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# Socio-hydrological resilience of an arid aquifer system, subject to changing climate and inadequate agricultural management: A case study from the Valley of Santo Domingo, Mexico

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ABSTRACT

Mismanagement has caused the overexploitation of one third of the major aquifers in Mexico, mainly due to excessive water extraction for agricultural irrigation. Santo Domingo (Baja California Sur, in northern Mexico, where agriculture absorbs nearly 80% of water) is the only aquifer in the Mexico where, after a period of overexploitation, equality between extraction and recharge rates was achieved, although this has not meant the securement of long-term water availability. This paper offers an analysis of hydrological resilience of a water-limited arid ecosystem under future extraction scenarios and changing climate conditions. A regional groundwater flow model is proposed using MODFLOW software. Then, different indicators were modeled as outcomes of coupled human-water systems to predict water trajectories under different human impacts. The aim was to recognize water insecurity scenarios and define appropriate actions to a more sustainable use of this scarce resource in the region. Thus, although runoff derived from extreme floods may favor infiltration, the involvement of local stakeholders and decision makers to reverse the adverse impacts of current water management and climate change is imperative if water availability and better quality are to be secured.

## 1. Introduction

Mismanagement has caused the overexploitation of 36% of the major aquifers in Mexico, mainly due to excessive water extraction for agricultural irrigation. In the case of coastal aquifers, this has led to seawater intrusion, increasing groundwater mineralization, less drinking water, and reduced irrigation sources (Cardona et al., 2004). Although dealing with complex human-impacted water systems, aquifer maximum groundwater availability in Mexico is defined in terms of a simple water balance concept. In this context, after 40 years of overexploitation, Santo Domingo (Baja California Sur, in northern Mexico, where agriculture absorbs nearly 80% of water) is the only aquifer in the country where equality between where the extraction- and recharge rates have been balanced. But secure long term water availability is a multi-faceted problem that goes beyond mere balancing of supply and demand to include the assessment of resilience to climate change and identification of adaptation measures. This assessment depends on a holistic approach to water resource management that involves local stakeholders and decision makers.

The main objective of this paper is to quantify the hydrological resilience of this water-limited arid ecosystem under future extraction scenarios and changing climate conditions, through a model that includes socially-sustainable management practices. This approach is important since, in a context of long-range predictions, the goal should be to provide alternative strategies and plausible and co-evolving trajectories of the socio-hydrological system, a holisticsocio-hydrological approach is important for providing alternative strategies and plausible and co-evolving trajectories of the socio-hydrological system, which will indicate cause-effect relationships and help stakeholders identify most desirable operating alternatives (Srinivasanet al., 2017). Limitations of the model relates to uncertainties linked to human-induced changes (Mao et al., 2017), as in case of climate change, where there is uncertainty as to where and how the impacts will occur, or the severity (Tye and Altamirano, 2017).

A central part of the methodology is the construction of a regional groundwater flow model, which represents an area of 10,781 km$^2$, using MODFLOW software. The database includes information on the irrigated area and type of crops, water consumption, soil texture and chemistry and water quality at 600 ranches in the irrigation district. These indicators were modeled as outcomes of coupled human-water systems to predict water trajectories

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under different human impacts in order to recognize water insecurity scenarios and define appropriate actions to a more sustainable use of this scarce resource in the region.

Yet, this situation may not occur under natural conditions as future scenarios indicate, calling for needed changes in water management and practices. Thus, we present actions to be implemented that allow, based on a socio-hydrological approach, the participation of stakeholders at multiple scales to facilitate improved feedback between the water sector and society.

## 2. Socio-hydrological resilience as a conceptual framework

It is widely accepted that integrated approaches can lead to sustainability. Sustainability is defined as a requirement of our generation to manage the resource base such that the average quality of life that we ensure ourselves can potentially be shared by all future generations. [...] Development is sustainable if it involves a non-decreasing average quality of life (Asheim, 1994). Hence, there is wide consensus on the need for multidisciplinary or multidimensional water resources management. Buytaert et al. (2014) and Paul et al. (2017) argue that water management problems are no longer predominantly addressed as technical issues, but have become part of a complex policy process in which different stakeholders and institutions are involved (Norgaard, 1981; Walker et al., 2004; Manson, 2008; Sandker et al., 2010) Sustainable growth is only conceivable if accompanied by the satisfaction of those cultural and material needs that are indispensable for all individuals (Sharma and Sharma, 2011, Jonathan et al., 2017) to live with the self-esteem to which every individual is entitled. Sivapalan et al. (2012, 2014) have foregrounded the human role in the water cycle by establishing "socio-hydrology" as a perspective to understand the complex approach in the hydrological resource management aimed to create resilience.

In this paper, we adopt socio-hydrology resilience for understanding and assessing resilience in combined socio-hydrological contexts (Mao et al., 2017), and apply it to the case study of Santo Domingo aquifer. Resilience is the capacity of individuals, ecosystems, or human communities "to persist in the face of change, to continue to develop with ever-changing environments" (Folke, 2016). As Mao et al. (2017) recall, this concept is understood as a set of systemic absorptive, adaptive, and transformative capacities in three dimensions: persistence for now, and response for future contingencies in incremental or in radical ways. Hydrological resilience is the ability of a catchment to absorb disturbance and maintain or quickly regain hydrologic function. It also provides new insights into the clarification and evaluation of different water management challenges (Mao et al., 2017).

According to such definition, we make reference to three resilience framings for different types of human–water systems and subsystems: (1) *water subsystem*, the hydrological resilience to anthropogenic impacts; (2) *human subsystem*, the social resilience to hydrological hazards and stress and (3) *combined human–water system*, which is explored using a strengths, weaknesses, opportunities and threats approach as a tool to enhance socio-hydrological resilience. Particularly important is the third type that emphasizes the interactions between human and water components within complex systems subject to internal or external disturbances. We argue that the combined water-human system is the most appropriate tool to design strategies for resilient management of the hydrological resources of Santo Domingo aquifer. Climate change or increased human hazards may degrade aquatic ecosystems or propel them to irreversible undesired end states (Magombeyi et al., 2006;), prompting a need to consider options for resilient socio-hydrological water management (Folke et al., 2010; Fernald et al., 2015).

## 3. Methodology

### *3.1. Santo Domingo aquifer as the area of study*

The Valley of Santo Domingo is located in the middle of the Mexican state of Baja California Sur, in the municipality of Comondú. The climate is characterized by very arid conditions (warm climate at the coast to temperate climate in the Sierra La Giganta mountain range), with a temperature interval ranging from an average maximum of 43.3 °C to a low of 1.89 °C. The predominant natural vegetation in the arid and semi-arid zone is Sarcocaulescent Scrubland. The average annual rainfall reaches only 150 mm (the range of precipitation is between 50 and 300 mm per year), of which 30% occurs in the winter and 70% during summer (CNA, 2002). In the summer season, runoff is frequently generated from rainfall caused mainly by tropical cyclones; the hurricane season begins in mid-May and ends in November (Wurl and Martínez Gutiérrez, 2006).

The Valley of Santo Domingo is subdivided into three watersheds: Santo Domingo in the north, Las Bramonas in the middle, and the Santa Cruz watershed in the south (Fig. 1).

The uncontrolled extraction of groundwater, and especially the over-exploitation of the Santo Domingo aquifer from 1957 onwards has caused modifications to the natural flow system and induced a lateral inflow of seawater from the Pacific coast. As a result the groundwater quality in the Santo Domingo Irrigation District (0 6 6) is deteriorating.

