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Groundwater Flow Model and Statistical Comparisons Used in Sustainability of Aquifers in Arid Regions

Javier Alexis Trasviña-Carrillo [1,*], Jobst Wurl [2] and Miguel Angel Imaz-Lamadrid [2]

[1] Faculty of Engineering, Autonomous University of Querétaro, Santiago de Querétaro, Querétaro 76010, Mexico
[2] Department of Marine and Earth Science, Autonomous University of Baja California Sur, La Paz 23085, Mexico
* Correspondence: ale_f7m@hotmail.com; Tel.: +52-612-15-62844

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Abstract: Groundwater provides the most important of the water resources used in the maintenance of communities in arid and semi-arid regions. In these areas, the usage of deep wells with motorized pumps in combination with the lack of effective regulatory policies and high human population growth (increase the water demand) impact the quality of the groundwater. This is especially the case for the San José del Cabo aquifer, in Baja California Sur. In the present study the groundwater flow system is analyzed in order to recognize the impact from variations in groundwater extraction and recharge on the phreatic levels and discharge values. In order to achieve this goal, a groundwater model was generated using the MODFLOW program. Different scenarios of extraction and recharge were calculated, based on different estimations of population growth. All the scenarios result in decreasing groundwater levels. As an important result, a relationship between the phreatic level and the extraction volume was found for the middle zone of the aquifer, where an average annual decrease of 0.5 m was observed from every 5×10^6 m^3 additional extraction volume. This zone is up to three times more susceptible to changes in extraction values than the southern zone. As the results show, the San José del Cabo aquifer is in a fragile state where an increment in extraction is not an option without the use of remediation technics or new sources for water supply.

Keywords: population growth; groundwater; MODFLOW

1. Introduction

As population, urbanization, and industrialization grows, also an ever-increasing demand for freshwater resources is created [1]. This is especially the case for arid and semi-arid regions, where most of the water resources are provided as groundwater. The wide-scale deployments of powerful motorized pumps and the absence of effective regulation are some of the factors that can lead to aquifer over-exploitation. The lack of high-quality observations, the inherent limitations obtaining subsurface measurements, and its great geological complexity make the study of groundwater difficult and often highly uncertain [2,3]. In order to overcome this problem, aquifer modeling is generally used, which can solve a wide range of groundwater problems and support the decisions on management strategies for groundwater resources and protection [2,4].

Arid and semi-arid regions with aquifer over-exploitation present problems associated with declining water tables, the loss of important habitats, deteriorating water quality, inflow of saline water in coastal aquifers, and land subsidence, among others [2]. One example is the aquifer of the San José del Cabo Basin (SJCB), which represents the main source of water for the cities of San José del Cabo,

Cabo San Lucas cities, and Ciudad del Sol [5,6]. This aquifer is considered over-exploited since 1985, and the water demand has increased since then, associated with a high rate of population increment (actually 3.8%) [5–14]. In 2018 an annual groundwater deficit of -5.9×10^6 m^3 was estimated for the San José del Cabo aquifer [15].

The physical characteristics of the SJCB aquifer have been described by many authors, i.e., [16–18]. Recently the effect that climate change and anthropogenic pressures over the San José estuary (the southernmost part of the SJCB) has been studied [19]. However, the effect of the increasing population and its consequential demand for additional water resource has not been studied in the whole aquifer. The SJCB aquifer satisfies almost all the water demand that accounts for the San José del Cabo and Los Cabos region, and an increment on the extraction of water is expected in the future. Changes need to be done in the socio-environmental conditions in order to improve the sustainability in the water sector [6]. This includes water consumption, water quality, and aquifer management. The population growth rate is still high and increasing along with the groundwater extraction (although the aquifer is already over-exploited). In this study, the behavior of the water table under different scenarios of water recharge and extraction, associated with the increment of the population in the San José del Cabo region is analyzed. On the other hand, synthesizing the available data in the model will improve the hydrogeological understanding of the SJCB aquifer. Both factors are important in order to achieve a sustainable use of groundwater resources in the area. The programs MODFLOW-2005 and ModelMuse [20,21] are used. These programs were selected due to their flexible use; the associated ASCII (American Standard Code for Information Interchange) format allows easy interchange of information with other programs due to its open source quality.

2. Study Area

The SJCB is located in the southernmost region of Baja California Sur, Mexico (Figure 1). SJCB is limited to the west by the Sierra de La Laguna mountain range, to the east by the Sierra La Trinidad, and to the south by the ocean (transition zone between the Cortes Sea and the Pacific Ocean).

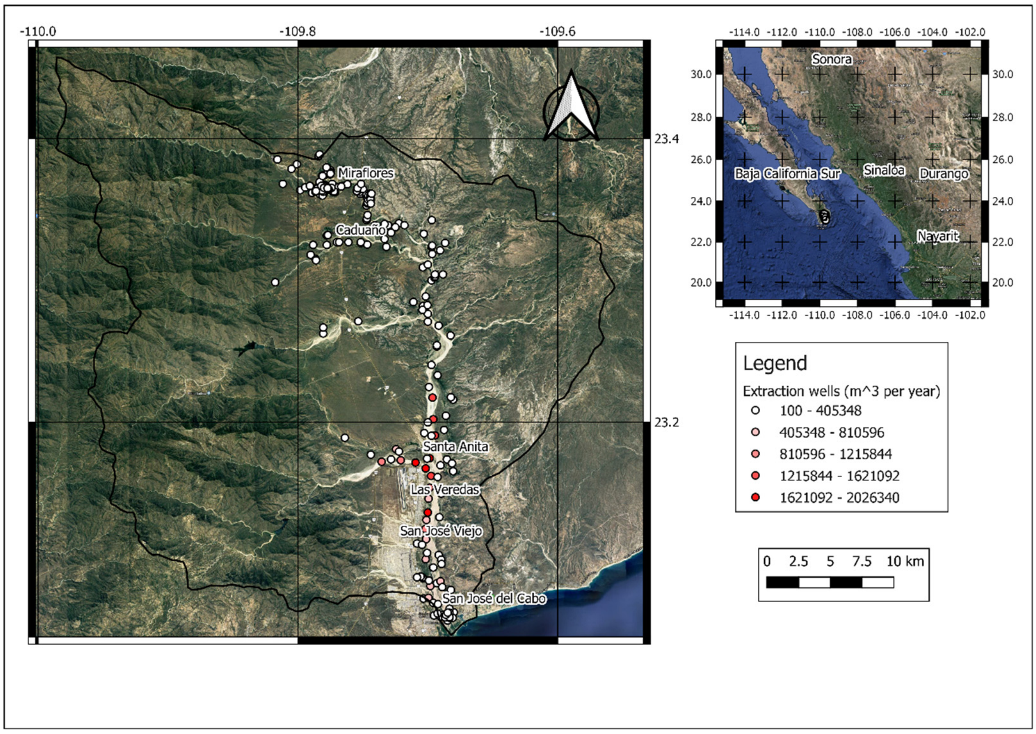

Figure 1. Location of the San José del Cabo Basin, Baja California Sur, Mexico. Extraction wells inside the basin are colored according to their annual extraction volume.

