquifer recharge is a promising solution against the drought in Baja California. Its implementation would not only ensure the water availability for food production and decrease the stress over water resources but also would reduce and counteract the salinization of the aquifer in a sustainable and cost efficient manner. The implementation of the mentioned project will require a series of actions that were addressed in this report.

First, in order to implement this project, the availability of existing water sources for infiltration had to be ensured. The water balance over the area gives a mapping of the current uses of the aquifer and proves that as projects using reclaimed water are relatively inexistent it represents a sufficiently available source for infiltration water.

Second, an evaluation of the existing law framework that would regulate the implementation of the project was performed. From this, it can be observed that the main requirements are a possible Environmental Impact Assessment presentation to SEMARNAT, the requirement of an exploitation concession by CONAGUA and the fulfillment of the water quality parameters specified by the applying NOMs. The latter was further evaluated by comparing a limited amount of available information with the specified parameters. This analysis showed some deviations for Settling solids, TSS, Total N, Total P and mercury. However, as this information is not considered to be representative and accurate, no treatment procedures were evaluated at this time.

Also, for achieving a smooth implementation of the project it is important to convince authorities and local people of its necessity. For this, an impact quantification of the drought and salinization of wells was performed showing that the project will address several problems in agricultural, social, economic and sustainable fronts. Exact economic impacts are hard to quantify and therefore were performed specifically for tomato production. Results of the analysis over the 2010-2014 period (considered the drought period) showed accumulated losses of $155MUSD plus 7,062 jobs lost and 9,164 non-used trucks. All the above-mentioned factors will have an important impact over the competitiveness level of the state.

An evaluation of the advantages for implementation of the project showed that the existing change of mind from the government has led to a series of plans and initiatives in favor of water sustainability actions. Baja California State development plan mentions specifically Maneadero aquifer recharge as a strategic project. It also considers the creation of desalinization plants as strategic, therefore it is thought that the implementation of SWS in the area has several competitive advantages as it is a more sustainable and cost efficient solution.

An important implementation challenge is the social acceptance to the use of reclaimed water as it is thought to represent health hazards in the crops and might threaten the importers acceptance towards the products. Aquifer passage promotes the removal of pathogens creating a microbiologically safe water for irrigation, yet the true capacity of the Maneadero aquifer to remove pathogens has not been quantified. A participatory Technology Assessment (pTA) is scheduled in September 2017 to discuss these and other challenges with all relevant stakeholders in Maneadero Valley.

Two reservoir (infiltration) ponds have been built by Baja State and are being fed with reclaimed water from the City of Ensenada. The current insights obtained from hydrological modelling and (worst-case) scenario analysis, indicate that freshwater production from a combined (existing) infiltration pond and Freshkeeper is limited but not unviable. A detailed quantification and optimization based on a detailed characterization and small-scale pilot is required for further assessment of the feasibility.

A field pilot design for Maneadero was drafted. Important issues to be addressed in the pilot include obtaining a better insight in the (local) hydrogeology and geology, more details on the salinity distribution close to the pond, an assessment and improvement of the infiltration rates, and of the chemical and microbiological water quality changes during infiltration and aquifer passage. The pilot design and objectives will be discussed with relevant stakeholders in June 2017.

12 **Bibliography**

CONAGUA. (National Water Comission) (2011) Agenda del Agua 2030. CONAGUA.

CONAGUA (National Water Comission) (2014) Estadísticas del agua en México. CONAGUA

Daesslé, L., et al. (2014). "A geochemical and 3D-geometry geophysical survey to assess artificial groundwater recharge potential in the Pacific coast of Baja California, Mexico." Environmental earth sciences **71**(8): 3477-3490.

FAO land and Water. Drought. http://www.fao.org/docrep/017/aq191e/aq191e.pdf

GARCIA, V. B. (2016). "Monitoreo de la pluma de agua tratada que se descarga en una zona costera del acuífero del Valle de Maneadero, Baja California, mediante métodos eléctricos."

Gil Venegas, L. (2010). Modelo numérico para determinar el impacto por la operación de pozos costeros en la zona del acuífero de Maneadero, Tesis de maestría en ciencias. Centro de Investigación Científica y Estudios Superior de Ensenada, México.

Gobierno Federal (2013) Plan nacional de desarrollo 2013-2018. Gobierno Federal.

Gobierno Municipal Ensenada, Baja California. (no date specified) Proyecto estratégico agrícola Ensenada. Gobierno Municipal

K.M. Lara and B. Weber (2010) Evaluation of sea water intrusion using Sr. Isotopes: An example from Ensenada, B.C., Mexico. Water-rock interaction

Langevin, C. D., et al. (2008). SEAWAT Version 4: A computer program for simulation of multi-species solute and heat transport, Geological Survey (US).

LUJÁN, V. and J. M. Romo (2010). "Audiomagnetotelluric investigation of seawater intrusion using 2-D inversion of invariant impedances." Geologica Acta **8**(1): 51-66.