The Valle de Santo Domingo represents the most important region for agricultural and livestock in the state, where agricultural activities cover an area of 72.409 ha. The first wells for agriculture use were installed in the late 1940s; two decades later, water withdrawals had already reached 250 million $m^3$ per year, which significantly exceeds the annual average recharge of 188 million $m^3$ estimated by the Mexican National Water Commission (CNA, 2002). In the 1970s, the number of wells was above 500 units, and extractions reached about 300 million $m^3$ per year. The highest extractions occurred in the late 1980s, with withdrawals of up to 450 million $m^3$ per year, 2.4 times the annual average recharge; over-exploitation between 1956 and 2002 meant a deficit of 4753 million $m^3$ of groundwater (SEMARNAP, 1996).

A gradual reduction in the extraction rate began in the 1990s in order to reduce the negative effects of over-pumping and to achieve an equal balance between recharge and extraction (Fig. 2). Although equilibrium in respect to the medium annual recharge rate was finally achieved in 2003, the extraction rate nearly equaled the estimated recharge rate of 188 million $m^3$ per year in the following years; the cone of depression stopped increasing its volume, but its size still grews, and its center deepenes. As a result of a 50-year over-exploitation, a change in the hydrochemical composition of groundwater has been observed (ACSA, 1969; TMI, 1978; DESISA, 1997; Cardona et al., 2004) due tu sea water intrusion, water returns derived from irrigation, and the mobilization of deeper groundwater with higher mineralization (SEMARNAP, 1996; Cardona et al., 2004; Wurl et al., 2008).

The recharge of groundwater depends on intense rainfall events which are produced by tropical cyclones, characterized by high intensity and short duration. Storm water enters rapidly into the valley's drainage system (ephemeral or intermittent streambeds, called arroyos) but, due to geomorphological conditions, subsurface drainage is generally incapable to infiltrate an important part of the runoff, which then flows into the Pacific Ocean.

Geomorphologically, Valley of Santo Domingo is divided into two main units: the upper parts (hills, plateaus, and hillocks of the Sierra La Giganta Mountains) are mainly composed of volcanic rocks, tuffaceous sandstones, and agglomerates of fine to medium

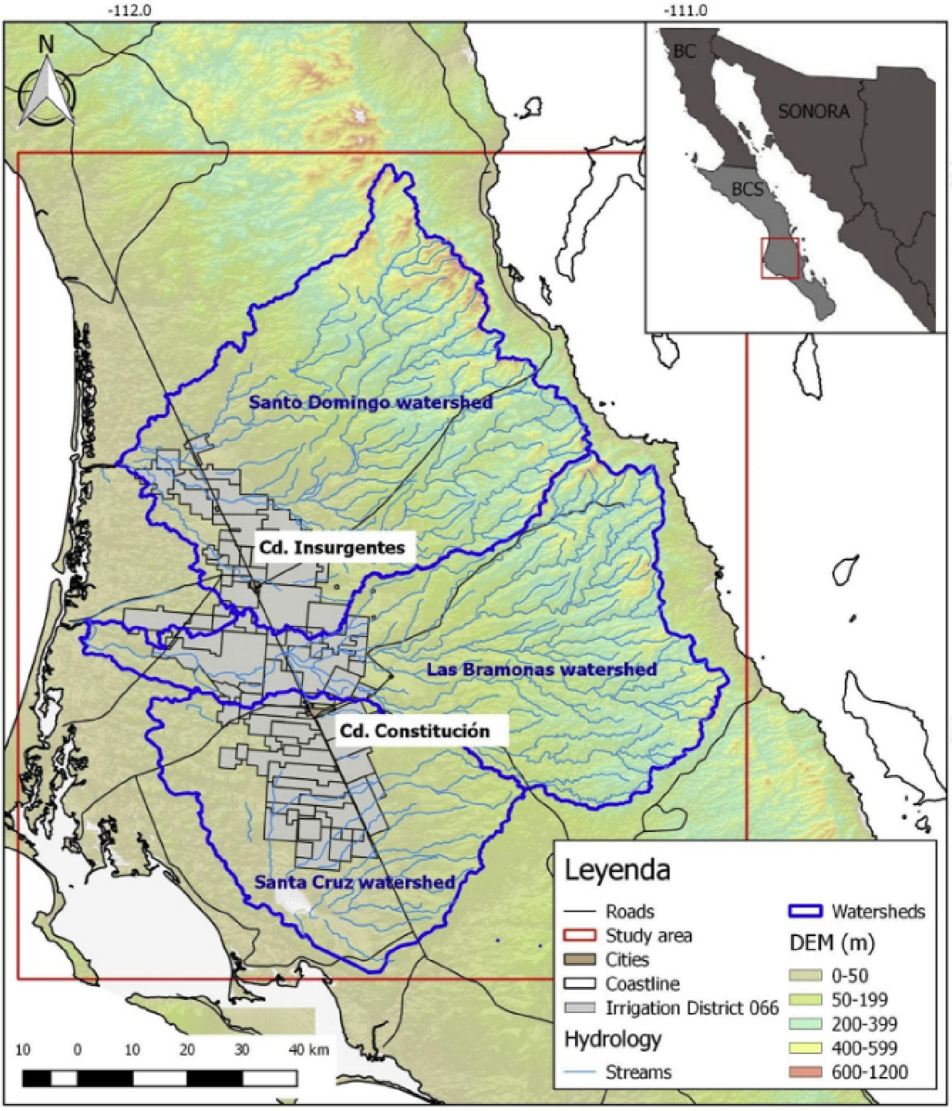

**Fig. 1.** Major cities, important watersheds and geohydrological features in the Valley of Santo Domingo.

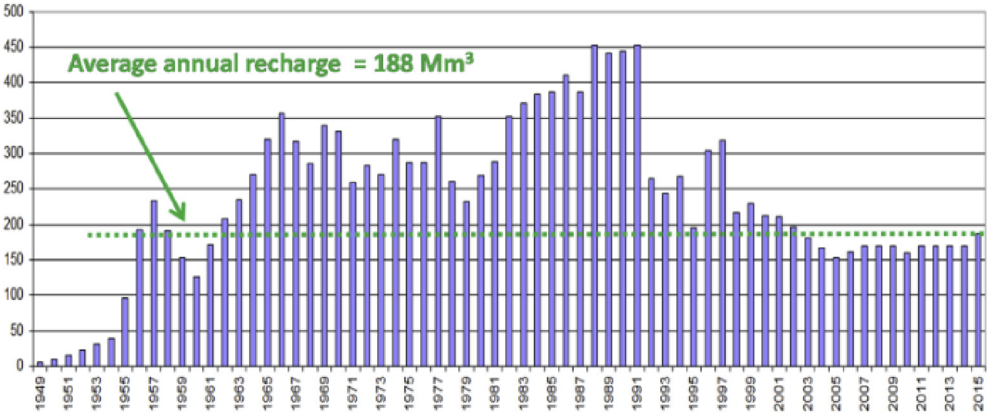

**Fig. 2.** Extraction rate (millions of cubic meters per year) of groundwater in the Valley of Santo Domingo between 1949 and 2015).

grain, with low infiltration capacity. The lower parts form a coastal plain of unconsolidated sediments, derived from the Sierra La Giganta, that covers sedimentary rocks. High infiltration capacities characterize this unit.

### *3.1.1. Climate variability and environmental change*

According to estimates of the IPCC a decrease in the annual rainfall rate in several geographical areas is expected, leading to a deficit in available water. A lower annual precipitation implies that the aquifers will tend to decrease in recharge and cause a deficit, amplifying the imbalance in water systems. On the contrary, an excess of rainwater may cause negative impacts to the population due to torrential floods that would eventually affect urban areas.