The prevailing climate in SJCB is arid, according to García [22]. This type of climate is associated with a mean annual temperature of 22 °C, with rainfall occurrence in summer and between 5% and 10% of winter rainfall accounting for the total annual [22]. The mean annual real evapotranspiration in the basin is 318 mm [23].

Tropical cyclones are one of the key factors that characterize the climate in the region. In Baja California Sur the rainfall associated with this type of phenomena account for the 47% of the total annual rainfall and play an important role during the months of August to October [24].

The main creek is represented the Arroyo San Jose, which can be classified as order seven (after Strahler) [25]. The predominant direction is N-S and leads to the outlet of Cortes Sea/Pacific Ocean transition, trough the San Jose Estuary. Topographically, the highest elevation of approximately 2080 m above the sea level is located to the west, in the watershed limit known as Sierra de la Laguna, while the lowest elevations are in the southernmost region, in the basin outlet of Arroyo San José, into the sea [7].

3. Geology and Hydrogeology

Most of the soils found in SJCB are composed by coarse texture [26]. Soils of medium to fine textures are associated with high slopes and instability of terrain, meanwhile in the creeks there is a predominance of coarse textures, with less consolidation, associated with constant removal and deposition of material [26].

The SJCB forms part of the Extensional Province of the Gulf of California [27]. This basin is considerate a half-graben and its origin has been related to the opening of the Gulf of California [28–30].

The limit between Sierra de La Laguna and the sediment deposit is denoted by the San José del Cabo fault. This fault is normal, has a strike approximately N-S and a dip almost vertical; however, in some segments of the fault, the strike could have a direction NE-SW and dip between 85° to 89° [28]

Martínez-Gutiérrez and Sethi were the first to distinguish five main formations [28]: Fm. Calera, composed of fluvial conglomerate and sandstone dating medium to superior Miocene; Fm. Trinidad, composed of laminated and no laminated shale and sandstones dating Late Miocene to late Pliocene [31]; Fm. Refugio, composed of course gran bioclastic sandstone of Pliocene [31]; Fm. Barriles, compose by course conglomeratic and sandstone dated Pliocene [31]; and Fm. El Chorro, composed by fluvial coarse sandstone and conglomerated dated late Pleistocene to Holocene.

The most recent sedimentary fill is the unconsolidated sediment, located in the channels of creeks with a depth between 20 cm and hundreds of meters [16,32–34]. The main water wells are located near the populations of San José del Cabo, Santa Rita, Las Playitas, and some other locations around San José del Cabo [7,16].

San Jose del Cabo Aquifer

The unconfined SJCB aquifer is constituted in its superior part by alluvial sediments and non-consolidated fluvial deposits across all the creeks. The inferior part of the aquifer is formed by igneous and metamorphic rocks, which presents fractures and alterations [7].

The water balance indicates that more than 75% of precipitation is evapotranspirated, 17% as runoff and only 5% recharges the aquifer [18]. Most of the recharge comes from the runoff generated in the elevated regions of Sierra de La Laguna, which infiltrates into the alluvium, the most important zone for groundwater extraction.

Most of the rainfall in the region is generated by tropical cyclones but the effect of extreme rainfall in aquifer recharge depends on many factors, for example, the initial water content of the soil, the environmental humidity, the runoff volume, and the intensity, frequency, and duration of the storms [18].

4. Social Importance and Historical Balance

Los Cabos is one of the five municipalities of Baja California Sur and is considerate one of the most important touristic destinations of Mexico. According to INEGI (National Institute of Statistics and Geography) the annual rate of demographic increase in the period 2000 to 2010 of Los Cabos was

8.2%, which is higher than in the rest of the country. One of the biggest challenges that Los Cabos municipality has to confront is the water shortage, associated with the arid climate [22]. According to Valdez-Aragón et al. [17], the main causes of the water problem in the state are the demographic growth, the increase of touristic activities, the lack of water extraction control, the irrational and irresponsible use of the resource, and the inefficiency of the water distribution systems for urban and agriculture.

According to CONAGUA [7], the SJCB aquifer presented annual extraction volumes of 8×10^6 m^3 by 1980; 20×10^6 m^3 in 1990; and 24×10^6 m^3 for 2000 [8]. By the year 2000 the extraction volume was 11% higher than its natural recharge. In 2002 CONAGUA concluded that "There is no available volume for new water concession in the hydrogeological unit known as San Jose del Cabo aquifer, Baja California Sur State". However, the extraction volume increased 29×10^6 m^3 in 2011 [7]. Between 2011 and 2018 the extraction volume did not change; however, the overall deficit increased from -2.623×10^6 m^3 in 2011 to -5.91×10^6 m^3 in 2018.

Population Growth Scenarios

The San José del Cabo and Los Cabos region is of great natural and economic importance in Mexico and has become one of the regions with the highest rate of population growth [6]. The region is associated with an increasing touristic activity which commonly is combined with increasing employment opportunities [5,6].

The aquifers of the SJCB constitute the main water resource for the Touristic Corridor of Los Cabos. This corridor is integrated by 116 locations, which sum a population of 96,543 inhabitants for the year 2000, representing 91.5% of the total population of Los Cabos Municipality (105,469 inhabitants) [5]. By 2015 the population of Los Cabos Municipality had increased to 287,671 inhabitants, from which 75.5% lived in Los Cabos Corridor [14].

It has been estimated that the population in the touristic corridor of San José del Cabo will continue growing in a significant way due to its persistent dynamism of the touristic activity defining three scenarios with different projections for the population increase for the touristic-urban corridor of Los Cabos Municipality in the period 2000–2030 [5]:

CONAPO (Consejo Nacional de Población)scenario: Employ the demographic increase of Consejo Nacional de Población (National Council of Population). This scenario begins with a rate of 6.34% for 2001, and then decreases in a constant manner until reaching 2.23% in 2030.

The pessimistic scenario: The rate of population increase in the corridor ascended in the decade 1990–2000 to 9.22% and will remain constant at this level, assuming that the population will continue increasing at the same rate during all the period given, and that the investment of urban and touristic infrastructure will continue growing.

The alternative scenario: Tor this scenario a rate of 9.22% was taken into consideration for the first decade, assuming that, for the following two decades, the rhythm of growth will decelerate. From 2011 on, the growth rate will be equal to the CONAPO scenario until 2030 (Figure 2).

Comparing the censuses, the inter-censuses surveys, and the projected scenarios of population growth, it can be denoted that the scenario that follows the current tendency until now is the alternative scenario for Los Cabos Municipality [10–14,35].

The mean expenditure of water per inhabitant in San Jose del Cabo region was 312 $L \times day^{-1}$; while for Los Cabos region was of 194 $L \times day^{-1}$ per inhabitant [5]. The mean expenditure of both locations was 253 $L \times day^{-1}$ per inhabitant (30 m^3/home/month). This expenditure was used in combination with the population growth scenarios to estimate the extraction in SJCB for the future.