Medellin, J et al. (2013). Pre-Feasibility Assessment of a Water Fund for the Ensenada Region: Infrastructure and Stakeholder Analyses. A Report for The Nature Conservancy. Prepared by the Center for Watershed Sciences, UC Davis.

NADM (North America Drought Monitor)

http://www1.ncdc.noaa.gov/pub/data/cbm/drought/nadm/nadm-201508.jpg

OEIDRUS (Baja California State Office of information for the rural sustainable development) (2012) Panorama general del Valle de Maneadero.

Sarmiento López, C. (1996). Modelo preliminar de Flujo tridimensional del acuífero de la planicie costera del Valle de Maneadero, B. C, México, Tesis de Maestría CICESE: 157 pp.

Schijven, J. F., G.J. Medema et al., 2000. Removal of microorganisms by deep well injection. J. Contam. Hydrol. 44: 301-327.

SEMARNAT, CONAGUA. (2014) Programa de medidas preventivas y de mitigación de la sequía. Consejo de Cuenca de Baja California y municipio de San Luís Río Colorado, Sonora.

SWFF Securing water for food. http://www.securingwaterforfood.org/the-challenge/

UABC. Avances sobre el estudio del acuífero de Maneadero ante la perspectiva de su sobreexplotación y recarga artificial. [PowerPoint slides]

Waller Barrera et al. (2009) Optimización económico-ingenieril del suministro agrícola y urbano: una aplicación de reuso del agua en Ensenada, Baja California, México. Ingeniería Hidráulica en México.

Van der Wielen, P.W.J.J., Senden, W.J.M.K and G.J. Medema, 2009. Removal of bacteriophages MS2 and ΦX174 during transport in a sandy anoxic aquifer. Environ. Sci. Technol. 42: 4589-4594

Appendix A- Economic impact quantification

The economic impact quantifications were performed exclusively based on tomato production decrease in Ensenada. Yearly production decreases were calculated using 2010 production values as a base line as drought period is consider to start in late 2010. After these values were calculated, they were converted into equivalents based on the following assumptions:

Jobs lost

Job losses were calculated with an average estimate of 7.5persons/ha required for food production. The final estimation of jobs lost is given by the average lost over the period.

Fertilizer and pesticide sales lost

Fertilizer and pesticides costs per hectare were extracted from a 2010 cost analysis of tomato production in Baja California (Gobierno Municipal Ensenada, NO date) and adjusted using the yearly average inflation (Table 16)

Product sale losses

Monetary losses were calculated using the yearly average cost/ton published by SAGARPA

Non-used trucks As Maneadero production is mainly for exportation purposes, non-used trucks equivalent were calculated using the maximum permissible capacity for tomato exportation to US, 22Ton/truck.

Impacts can be divided in two subcategories: related to harvested surface and related on production volume Table 14 and

Table 15 show the details for each case and Table 16 shows the average yearly values for inflation and exchange rates for MXN/USD and MXN/EUR.

Table 14 Economic impacts related to Harvested surface reduction

Year	Harvested Surface (Ha)	Ha reduction[1]	Jobs lost[2]	Fertilizer cost/ha [MXN][3]	Fertilizer sales lost [MXN][3]	Pesticide cost/ha [MXN][3]	Pesticide sales lost (MXN)
2010	3,525			50,950		17,979	
2011	2,685	-840.14	(6,301.05)	53,192	(44,688,559)	18,770	(15,769,492)
2012	2,914	-611.00	(4,582.50)	55,224	(33,741,697)	19,487	(11,906,614)
2013	2,759	-766.30	(5,747.25)	57,195	(43,828,692)	20,183	(15,466,066)
2014	1,976	-1,549.30	(11,619.75)	59,466	(92,130,463)	20,984	(32,510,571)

[1]Compared to 2010 as standard

[2]Considering 7.5 persons/ha

[3]Data of 2010, adjusted by inflation

Table 15Economic impacts related to Production volume reduction

Year	Production Volume (Tonne)	Tonne reduction[1]	Price ($/Tonne)	Product sale losses (MXN)	Non used trucks[4]
2010	220,754		11,428		
2011	161,942	(58,812)	5,906	(347,349,324.42)	(2,673)
2012	188,970	(31,784)	7,798	(247,857,126)	(1,445)
2013	195,464	(25,290)	8,717	(220,464,222)	(1,150)
2014	135,030	(85,724)	10,644	(912,422,561)	(3,897)

[1]Compared to 2010 as standard

[4]Considering 22Ton/truck (maximum permissible for exportations to US)

Table 16 Average yearly Inflation and exchange rates (MXN/USD and MXN/EUR)

Year	Inflation [%][5,6]	MXP/USD[5]	MXN/EUR[5]
2010	4.4	12.63	16.73
2011	3.82	12.42	17.28
2012	3.57	13.17	16.91
2013	3.97	12.77	16.96
2014	4.08	13.30	17.66

[5] yearly average Source: BANXICO

[6] Based on INPC general index