The two models selected for the comparison of probable climate changes in the near and far future for the study area are the HADGEM2-ES model and the REA assembly (Giorgi and Mearns, 2002), whose adaptation was established in reference to the climatological database of the National Meteorological Service (SMN, 1961–2000). The REA assembly model for Mexico is based on information from 15 MGC (details on the methodology and weighting are given by Conde et al., 2011).

The HADGEM2-ES model for the study area (Figs. 3 and 4) shows notable differences in future estimates of temperature and precipitation with respect to the REA assembly (Figs. 3 and 4), which behaves more discreetly.

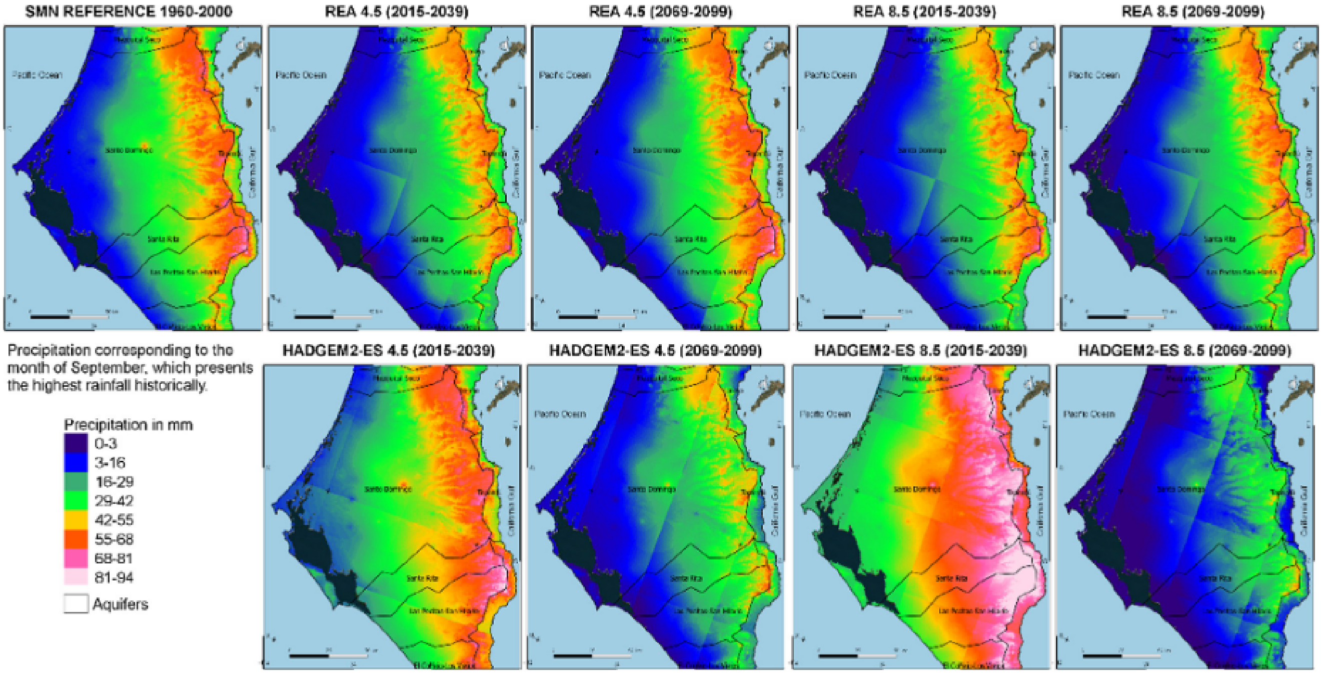

**Fig. 3.** Current average monthly precipitation of the wettest period and the trends indicated by the future climate change scenarios (2015–2039, 2065–2099) in a concentration path (RCP) at 4.5 and 8.5 W/m$^2$ (raster database after Fernández Eguiarte et al., 2015).

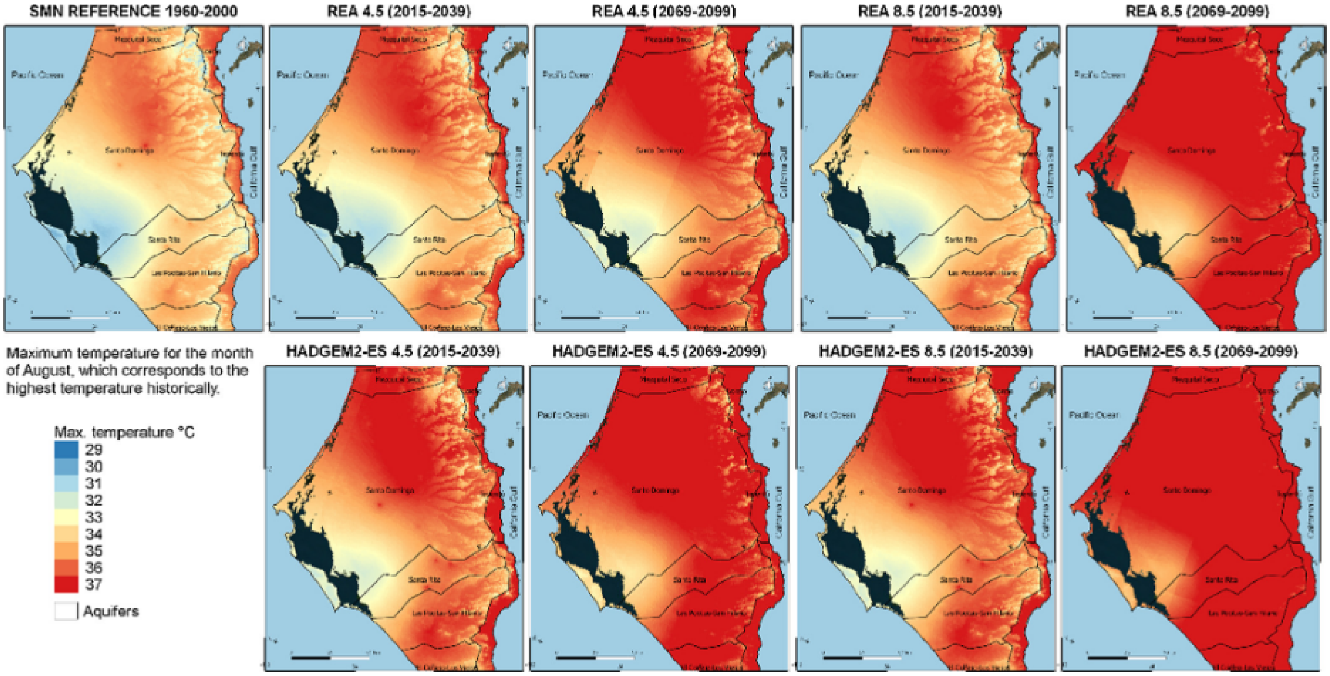

**Fig. 4.** Current maximum monthly temperature of the warmest period and the trends indicated by future climate change scenarios (2015–2039, 2065–2099) in a concentration path (RCP) at 4.5 and 8.5 W/m$^2$ (raster database after Fernández Eguiarte et al., 2015).