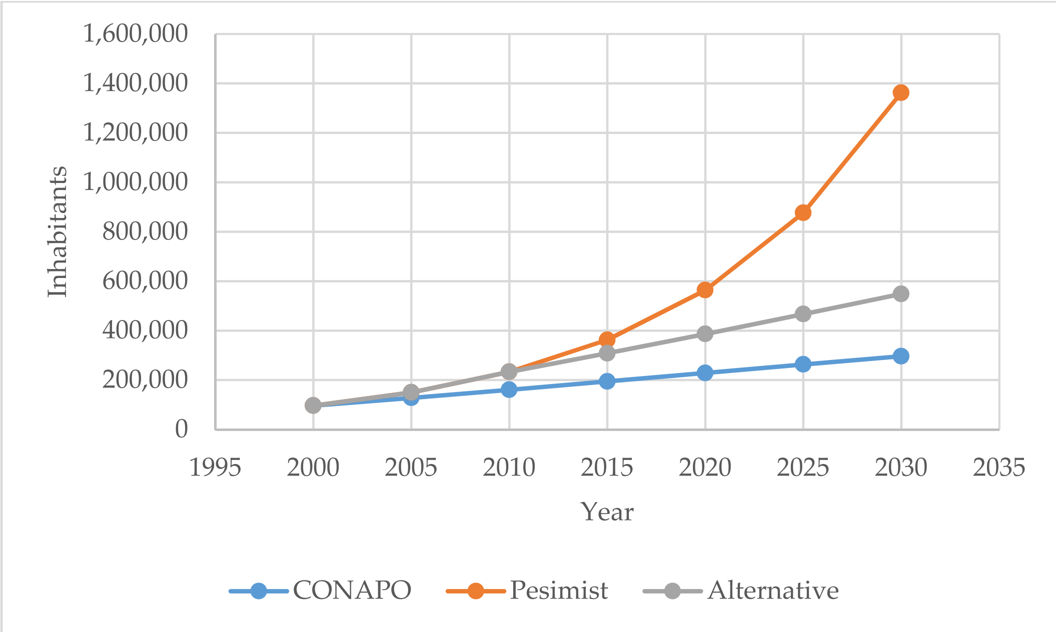

Figure 2. Population increase projections for Los Cabos Touristic Corridor, taken and modified from [5].

5. Model Creation

A groundwater model is a computer-based representation of the essential features of a natural hydrogeological system. The two key components are the conceptual model and the mathematical model. The conceptual model is an idealized representation of a hydrogeological system based on the up to date understanding of the key flow process of the system. The mathematical model is a set of equations which is based on certain assumptions and quantifies the physical process active in the aquifer system being modeled [36].

While groundwater models are a simplification of a more complex reality, they have proven to be useful tools over several decades for addressing a range of groundwater problems and supporting the decision-making process. Groundwater models provide a scientific and predictive tool for determining appropriate solutions to water allocation, surface water–groundwater interaction, landscape management, or impact of new development scenarios [37].

The SJCB aquifer model was generated with MODFLOW-2005 in conjunction with ModelMuse. This tool was created by United States Geological Survey [20], which solves the groundwater flow equation by the finite differences in numerical analysis.

The three-dimensional movement of groundwater of constant density through porous earth material may be described by the partial-differential Equation as (1).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + W = S_s\frac{\partial h}{\partial t} \quad (1)$$

where K_{xx}, and K_{zz} are values of hydraulic conductivity along the x, y, z coordinates axes, which are assume to be parallel to the major axes of hydraulic conductivity (LT^{-1}); h is the potentiometric head (L); W is the volumetric flux per unit volume representing sources and/or sinks of water, with $W < 0.0$ for flow out of the groundwater system, and $W > 0.0$ for flow into the groundwater system (T^{-1}); S_s is the specific storage of the porous material (L^{-1}); and *t* is time (T).Model Design.

The initial point of the model, which is the inferior left corner of the mesh, was set in the coordinates 23°2′18.54″ N and 109°50′27.53″ W. The dimensions of the model were: 50 km height and 25 km wide; divided into 200 rows by 100 columns (each cell having 250 ×× 250 m size). The model had 3 layers, which were characterized according to the spatial disposition of the aquifer and its surroundings.

The conceptual model is centered in the alluvium area of the basin, limited by sedimentary and igneous rocks. Sedimentary and igneous rocks were considered as aquitards since they have certain hydrological characteristics, compared to the non-consolidated sediment. The spatial delimitation and depth of the aquifer units were recreated according to [32–34]. Initial heads for the model were obtained from Comisión Nacional del Agua [8] (Figure 3).

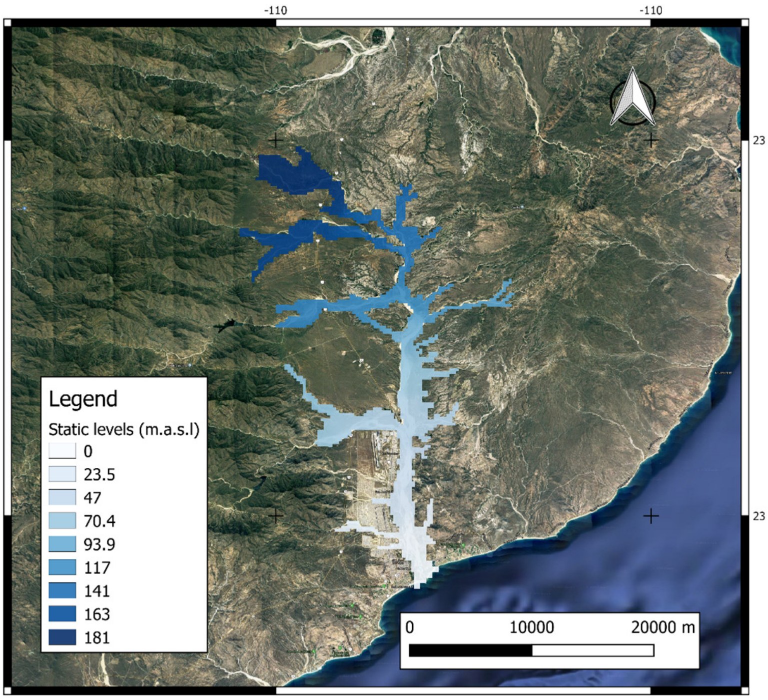

Figure 3. Spatial discretization of the model with groundwater levels obtained in the year 2016.

The superior limit of the model (the top of the layer one) was limited by the surface of the terrain. Altitude values were obtained from the AsterGDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer). The aquifer was subdivided into the superficial aquifer and the underlying fractured igneous rocks that composed the basement [38]. The depth of the granitic basement and the depth of the aquifer were obtained from geophysical data from [32], and the sections documented in [33,34]. Historical extraction values were obtained from CONAGUA [7,8,39]. Initial data for hydraulic characteristics, the values of evapotranspiration, recharge, discharge, among others, were obtained from [7,8,24,32–34].