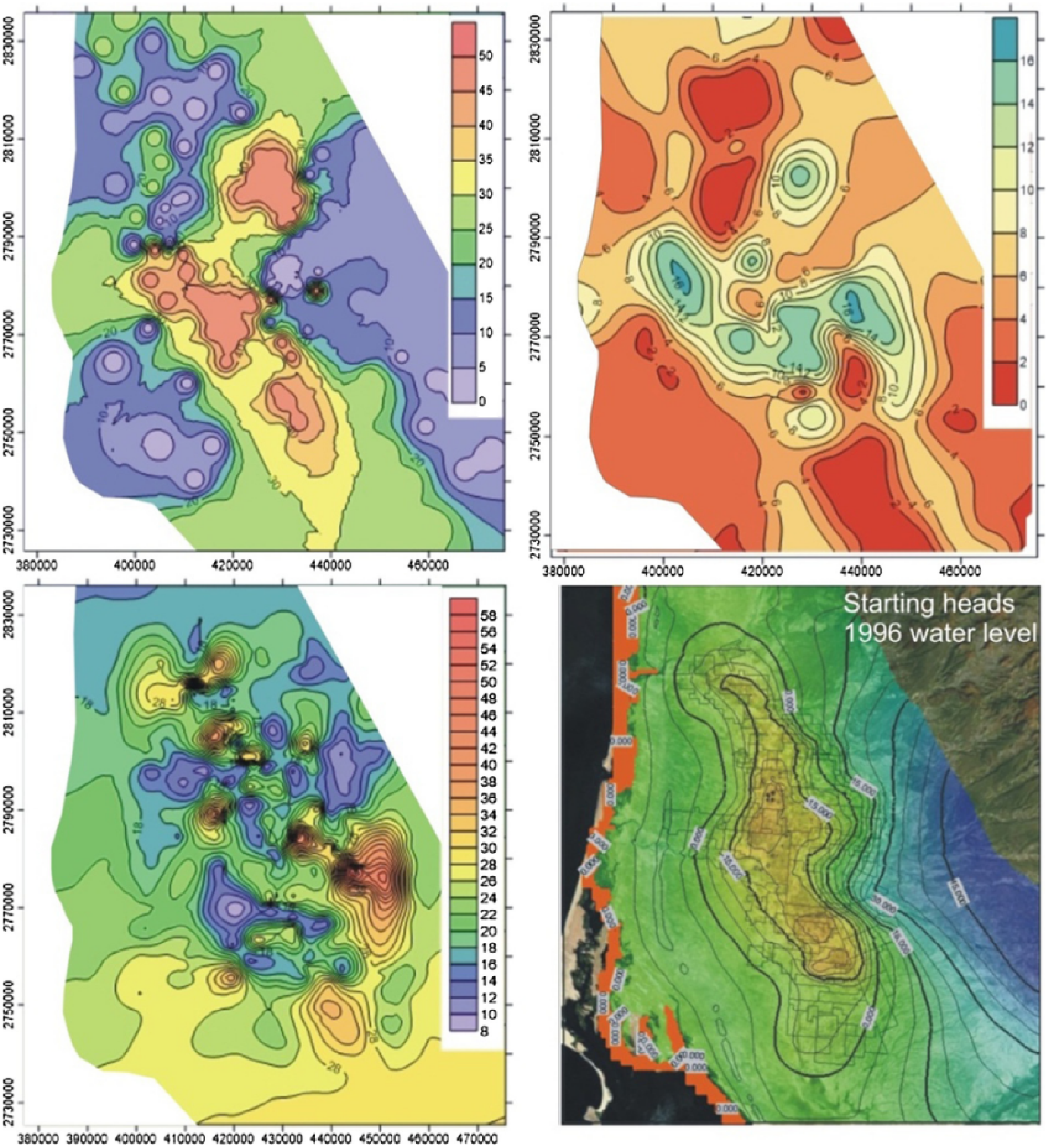

**Fig. 5.** Hydraulic parameters and starting heads in the modeled aquifer (Valley of Santo Domingo) after the calibration. Top left is specific storage, top right specific yield, bottom left is hydraulic conductivity and bottom right are the starting heads.

### *3.2. Groundwater model*

To understand the hydraulic behavior of seawater intrusion, a groundwater model was developed to model different recharge reduction scenarios according to the REA Assemblage RCP 8.5 provided by National Institute of Ecology and Climate Change (INECC, 2013; 2014), which estimated a rainfall mean reduction up to 37% for the short-term future. In the manual calibration process the hydraulic conductivity, specific yield, and specific storage were used in order to achieve the observed hydraulic head levels during the period 1996–2013. Modeled scenarios were the years 2020, 2030, 2040 and 2050 in order to define a critic date when the drawdown cone will reach the coast increasing the inflow of seawater into the aquifer.

#### *3.2.1. Model design*

The groundwater model was constructed using Modflow-2000 and includes the following two natural boundaries: the coastline of the Pacific Ocean to the west, and the fractured aquitard of the Sierra de la Giganta Mountains to the east (Fig. 3). Sea level was simulated with specific head conditions at the coastline. The starting heads were obtained from SEMARNAP (1996); to the north, south, and east the model is limited by no flow conditions, where an influx can be neglected. The finite difference mesh consisted of 221 columns and 197 rows with a size of 500 m per cell so that the model includes 43,537 cells and represents an area of 10,781 km$^2$. The initial conditions of the model were the 1996 water levels provided by CONAGUA.

The top of the aquifer was recalculated from a Digital Elevation Model with a resolution of 30 m, obtained from INEGI. The thickness of the aquifer was defined from bore logs and based on geologic cross sections and the re-interpretation of resistivity soundings, documented in SEMARNAP (1996).

### 3.2.2. Hydraulic parameters

The initial specific yield and specific storage were obtained from SEMARNAP (1996) and introduced cell by cell. After the calibration step, specific storage and specific yield values are ranging between 0.0008 to 0043 $m^{-1}$ and 0.07 to 0.26, respectively (Fig. 5).

The hydraulic conductivity was calculated from the textural classification data of 554 sediment samples taken in the Valley of Santo Domingo, applying the methodology from Shiozawa and Campbell (1991). The resulting values range from 8 to 58 m/d (see Fig. 5).

### 3.2.3. Recharge

According to CONAGUA (2015), the average annual recharge of the aquifer in the Valley of Santo Domingo is 188 million $m^3$, of which 77% correspond to natural infiltration, while the remaining 23% are due to an irrigation return flow (CONAGUA, 2015). This recharge results from four different processes: recharge from direct infiltration of rainfall, recharge resulting from the infiltration of surface water in the arroyos after storm events, horizontal groundwater flow from the Sierra de la Giganta aquitard, and seawater intrusion from the river mouths of the arroyos Santo Domingo and Las Bramonas into the aquifer. The recharge package was used to simulate recharge from direct infiltration of rainfall. The recharge resulting from the infiltration of surface water in the arroyos after storm events was simulated through the streamflow package (STR1) which uses Darcy's law and assumes a continuous stream flow from the stream surface to the aquifer and calculates its corresponding volume introduced into the aquifer Prudic et al. (2004). The main drainage system was introduced into the groundwater model and based on the streamflow module results from synthetic hydrographs, calculated with the amount of surface water generated in the watershed of the Sierra La Giganta Mountains were calculated with the HEC – 1 program 1 (HEC, 1990) taken in account different rainfall scenarios; the relation between precipitation and total runoff volume was reported from [3]. Runoff rates introduced to STR1 were obtained from synthetic hydrographs calculated with HEC-1 (HEC, 1990) and taken different rainfall scenarios; the relation between precipitation and total runoff volume was reported from SEMARNAP (1996). Horizontal groundwater flow from Sierra de la Giganta fractured aquifer was simulated with a volume of 40 $Mm^3$ per year as influx to the model.

### 3.2.4. Extractions and time steps

A total of 710 wells and the corresponding extraction rates were introduced into the model, taking in account the variations, observed between 1996 (SEMARNAP, 1996) and 2007. From 2008 onwards, we assumed near equilibrium conditions as indicated by CONAGUA (2015) for the future scenarios. A 23% of the extractions were reduced in order to simulate an irrigation return flow. For each year, the model includes infiltration caused by runoff (calculated based on the maximum the rain events and obtained from the hydrological model during a maximum of 10 days.

### 3.2.5. Calibration and prognostic run

Well head data observed between 1996 and 2007were obtained by the National Water Commission (CONAGUA) and the 2013 data were obtained from García-Martínez (2014) to calibrate the model in transient state mode. For each year, the model includes infiltration caused by runoff (calculated based on the maximum the rain events and obtained from the hydrological model) during a maximum of 10 days. The original hydraulic parameters were calibrated. After calibration step, the reduction of recharge scenarios due to climate change was simulated. The estimation of seawater intrusion for the Santo Domingo arroyo rivermouth was calculated with the water balance of this specific zone, considering an inverse flow of water levels.

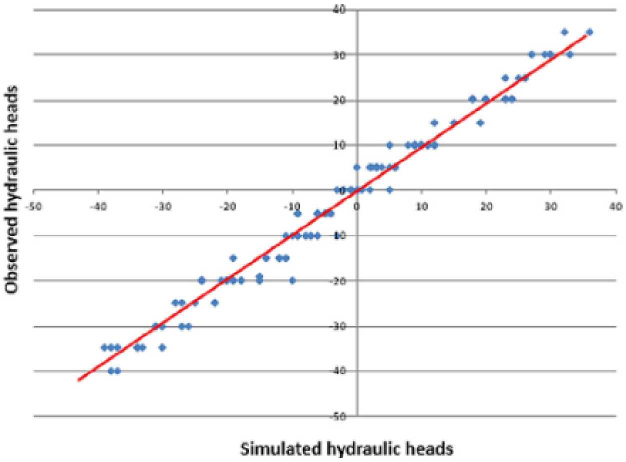

**Fig. 6.** Difference between calculated and the observed levels using 119 randomly chosen points for the year 2013.

In the manual calibration process the hydraulic conductivity, specific yield, and specific storage were changed by zones to achieve a concordance between the observed and simulated hydraulic head levels during the period 1996–2013. A total of 119 randomly chosen points were selected for each year of calibration. After the model calibration, different scenarios were generated maintaining or reducing extraction rates. The difference between the calculated and the observed levels at 119 randomly chosen points for the year 2013 is presented in Fig. 6.

### 3.2. Hydrochemical analysis

The composition of major ions in ground water permits to determine the relation between the groundwater and intruded seawater in coastal aquifers, especially the total mineralization, $Na^+$, and $Cl^-$. CONAGUA provided us with the concentrations of the macro-constituents in 4375 ground water analyses, taken from 710 agriculture wells between 1986 and 2005, which were interpreted with respect to changes in the groundwater composition. This interpretation is based on Piper Ternary diagrams, maps of sodium and chloride concentrations in groundwater and the ratio of $Cl/(HCO_3 + CO_3)$ as an indicator to define seawater intrusion, as proposed by Bear et al. (1999).

## 4. The role of stakeholder engagement in water use assessment and resilience strategies design

The term *participation* typically refers to some aspect of local community involvement in the design, implementation, and evaluation of a project or plan (Brown and Wyckoff-Baird, 1992). *Public participation* encompasses a range of procedures and methods designed to consult, involve, and inform the public to allow those that would be potentially affected by a decision or policy to have input into the process. The latter is also known as stakeholders (IAP, 2007). Public participation or stakeholder's engagement involves both individual and group input (Carr, 2015; Krueger et al., 2016).

Stakeholders' participation is key to evaluating resilience in any system. Adaptation is a process by which strategies to moderate, cope with and take advantage of the consequences of climatic events are enhanced, developed and implemented (Conde and Lohsdale, 2005). Adaptation occurs through public policy-making and decisions made by stakeholders, i.e., individuals, groups, organizations (governmental agencies or non-governmental organizations (NGOs)) and their networks. Relevant stakeholders need to be brought together to evaluate the resilience and to identify the most appropriate forms of adaptation (Jones et al., 2001). Analysing the capacity of stakeholders to cope with and adapt to climatic events is fundamental to characterizing current and possible future resilience (Jones, 2000). Understanding the role of stakeholders in the decision-making process will assist in the implementation of adaptation policies. In short, stakeholders are central to the resilience assessment and adaptation process. In order to assess social resilience regarding the water system, we used SWOT (strengths, weaknesses, opportunities, threats) analysis as part of socio-hydrological resiliency planning. The main idea of the analysis is to see how to maximize opportunities and efficiently protect against threats. According to David (1997), building an assessment matrix allows the formulation of future improvement and development strategies. During the process, we were seeking and valuing diverse voices, making a special effort to hear and understand those who, for various reasons, may otherwise go unheard. The stakeholders were selected by following criteria: (1) they represent a particular community or an important subgroup of population of the Santo Domingo Valley; (2) they would provide technical knowledge and / or essential information to the process; (3) to ensure the coherence of the project; (4) to ensure the application of the project, (5) because they are holders of rights in the project area. The following key principles were considered in the implementation of the public participation or stakeholder engagement process (IFC, 2007):

- Providing meaningful information in a format and language that is readily understandable and tailored to the needs of the target stakeholder group(s). An accessible slide presentation was delivered to the stakeholders before the meeting.
- Providing information in advance of consultation activities and decision-making. Some of the results were shared in advance with NGOs and business sector by e-mail.
- Disseminating information in ways and locations that allow ease of access by stakeholders. The main results and related data were uploaded to the website of the University and municipality.
- Respect for local traditions, languages, time frames, and decision-making processes.
- Two-way dialogue (research team and stakeholders) that gives both sides the opportunity to exchange views and information, to listen, and to have their issues heard and addressed.
- Inclusiveness in representation of views, including women, vulnerable and/or minority groups.

The three last principles were implemented by the following work dynamics. The stakeholders were divided in three panels with facilitator. After clearly explaining the issue or topic, the facilitator asked the participants to write each idea or information element. The files of the participants were collected and the information was synthesized on a flipchart (eliminating all repetitions). Then each element of the responses was discussed.

Afterwards, each panel proceeded to agree on ideas and discuss possible solutions to the problems detected. One of the most common techniques we used was to encourage debate and organize ideas into cards. The ideas adopted by each panel as a result of the discussion, and complemented by survey results, are presented in the PESTE matrix.

Public participation is important as a mechanism to break down and address complex decisions by different stakeholders who can provide new information, views, needs, and interests. This approach offers an opportunity for stakeholders to better understand the range of views on an issue. Implementation can also be improved with public consent and commitment on the process, yielding higher quality decisions, and the ability to better allocate scarce resources (Yee, 2010). The generic profile of stakeholders in resilient water management strategies design was categorized into the following types: government agencies, agriculture representatives, research or academic institutions, special interest groups, local community representatives, interest groups or other organizations [government agencies (15%), agriculture representatives (30%), research or academic institutions (10%), local communities representatives (30%), interest groups or NGOs (15%)].

Between 2008 and 2010, four Consultation Forums were held on the recovery plan of the Valle de Santo Domingo aquifer. On the event held in Ciudad Constitución, the main population center in the Santo Domingo Valley, 85 panelists participated representing communities; all municipal, state and federal governments; and non-governmental organizations. Another three fora were held in small communities with the participation of 15–20 persons at each. The objective was to access most of the local population, although the type of participants and the work dynamics was very similar. The methods to engage with stakeholders and register their public participation were the following:

- Public meetings that offered an opportunity for anyone with an interest in the subject of the consultation to express concerns and gain a broader perspective of concerns in a short period of time. Public meetings started with a technical overview of the situation and process, then provided opportunity for members of the public to speak from the floor regarding their concerns or to ask questions of expert panelists.
- Surveys were applied to collect information, solicit opinions and build a profile of the groups and individuals involved. Survey data provided information and helped focus the large number of stakeholder views.