According to CONAGUA [8], the recharge volume in the year 2002 was 24×10^6 m^3. This value was used as the constant annual recharge for the period 1995 to 2002. The estimated recharge value for 2011 was 30.3×10^6 m^3 annual. Estimated recharge for the period 2003 to 2010 was taken as linear increment between 2002 and 2011.

An induced recharge volume of 5.6×10^6 m^3 results from leaks in the urban sewage system [8]. Since most of the volume extracted from the aquifer is used outside of the SJCB, the return flow through urban sewerage leaks was not taken into consideration. Induced recharge by irrigation return was set in punctual form for the agriculture area. Extraction values used for the 1995–2007 period were obtained from the literature [24]. The period 2008 to 2010 was calculated using a linear increment between the years 2007 and 2011. Extraction in 2011 was 29×10^6 m^3 per year. For the period 2012 to 2016 the extraction was the same as in 2011 [15]. The hydraulic conductivity of the aquifer was estimated from the literature [7,8,28,31–34] and finally obtained due to the calibration process.

The method "one-at-a-time" was used in order to analyze the sensitivity of those variables whose ranges were open because of a lack of information. A fractional design and linear multivariable analysis permitted denoting only individual effects, with respect to 36 variations of the model characteristics.

This design took in consideration the variations of the hydraulic conductivity with values of 9×10^{-3}, 9×10^{-5}, and 9×10^{-6} ms^{-1}; specific yield with values of 15%, 20%, and 25%, and specific storage with values between 1%, 5%, 9%, and 13%. The values were chosen due to the variations of the characteristics of the sediment and using the programming environment R [40]. The result of the sensitivity analysis took into consideration the effects of the groundwater volume that goes to the sea and the mean variation of the static levels. The scenario model was run for the time span 1995–2000, according to the values of recharge, extraction, and evapotranspiration denoted by CONAGUA [8]. The result indicates that the significant variables are the hydraulic conductivity and specific yield, being the hydraulic conductivity the most significant.

The calibration was performed with the package preconditioned conjugate-gradient [20] the model run until year 2011. For the years 1995, 2000, and 2011 the obtained hydraulic heads were compared at 100 location points, randomly collocated across all the area. At these points, the documented water table elevation was compared to the hydraulic heads, obtained by the model. The final configuration was chosen, based on the lowest error in comparison to the phreatic levels and discharge volumes. The following correlation coefficients between observed and calculated hydraulic heads (R^2) obtained were: 0.9896, 0.9872, and 0.9907 for the years 1995, 2000, and 2011, respectively. The results were evaluated, following the criteria defined by Heath; Morris and Johnson; Bear [41–43].

The values for the hydraulic conductivity for unit A were obtained between 0.007 and 0.00005 ms^{-1}, specific storage of 3% and a specific yield between 15% to 20%. This layer represents the superficial aquifer. This values are agree with the values of pump tests, reported in literature [24]. Unit B obtained a hydraulic conductivity of 1×10^{-6} ms^{-1}, a specific storage value of 0.08%, and a specific yield value of 0.09%. This layer represents the transition zone between the aquifer and igneous basement. Unit C obtained a hydraulic conductivity of 12×10^{-12} ms^{-1}, specific storage of 0.01%, and a specific yield of 0.09%. This layer represents the igneous basement and bottom of the aquifer (Table 1, Figure 4).

Table 1. Hydraulic parameters obtain after calibration.

Unit	Hydraulic Conductivity (ms^{-1})	Specific Storage (%)	Specific Yield (%)	Thickness (m)
A	0.007 to 0.00005	3	15 to 20	500 to 50
B	1×10^{-6}	0.08	0.09	180~280
C	12×10^{-12}	0.01	0.09	100

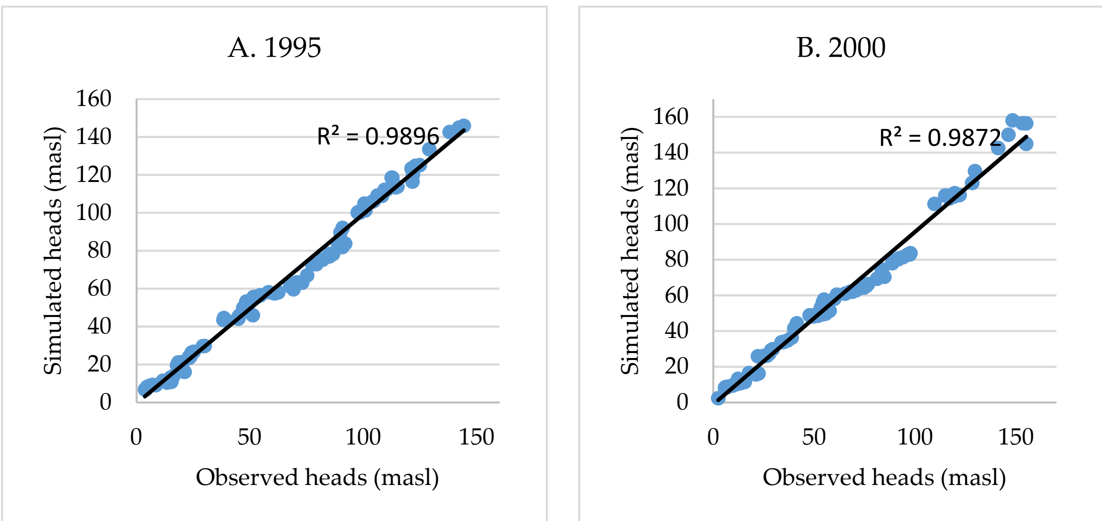

Figure 4. *Cont.*

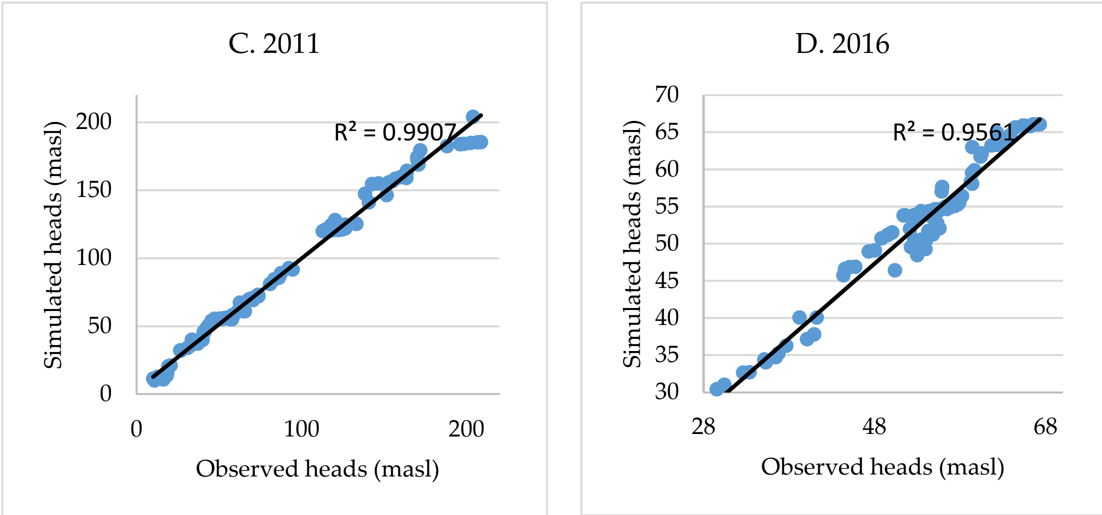

Figure 4. Correlation plots of the adjustment between model data and observed data for phreatic levels for years 1995 (**A**), 2000 (**B**), 2011 (**C**), and 2016 (**D**) were used for validation.