Aside from the system's internal resources and factors, there are several other macro-economic factors that can have a profound impact on the performance of socio-hydrological management. These factors need to be carefully analyzed in order to determine their role in resilience building success. That is why the SWOT analysis is combined with a PEST (Political, Economic, Social, Technological) analysis in this study (Aguilar, 1967), which looks at the broader political, economic, social, and technological factors, and provides a macro-environmental view. PEST methodology was developed with the following additions: economic factors are complemented by financial considerations, and social components are enriched by cultural aspects (very specific to our case study). We have also included environmental factors due to their importance in assessing socio-hydrological resilience. Therefore, the PEST analysis in this study becomes a PESTE (political, economic, social, technological, environmental) analysis.

## 5. Results

### 5.1. Principal types of groundwater

The analyses were considered reliable, applying the rules established in DVWK (1992), where the following two main groundwater types can be distinguished. In the first type (89% of the cases) chloride represents the main anion. The main cation is sodium in 77%, calcium 17%, magnesium 7%. The second group with bicarbonates as main anion represents 33% of the samples. Seawater intrusion affected samples represents 15% of group 1. The relationships between main cations and anions in groundwater are shown in a Piper trilinear diagram (See Fig. 7).

### 5.2. Seawater intrusion chemical signature

Two zones were identified with high concentrations of chlorides and sodium, and values of Cl/($HCO_3 + CO_3$) ratio above 2. The first one, located in the Santo Domingo basin, on its western side, shows values of sodium above 400 mg/l, chloride from 800 to 1500 mg/l, and Cl/($HCO_3 + CO_3$) ranging from 3 to 6. The second zone is located in the Las Bramonas basin, on its western side. Values of sodium range from 400 to 500 mg/l, chloride from 600 to 1500 mg/l and Cl/($HCO_3 + CO_3$) ranging from 3 to 6. In both sites, a dispersion plume orientated to the southeast is observed (see Fig. 8). In the Santo Domingo Basin, values of electrical conductivity near the coast range from 780 to 8760 µS/cm.

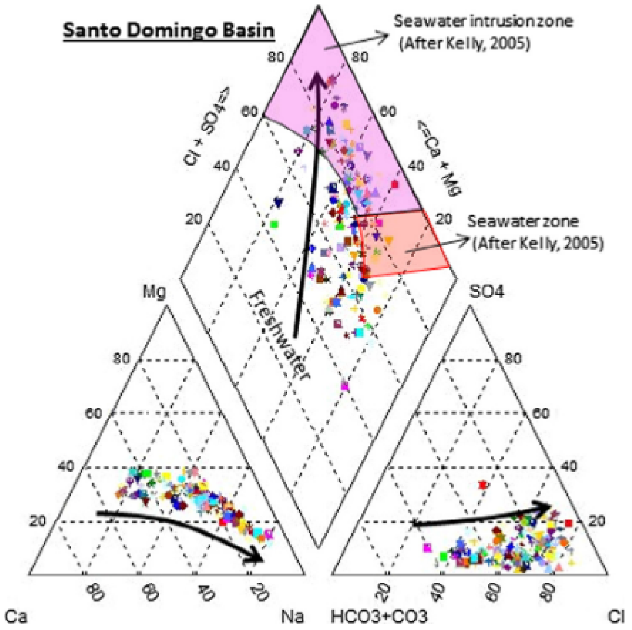

**Fig. 7.** Piper diagrams for samples located in Santo Domingo watershed. Zone colored in purple represents samples affected by seawater intrusion after Kelly (2005). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 5.3. Estimation of seawater inflow for Santo Domingo basin

The results from likely scenarios on the hydrogeological conditions of the Santo Domingo Aquifer show that the total runoff derived from extreme floods, mainly generated by tropical cyclones, represents the most important additional source of water as it infiltrates and recharges the aquifer. Simulations indicate that a reduction of the recharge related to climate change will increase the maximum depth of the drawdown cone from −48 m in 2017 up to −78 m for 2050 and it is expected that the "0" level of the drawdown cone will reach the coast between 2030 and 2040, as seen in Fig. 9. The amount of seawater being intruded just from the river mouth of Santo Domingo creek will increase from 0.36 to 1.3 $Mm^3$ a year.

### 5.4. Results of the SWOT- PESTE analysis: human resilience in the agricultural sector of the Santo Domingo Valley

As mentioned before, the Santo Domingo Valley is the most important agricultural center in Baja California Sur. Its origins go back to the 1940s as the Mexican government's attempt to populate a distant and isolated territory with people from other parts of the country. As a result, 73 agricultural colonies were established with subsidies and financial support from the government: land, water well perforation, machinery, seeds, trained personnel, and social infrastructure were available to settlers. The Green Revolution had a relevant part in the subsequent agricultural boom which was met with a growing demand in the United States. However in 1954, only five years after it became fully productive, more water well perforation was prohibited as water became scarce and its quality compromised by excessive extraction (Márquez Salaices, 2017).

Currently, as in the rest of the peninsula of Baja California, export-oriented agricultural production is on the rise, mainly by foreign investment. The introduction of high water-consuming crops such as oranges, wheat, tomatoes, watermelon, and potatoes

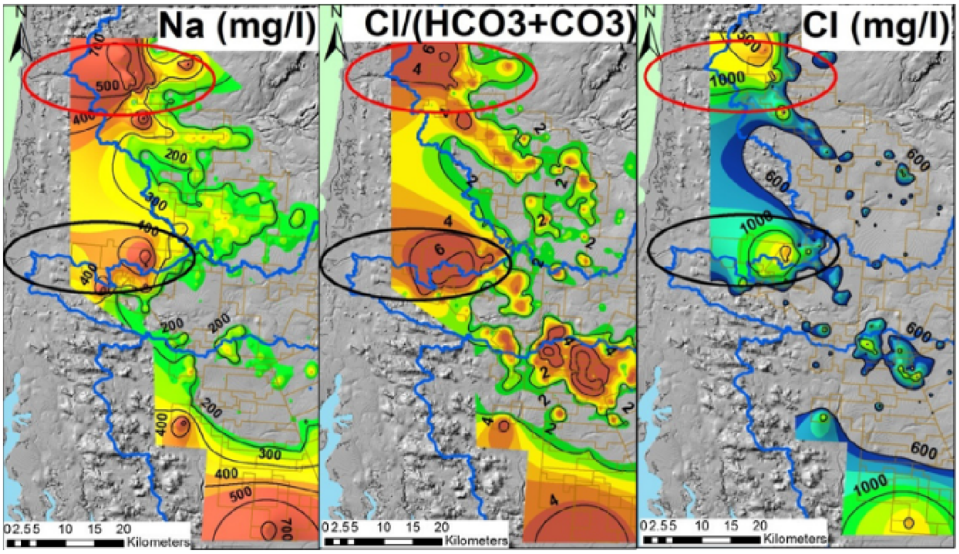

**Fig. 8.** Concentration of Na, Cl and spatial distribution of Cl/($HCO_3 + CO_3$) index. Red circles top of each map represents high values of Na, Cl, and Cl/($HCO_3 + CO_3$) > 2 for Santo Domingo creek, while black circle at middle shows concentration values for Las Bramonas creek. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

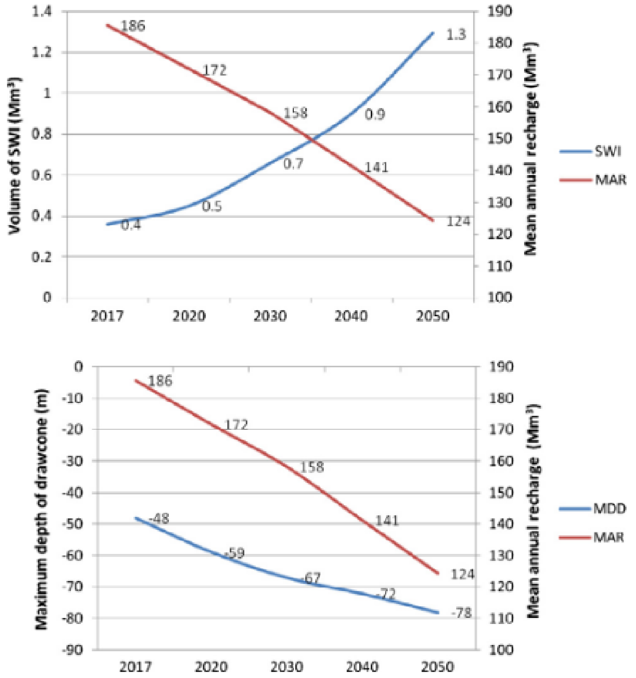

**Fig. 9.** Seawater intrusion inflow according to different scenarios and for the period 2017–2060 (SWI = seawater inflow (Mm$^3$); MAR = mean annual recharge (Mm$^3$); MDD = maximum depth of the drawdown cone (m.a.s.l.).

persist and, although there is a high degree of modern irrigation technics (greenhouses and technified irrigation), water remains scarce and local producers face polluted soils by agrochemicals and fertilizers, debt and low productivity. Renting their land or water concessions has become a means of income, but the region has become increasingly depopulated. In a context in which agriculture is still the main economic activity, local producers need to be persistent, adaptive, and transformative (Bennett et al., 2014), especially considering climate change. Producers have to be persistent in their efforts to preserve the economic activity on which their livelihood is based, they must adapt to the present and expected impact of climate changes transforming the traditional pathways of farming through implementation of new technologies, crop changes and water use optimization.

Table 1 shows the main results of the consultation forums carried out with the participation of stakeholders in the Santo Domingo Valley from the Strengths, Weaknesses, Opportunities and Threats/Political, Economic, Sociocultural, Technological and Ecological Analysis, which recent applied research has confirmed with (Márquez Salaices, 2017).

## 6. Discussion

It is important to highlight that the interdisciplinary work in this article was inspired by the indications of the Fifth Assessment Report (AR5) of the IPCC. In the AR5, the Bureau of the IPCC managed to include several issues that were previously considered outside the scope of research on climate change. These topics indicate the need to relate scientific research (eg, scenarios, water resources, extreme events) to social science topics. Such are sustainable development, ethics, equity, and human rights. Including these issues and relating them to the main strands of climate action (mitigation and adaptation) is of the utmost importance to make decision-makers see that climate policies should be an integral part of the broader sustainable development policies, and that resources to combat climate change at the same time are addressing socio-economic development priorities (vulnerable communities, food supply, creation of green jobs, etc.) (Ivanova Boncheva and Pichs, 2017).

As a result of this collaboration, the scenarios for the AR5 are prepared in a combined manner between (1) projections of future emissions; (2) projections of future climate change; (3) narrative descriptions (quantitative and qualitative) of socioeconomic conditions and stakeholders opinions, which represent challenges to mitigation and adaptation; and (4) mitigation and adaptation policies. The developed scenarios provide an integrated framework for creating and comparing mitigation, adaptation and residual climate impacts at the sectoral and regional levels (*Ibidem*).

Even though the Mexican government claims that the Santo Domingo Valley aquifer is stabilized in terms of a water mass balance between recharge versus extraction rates, this calculation does not exclude the volume of seawater intrusion from the calculated recharge volume. The flow model presented here indicates that initial saltwater intrusion has occurred and that water quality of the northern part of the aquifer (Santo Domingo watershed), as well as in the central part (Las Bramonas watershed), is seriously compromised. The amount of seawater intrusion from the Santo Domingo mouth will be 3.6 times in 2050. The resulting increment of groundwater salinization will lead to soil chemistry and permeability deterioration, with adverse consequences for the region's environment, economy and population.

It is likely that more water will be used in order to wash out soil salinity. The intrusion of seawater into the Santo Domingo aquifer dates back to the year 1968 when agricultural production increased in the context of the *Green Revolution*, causing overexploitation of the aquifer (Troyo et al., 2010). The aquifer of Hermosillo, in the neighboring state of Sonora, faced a similar situation and may serve as an example of a worst case scenario given its comparable conditions to the Santo Domingo aquifer.

In the Hermosillo aquifer a saline water intrusion front started since 1975 at a 0.65 m/year velocity rate (Rangel et al., 2003) and, until 2008, had formed a 80 km parallel fringe to the shoreline, penetrating the aquifer to a depth of 28 km to 32 km with E.C. values up to 40,000 μS/cm (Szynkiewicz et al., 2008). Reverting and (at least partly) restoring the natural condition of the Hermosillo aquifer requires decades of time and government investment, which in turn implies high social and economic costs (Rangel-Medina et al., 2004).

Several initiatives in the Santo Domingo valley have been put forward for the agriculture activity to continue. Relying mostly on government subsidies, more than 50% of the farms have installed automatized irrigation systems. Additionally, an agricultural experimental research center located in the Santo Domingo Valley suggests farmers options to optimize land use, change crop patterns and introduce advanced irrigation methods since the nineties (Urciaga, 1992). Farmers can access this information through a consultation system on Internet, where the environmental characteristics, potential areas and technology of crop production are documented for each farm of the Valle de Santo Domingo Irrigation District (Meza and Ojeda, 2006).

In general, farmers have followed both strategies and nowadays produce is mostly fruits and vegetables rather than cotton or wheat, as before. However, even using high-tech irrigation has not solved water overexploitation. This is of concern since climate conditions may be more extreme in the nearer future. According to HADGEM2-ES and REA assembly climatic models (Giorgi and Mearns, 2002; Conde et al., 2011), seasonal rainfall will be reduced which will lead to decreasing water levels. This situation will boost extraction and production costs and could imply well abandonment, thus affecting the population and economy of the Santo Domingo Valley region, which is the largest agricultural area of the state. This process will continue if not additional influx of fresh water occurs.