Finally, the model was validated for the year 2016, based on the phreatic levels at 100 randomly collocated points. The value of R^2 obtained for this year was 0.9004 and absolute mean error of 5.4 m, which is considered acceptable because of the scale and resolution of the model [4,36,44–47].

Once the model had been validated different scenarios of recharge and extraction were calculated, based on the population increase estimated in literature [5] (Figure 5). The mean water consumption per inhabitant in the whole Los Cabos region for 2000 is 312 L $\times$ day^{-1}, estimated by Valdez-Aragón [17]. The variations in extractions were proportionally distributed to the extraction wells for years after 2016. In this paper the future extraction was estimated, based on 3 scenarios of population growth during the period 1990 to 2015, and following a linear trend, as suggested by different studies [10–14,35] (Figure 5).

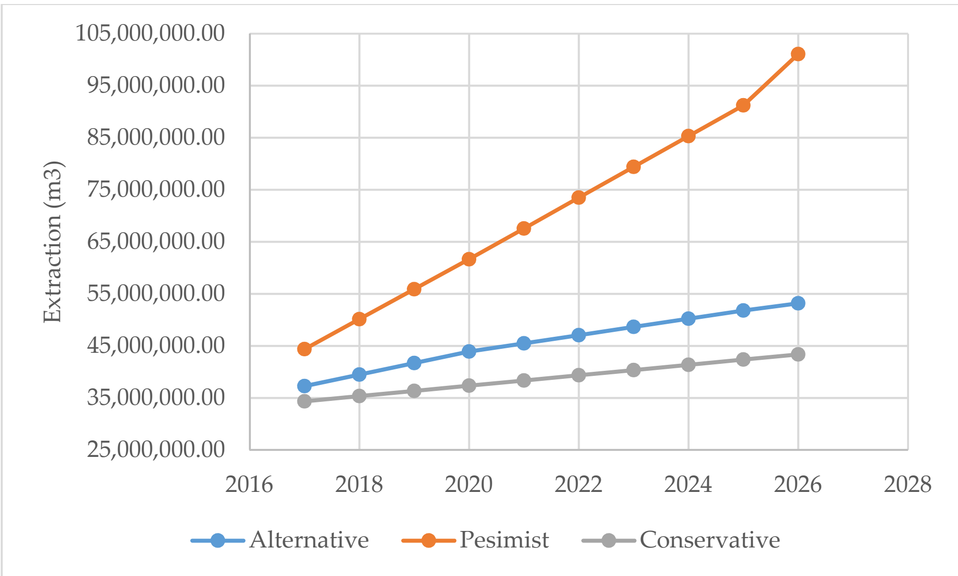

Figure 5. Comparison of two scenarios taken and modified from [5].

Six hypothetical scenarios were created in order to forecast the general extreme variation of the phreatic levels and discharge of the SJCB aquifer.

- Scenario 1. Alternative extractions with recharge equal to the one registered in 2002 [8].

- Scenario 2. Alternative extractions with recharge equal to the one registered in 2011 [7].
- Scenario 3. Pessimistic extractions with recharge equal to the one registered in 2002 [8].
- Scenario 4. Pessimistic extractions with recharge equal to the one registered in 2011 [7].
- Scenario 5. Conservative extractions with recharge equal to the one registered in 2002 [8].
- Scenario 6. Conservative extractions with recharge equal to the one registered in 2011 [7].

In order to recognize the changes in phreatic levels, 3×10^6 m^3 of artificial recharge were added to each scenario. This additional volume was set, beginning from 2017 to 2016, as an injection into the main creek at the village of Santa Anita.

6. Results

According to the obtained water budget, the following results were obtained: a deficit of -32.02×10^6 m^3 and a compromised discharge of 3.24×10^6 m^3 for the last year of scenario 1; a deficit of -26.35×10^6 m^3 and a compromised discharge of 3.56×10^6 m^3 for the last year of scenario 2; a deficit of -78.89×10^6 m^3 and a compromised discharge of 2.26×10^6 m^3 for the last year of scenario 3; a deficit of -73.29×10^6 m^3 and a compromised discharge of 2.61×10^6 m^3 for last year of scenario 4; a deficit of -22.37×10^6 m^3 and a compromised discharge of 3.23×10^6 m^3 for the last year of scenario 5; and a deficit of 16.62×10^6 m^3 and a compromised discharge of 3.55×10^6 m^3 for the last year of scenario 6 (Table 2).

Table 2. Water budget for the beginning and the end of each scenario. Values are presented in 10^6 m^3. Mean annual recharge (R), induced recharge (Ind. R), compromised discharge (DIS), pumping wells (Wells). Variation in phreatic levels in the middle basing zone (Mid) and near the coast (Co) and near the coast with artificial recharge (A. R. Co.) are presented in meters.

	R	Ind. R	DIS	EVT	Wells	In	Out	Balance	Mid	Low
E1.-2017	24	1.50	3.48	1.10	37.28	25.50	41.86	−16.36		
E1.-2026	24	1.50	3.24	1.10	53.18	25.50	57.52	−32.02	−10.49	−2.20
E2.-2017	30	1.50	3.59	1.10	37.28	31.50	41.96	−10.46		
E2.-2026	30	1.50	3.56	1.10	53.18	31.50	57.85	−26.35	−9.07	−1.50
E3.-2017	24	1.50	3.45	1.10	44.37	25.50	48.93	−23.43		
E3.-2026	24	1.50	2.26	1.10	101.08	25.50	104.44	−78.94	−37.16	−8.80
E4.-2017	30	1.50	3.59	1.10	44.37	31.50	49.06	−17.56		
E4.-2026	30	1.50	2.61	1.10	101.08	31.50	104.79	−73.29	−35.47	−8.10
E5.-2017	24	1.50	3.40	1.10	34.35	25.50	38.85	−13.35		
E5.-2026	24	1.50	3.23	1.10	43.37	25.50	47.87	−22.37	−4.53	−1.78
E6.-2017	30	1.50	3.60	1.10	34.35	31.50	39.05	−7.55		
E6.-2026	30	1.50	3.55	1.10	43.37	31.50	48.12	−16.62	−4.24	−1.37

The results indicate that the main variation of the phreatic levels occur in the middle zone of the aquifer. This area stretches from the Santa Anita creek southward to the town of San José, and includes the pumping wells with the highest extractions volumes of the aquifer; here the water is used for urban and agricultural.

The results of the model with respect to the mean phreatic levels in the low-middle part of the basin indicate: For scenario 1 a decrease of the phreatic levels between 7 and 12 m was observed, with an average value of 10.4 m, and a decrease between 0.5 and 4 m with an average of 2.2 m in the zone near San José del Cabo town. Scenario 2 presented a decrease between 5 and 10 m with an average of 9.1 m in the low-middle section, and between 0 and 3.5 m with an average of 1.5 m for the zone near the town of San José del Cabo. For scenario 3, a decrease between 25 and 47 m was calculated, with an average value of 37.2 m, in the low-middle zone, and between 2 and 16 m, with an average of 8.8 m, for the zone near San José del Cabo. For scenario 4, there was a decrease between 23 and 45 m with an average of 35.5 m for the low-middle section of the basin, and a decrease between 2 and 15.5 m with an average of 8.1 m for the zone near San José del Cabo. For scenario 5, there was a decrease between 1.99

and 5.4 m with an average of 4.24 m for the low-middle section of the basin, and a decrease between 1 and 2.55 m with an average of 1.78 m for the zone near to San José del Cabo. For scenario 6, there was a decrease of 1.7 and 5.68 m with an average of 4.52 m for the low-middle section of the basin, and a decrease between 0.4 and 2.26 m with an average of −1.37 m for the zone near San José del Cabo (Figures 6–8).

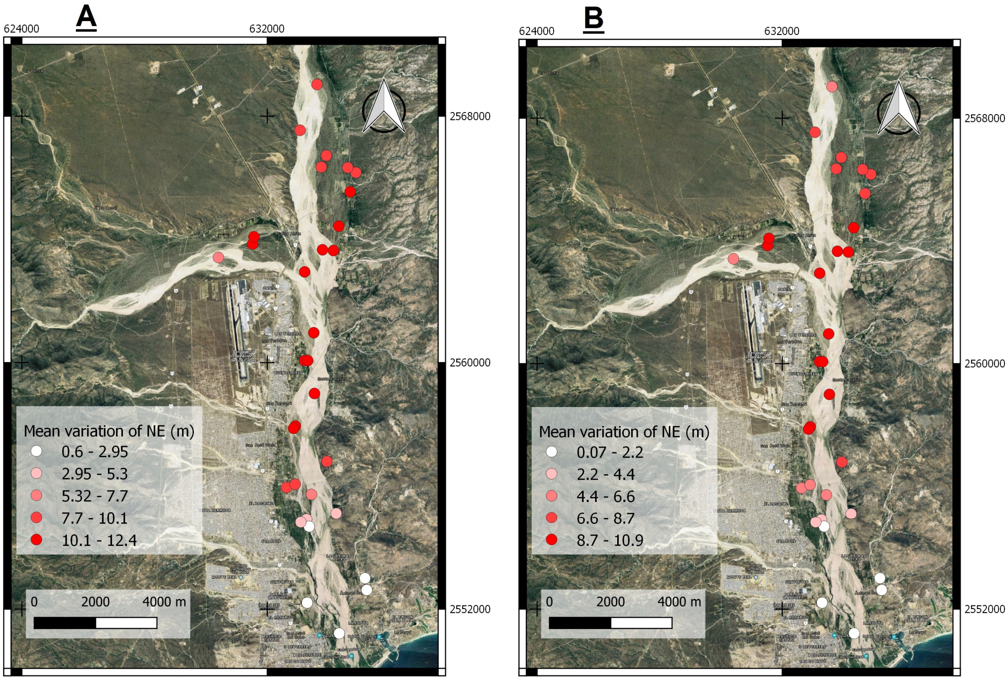

Figure 6. Spatial arrangement of the observation points and its decreased values for the final stage of scenario 1 (**A**) and scenario 2 (**B**).

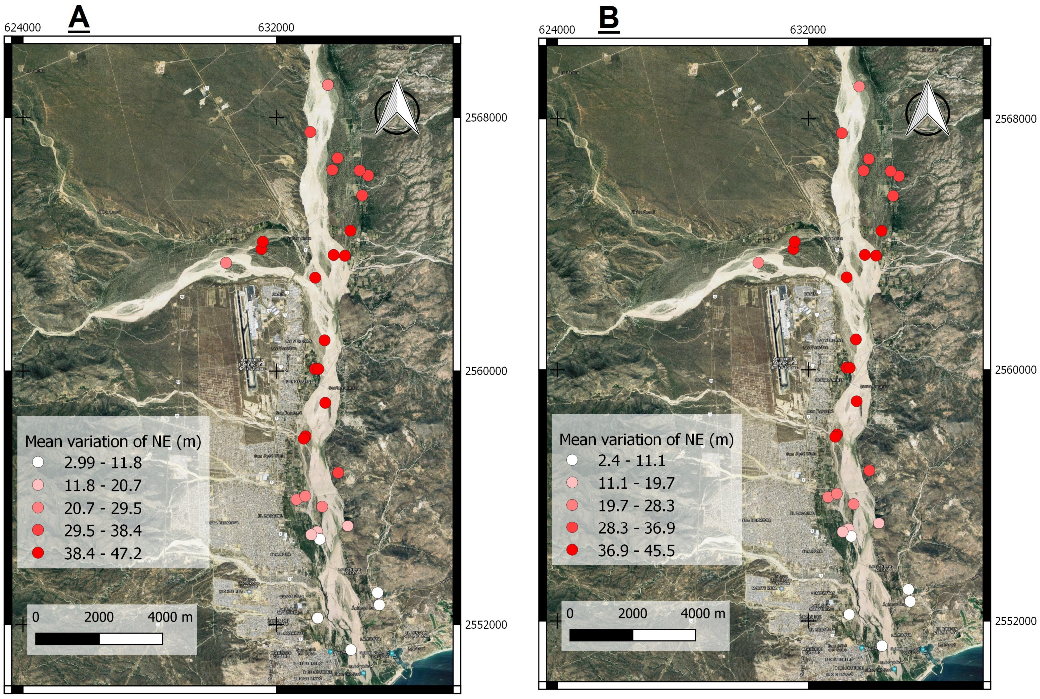

Figure 7. Spatial arrangement of the observation points and its decreased values for the final stage of scenario 3 (**A**) and scenario 4 (**B**).