**Table 1**
Human resilience in the agriculture sector. Main results from the SWOT and PESTE analysis.

| Internal factors | |
|---|---|
| Strengths (+) | Weaknesses (−) |
| **Political**<br>• Water users are organized for management, maintenance, and preservation of the irrigation infrastructure available.<br>• Some producers have a water management culture.<br>• Willingness of producers to use water-saving technologies.<br>• Disposition of the population to implement alternative economic activities in the face of insufficient water availability.<br>• University and technological institutes offer educational programs in agricultural, technological and industrial engineering.<br>• Producers agreeing to reduce the use of water in agricultural activity have precedents (30 years ago).<br>**Socio-cultural**<br>• A population identified with agricultural activities.<br>• Inhabitants participate in organizations with access to financial resources.<br>• Some producers are aware of the need of better water management<br>• Willingness of producers to use water-saving technologies.<br>• Agreement to implement alternative economic activities to face scarce water availability<br>**Technological**<br>• There is water exchange between agricultural ranches<br>• 100% coverage of water meters<br>• A secondary treatment plant reuses sewage water<br>• There are small primary water treatment plants<br>• Existence of some hydraulic infrastructure | **Political**<br>• Legal standards allow obsolete methods of estimating groundwater availability.<br>• A poor recharge calculation method is used: saline intrusion and polluted water are deemed as recharge.<br>• Deficiencies in level monitoring: different times of the year, obsolete equipment, lack of budget.<br>• Misalignment between water policy and agricultural policy: water concessions not used in their entirety get lost.<br>• Inadequate and incomplete legal framework regarding water (the water market is not included)<br>• Insufficiency of programs to promote savings and adequate use of water.<br>• Problems regarding land tenure in certain localities.<br>• Authorities lack credibility regarding proposals to solve water shortage.<br>**Economic-financial**<br>• Individual subsidies are not optimized.<br>• Recurring portfolio problems due that limit access to credit<br>• Insufficient strategic infrastructure: roads and ports<br>• Insufficient supply of strategic services: equipment repair, training. Advising<br>• High equipment prices due to isolated location and lack of competition among local suppliers.<br>• Subsidies for well drilling which raises prices<br>**Socio-cultural**<br>• Lack of water culture<br>• Recidivism in the sowing of crops with high water consumption<br>• Lack of entrepreneurship: land rent instead of working and rent/sale of water<br>• Generational transition: disinterest in agricultural activities<br>• Insufficient organization of producers to commercialize the production and purchase of equipment<br>• Insufficient mechanisms that promote organized citizen participation<br>• Lack of training, although there are INIFAP options, UABCS campus. Lack of interest<br>• There is no social cohesion to optimize the use of technology and financial resources<br>• Inadequate management of the hydraulic infrastructure.<br>**Technological**<br>• Each farmer has his own team: low efficiency. Now the ranches are being segmented even more.<br>• Under-utilization of irrigation technologies<br>• Insufficient hydraulic works<br>**Environmental**<br>• Variable aquifer recharge (not quantified)<br>• Poor water quality due to marine intrusion, agricultural activities (irrigation recycling), pumping of deep saline waters<br>• Sandy soils: not suitable for all crops<br>• Soils affected by chemicals, pesticides, and fertilizers hinder organic cultivation<br>• Pests, which do not allow all crops (e.g. olive trees) |
| External factors | |
| Opportunities (+) | Threats (−) |
| **Political**<br>• Legislation and institutional and political concern for environmental protection and water savings<br>• Sustainable Rural Development Law of Baja California Sur, 2017<br>**Economic-financial**<br>• Closeness to the state capital and to tourist centers that consume a large amount of agricultural products<br>• International demand for agricultural products produced in the municipality (e.g. asparagus)<br>• Growing demand for organic products worldwide<br>• Existence of financing sources for water-saving technologies<br>**Socio-cultural**<br>• Existence of professional technical training centers in agriculture.<br>• Increasing access to education and training for the rural population.<br>• Existence of entrepreneurs in the organization of productive processes<br>• Successful experiences<br>**Environmental**<br>• Availability of surface water for capture and agricultural use.<br>• Baja California Sur is fruit fly (Tephritidae Species) free area | **Political**<br>• Lack of regulation of non-local investment in agriculture<br>**Economic-financial**<br>• High prices of inputs and services for production and marketing<br>• Perverse subsidies<br>• Difficult conditions for access to credit (high interest rates, guarantees<br>**Socio-cultural**<br>• Lack of water culture<br>• Lack of social cohesion<br>**Environmental**<br>• Drought increase<br>• Flood threat<br>• Tropical cyclones affect infrastructure<br>• Frosts affect irrigation patterns |

Another factor to consider is the increase of evapotranspiration resulting from an expected increment of 2–4 Celsius degrees during the period 2069–2099, a situation that will exacerbate these trends. As a result of higher temperatures, cyclonic rainfalls could be stronger, increasing runoffs. However, results from PEACC (2012) suggest that more runoffs will not necessarily improve infiltration, as sediments tend to saturation.

The above-mentioned situation suggests the convenience of building reservoirs and recharge dams in order to storage surface water, before it reaches the ocean.

In a context of water scarcity and expected adverse impacts of climate change, the options for adapting agricultural activity and water use were discussed in consultation forums with members of the local communities alongside the Santo Domingo Valley. The sessions showed that communities are aware of the impacts of climate change, and that the alignment of water and agricultural policies is an essential condition to foster socio-hydrological resilience and sustainable agricultural practices. This includes changes to legal standards in order to avoid obsolete methods of estimating water availability, which otherwise lead to unsupported claims of water abundance.

Further steps can be taken to revert water depletion in the Santo Domingo Valley. Water saving technologies should be introduced in greater scale based on available technology, financing sources to acquire it and the population willingness to use it. Dams and major storage works can capture superficial water since the amount of water delivered by cyclones will raise in the future. Captured water volumes could be transferred to smaller recharge dams as proposed by Wurl et al. (2008). Construction of a line of observation wells near the coastline is advisable to recognize the advance of seawater intrusion and as an early warning system. Crop change is needed accordingly to future climate change scenarios (increase of evapotranspiration and water scarcity (Maleksaeidi et al., 2017; Reyhani et al., 2017)) and some important opportunities (international demand of organics and the status of a fruit fly free area) must be further exploited. Capacities building in entrepreneurship and advanced technologies use, as well as water culture enhancement, are very important for socio-hydrological resilience. Overall, limits have to be drawn as to how much agriculture can be deployed on sustainable terms in a water-overexploited region.

## 7. Conclusions

The characterization of sociohydrological resilience of the Valley of Santo Domingo, a water-limited arid ecosystem was achieved through a SWOT analysis in combination with a PEST analysis; as well as through future extraction scenarios based on changing climate conditions. From this, a hydrogeological flow model was advanced, to which socially-sustainable management practices are crucial in order to restore ecosystems and benefit society.

The hydraulic model at a regional scale permitted demonstrating, that an inflow from seawater into the aquifer is ongoing. The salinization in the aquifer is mainly resulting from seawater intrusion, due to the development of a huge depression cone, caused by the extraction of groundwater in excess in the center of the Santo Domingo Basin. Future aquifer management will have to focus on the coastal zone, where monitoring groundwater heads and quality will be necessary to obtain the information necessary to assess remediation strategies against the saltwater intrusion.

After the definition of the main hydrological components and future climate change impacts, the main topics of the SWOT analysis were introduced. These are based both on field research and surveys and interviews applied to key stakeholders. The SWOT analysis combines the hydrological considerations with the most important PESTE components.

This is one of the few studies that propose an interdisciplinary analysis, where hydrogeological and socio-economic components are linked together. This contributes to future scenarios by integrating not only the hydrogeological but also economical dimensions. Additionally, the integration of the community perspective was achieved, respecting their points of views and traditional knowledge, including them in strategies for resolving the water-related problems. The acceptance by local actors and their active participation in the design, implementation, and monitoring of adaptation and remediation measures are crucial, strengthening resilience and reducing the impacts of climate change on water resources, agricultural activity and, consequently, improving the living conditions of the population. In future studies it will be important to check the effectiveness of actual programs introducing advanced irrigation technics, like center pivot irrigation, and pattern crops that are better adapted to local conditions.

Rethinking the policy of granting water rights, as well as reviewing the system of subsidies to agricultural activity (avoiding the stimulation of agricultural practices that worsen the overexploitation of groundwater instead of remedying it) will strengthen water conservation. This process must be accomplished by monitoring the saltwater intrusion in combination with reliable and more frequent measurement of the water table and the construction of a hydraulic infrastructure for flood control and capturing of surface water after extreme rain events.

Components of the SWOT analysis show the pathway to enhance the social-hydrological resilience in Santo Domingo V, an analysis that can be further developed by the quantification of socio-hydrological resilience components.

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