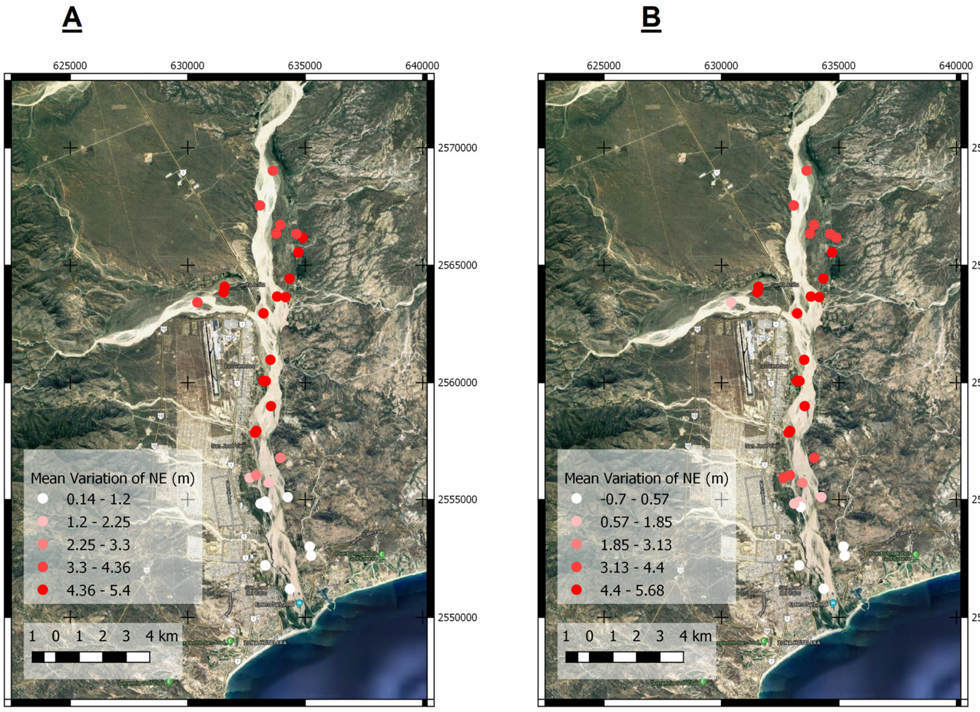

Figure 8. Spatial arrangement of the observation points and its decreased values for the final stage of scenario 5 (**A**) and scenario 6 (**B**).

The results were analyzed by using multiple linear regression in Rstudio coding environment [40]. The dependent variables were recharge and extraction, and the response values were discharge and mean variation of phreatic levels (for the middle and lower sections of the aquifer). All *p*-level values are acceptable under 0.95% of confidence, except for the recharge variable in the lower part of the aquifer. The t-test coefficient for extraction is higher than the recharge values in all cases, showing the expected negative trend for extraction and a positive for trend for recharge. The obtained Pearson correlation coefficients were: 0.875 for discharge estimation; 0.997 for phreatic level variation in the middle part of the aquifer; and 0.963 for the lower part of the aquifer (Table 3).

Table 3. Multiple linear regression coefficients and their significance for the associated mean difference of phreatic levels for the middle part of the aquifer (B), for the lower part of the aquifer (C), and for the discharge volume to the sea (A). The table presents the standardized regression coefficients (B), standard error (SE), t-test regression coefficient for each regression coefficients (t), *p*-level, and Pearson correlation coefficient. Regression equations are presented for each case.

	Parameters	B	SE	t	*p*-Level	Cor. Pearson
A						
	Int	3.2	$2.57 \times 10^{+5}$	12.435	7.81×10^{-16}	
	Ext	-1.21×10^{-2}	$1.231.61 \times 10^{-3}$	−9.795	1.61×10^{-12}	
	Re	2.83×10^{-2}	8.29×10^{-3}	3.41	0.00142	
B						
	Int	2.23	2.22×10^{-1}	10.079	6.79×10^{-13}	
	Ext	-9.17×10^{-8}	1.06×10^{-9}	−86.319	2.00×10^{-16}	
	Re	1.92×10^{-8}	7.14×10^{-9}	2.689	0.0102	
C						
	Int	1.03	2.67×10^{-1}	3.856	0.000372	
	Ext	-2.77×10^{-8}	1.24×10^{-9}	−22.367	2.00×10^{-16}	
	Re	1.27×10^{-9}	8.70×10^{-9}	0.146	0.884	
Regression Equation A		df = 3.2 − 0.01209 x ext + 0.02827 x re				0.857
Regression Equation B		df = 2.233 − 9.17×10^{-8} x ext + 1.92×10^{-8} x re				0.997
Regression Equation C		df = 1.029 − 2.77×10^{-8} x ext + 1.27×10^{-9} x re				0.963

The phreatic levels in the low-middle section of the aquifer presented a tendency of decrease which can be classified as linear, with a mean decrease of 1 m annually per 10^7 m^3 over the extraction reported by CONAGUA in 2015 of 29 × 10^6 m^3 [7]. Near the coast the decreasing trend is 0.3 m annually per 10^7 m^3 over the same extraction. It is important to denote that this trend is present in all six scenarios (Figures 9 and 10).

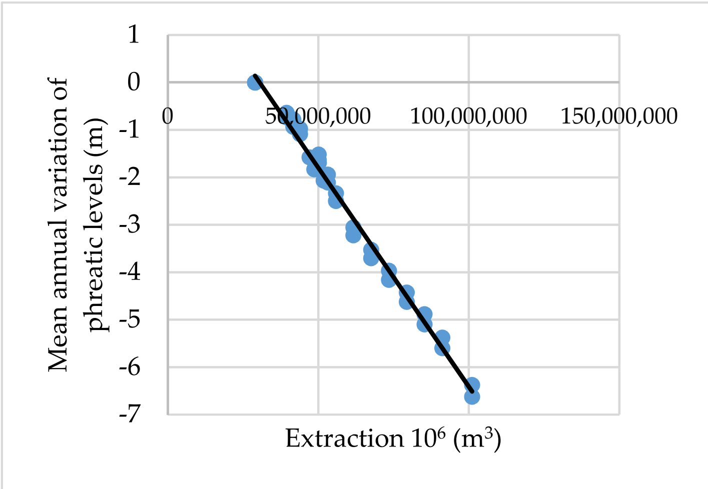

Figure 9. Mean annual variation of phreatic levels per scenario in the middle aquifer. Outlier values were excluded in order to observe the trend more clearly.

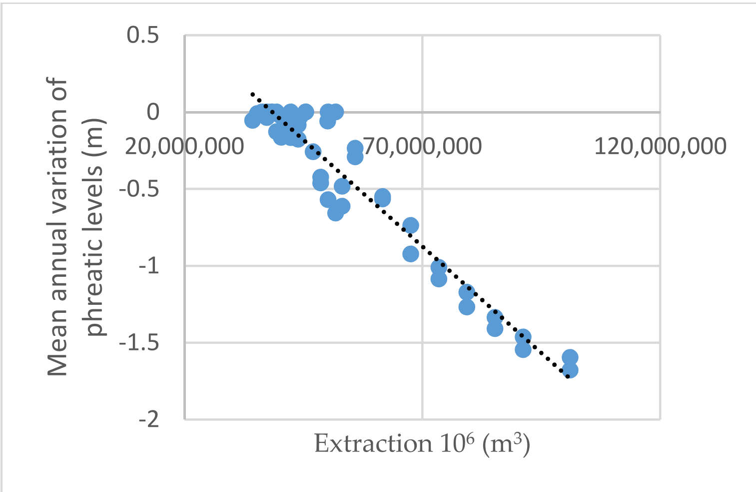

Figure 10. Mean annual variation of phreatic levels per scenario in the lower aquifer. Outlier values were excluded in order to observe the trend more clearly.

The average discharge values had a decreasing trend when the extractions reach 40 × 10^6 m^3 annually. All scenarios indicate that the system is highly responsive to changes in recharge values while the extraction effect is delayed by means of 2~3 years.

This could explain why the middle section of the aquifer is more sensitive to changes in the phreatic levels since the overall trend of groundwater flow is southward. The induced recharge does not affect the overall variation of phreatic levels in the aquifer. The additional 3 × 10^6 m^3, applied by injection wells, affected the phreatic levels positively, that is, by means of 2.2 m less decrease in the middle zone of the aquifer and 0.9 m less decrease in the lower zone of the aquifer.

Scenario 2 presents an increment in discharge, even when the extraction increases. However, near the final years of the simulation, a negative trend can be detected. It is assumed that in later years this negative trend would continue. From the model can be inferred that the changes in overall discharge are highly dependent on extraction values; however, recharge and induced recharge also have an important role in absorbing this variation.

Scenarios 5 and 6 seem to have the most positive outcome; however, the uncertainty in recharge values do not allow the incrementation of the extraction volumes.

7. Discussion

The model presented in this paper is calibrated and validated following standards commonly used; calibration and validation had R^2 values over 0.95 and the absolute mean error is less than the 10% of the maximum difference presented in the area [4,36,44–47].

Due to the scale, the model can be considerate as a coarse model or low-resolution model [4,36,37,44]. Models within this category are commonly used in the assessment of general changes in aquifers. However, in order to assess the effect of specific pumping wells, the influence of geological structures on the phreatic levels or seasonal variability, more information is needed [48]

As mentioned by various authors [48,49], multiple linear regression is a useful and effective tool for groundwater estimation, especially for zones where only little information is available. As a result of the multiple linear regression, the recharge and extraction rate have the most significance when explaining the variation of discharge values and phreatic levels for the middle zone of the aquifer. However, extraction effects in the lower zone of the aquifer seem to overlay the effects of recharge. Since it is not possible that recharge is not related with phreatic levels variation, it was still considered in the analysis. Extraction values seems to have a stronger effect over the variation of phreatic levels, while only a low effect exist over the discharge when compared to recharge. Lower significance levels for the recharge (identified by p-level) seem to reflect the lack of data found in the literature. The t-test coefficient indicates that there is a strong relative effect of the extraction over the recharge in the model. As the Pearson coefficient and the standard error for discharge values indicate, more variables are needed in order to explain the uncertainty of the discharge fluctuation.

In this study, the extraction volume was found to have a strong influence over decrement in phreatic levels, which the actual recharge volume, as reported, cannot compensate. Variation in the phreatic levels show a trend of 1 m of decrease each year per every 1×10^7 m^3 additional extraction for the middle zone of the aquifer. For the lower zone of the aquifer a trend of 0.3 m of decrease each year per 1×10^7 m^3 additional annual extraction volume was observed. Both trends are somehow linear so the values can be extrapolated.

In Baja California Sur several studies have been conducted, which include aquifer modeling and parameterization [19,50,51]. Prior studies found that even if the change in water policies helped to reach an equilibrium in water balance after years of over-exploitation, the deteriorating groundwater quality may still continue [51]. Artificial recharge for non-confined aquifers has shown to be of great importance when dealing with the improvement of recharge capability of potential areas the sustainment of the aquifer and the capability to cope with stresses on groundwater resources [52,53]. According to the result, the infiltration of 3×10^6 m^3 of annual artificial recharge produced a counter effect of on the phreatic level decrement of 2.2 m in the middle zones of the aquifer and 0.9 m of less decrease in the lower parts of the aquifers. Even though, the application of this volume is not enough to stop the decrement, it gives at least some referent on what effect could be expected, if artificial recharge techniques were applied in the SJCB aquifer. These types of structures may also help to reduce the extraction cost, which is of special significance as the registered overall global volume of extraction is expected to increase, especially for domestic, agricultural, and energy sectors [54,55].

In the calculated scenarios, the effect of climate change was not considered. Previous studies denoted that the effects of climate change and sea level rise will impact negatively on San José del Cabo Lagoon from the year 2040, which is the last simulated year [19]. The results of this study indicate that even for the more conservative scenarios, there is a range between 1.78 and 1.37 m decrement of phreatic levels in the lower aquifer. Extrapolation of a linear trend leads to approximately 3 m of decrement in the lower part of the aquifer for the year 2040. Therefore, it is expected that since from year, with combination of effects (extraction increment and climate change), the southernmost part of the SJCB aquifer will be affected.

8. Conclusions

In this study, the effects of population increase scenarios on an unconfined aquifer were determined. The groundwater model has shown that all expected scenarios are prone to decrements in phreatic levels. According to the model, the adjustment of the extraction volume was found to have a strong influence over the phreatic levels that hardly could be lessened by the recharge volume reported. This estimation shows a linear trend of decrement of 1 m of annual decrease per every 1×10^7 m^3 of additional extraction last registered for the middle zone of the aquifer. This trend is three times higher than in the lower section of the aquifer, which shows a trend of 0.3 m of annual decrease per every 1×10^7 m^3 of an additional extraction to the last reported.

This study was not intended to predict a specific phreatic level for a certain year in the future (uncertainty of the phenomena), but to substantiate a prospect of the effects that would cause over-exploitation in the next years. On the other hand, it proposed a way of analyzing results by combining aquifer modeling with multiple linear regressions to analyze possible trends and identify the individual effect and sum results of badly planned and inherent increasing demand of groundwater resources.

The results indicate that the effect of an additional extraction would cause serious damage on the stability of the aquifer balance. The current trend of deficit has to be changed before any attempt to increase the volume extraction.

The model could be improved: 1) If seasonal variation data of the groundwater levels were available; 2) with a refinement of the cells could lead to the detect the effects of individual wells; and 3) by taking in consideration the effects of climate change. Furthermore, the realization of a shorter discretization of spatial and temporal model, and infiltration test in the middle and lower zones of the aquifer could serve to prove the effects of superficial artificial recharge infrastructure. This type of structure is a more viable option when compared with direct artificial infiltration (like injection wells). A more detailed analysis could serve as support for the implementation of this work and the improvement of the aquifer balance. However, the current state of the model could serve to support more conservative water usage policies to achieve a sustainable use of groundwater resources.

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