Geofísica Internacional (2011) 50-4: 425-438

Original paper

Sustainable geohydrological model of San Luis Potosí aquifer, Mexico

E. Leticia Flores-Márquez*, Ingrid Kohn Ledesma and Claudia Arango-Galván

Received: November 18, 2010; accepted: June 7, 2011; published on line: September 30, 2011

Resumen

Un estudio geofísico e hidrogeológico se llevó a cabo en el acuífero de San Luis Potosí, con la finalidad de realizar un modelo transitorio de flujo de agua subterránea que reproduzca el estado actual del acuífero, para posteriormente proponer escenarios alternativos de explotación del acuífero. Este estudio permitió hacer importantes revelaciones sobre el estado del acuífero: el balance de recarga-extracción de agua presentó un déficit de 100 Hm^3 en el año 2005; los niveles potenciométricos de datos recuperados entre 1972 y 2005 muestran un cono de depresión de 80 m de profundidad y 70 km^2 de área en la ciudad de San Luis Potosí; el modelo numérico realizado muestra que el acuífero es muy sensible a la localización de los pozos de extracción. También se realizaron modelos predictivos y algunas medidas de remediación fueron propuestas para obtener una recuperación del sistema acuífero.

Palabras clave: modelo hidrológico, sustentable, acuífero de San Luis Potosí, escenarios predictivos y de remediación.

Abstract

An integrated geophysical and hydrogeological study is carried out on the San Luis Potosí aquifer system and a transient flow model and are proposed alternative exploitation scenarios. The aquifer water balance between recharge and extraction indicates a deficit of 100 Hm^3 by the year 2005. A comparison of the historical potentiometric levels recorded between 1972 and 2005 shows a cone of depression 80 m deep extending over an area of 70 km^2 inside of San Luis Potosí City. The model suggests that the aquifer is sensitive to the locations of extraction wells. Predictive models are developed and remediation measures are proposed as alternatives to current extraction procedures in order for the aquifer system to recover.

Key words: hydrological model, sustainable, San Luis Potosi aquifer, predictive and remediation scenarios.

E.L. Flores-Márquez*
Instituto de Geofísica
Universidad Nacional Autónoma de México
Ciudad Universitaria
Delegación Coyoacán, 04510
México D.F., México
*Corresponding author: leticia@geofisica.unam.mx

I. Kohn Ledesma
Posgrado en Ciencias de la Tierra
Universidad Nacional Autónoma de México
Ciudad Universitaria,
Delegación Coyoacán, 04510
México D.F., México
E-mail: ingridkl@gmail.com

C. Arango Galván
Instituto de Geofísica
Universidad Nacional Autónoma de México
Ciudad Universitaria
Delegación Coyoacán, 04510
México D.F., México
E-mail: claudiar@geofisica.unam.mx

Introduction

Around the world, groundwater studies beneath large cities are becoming increasingly important, as they are linked to economical, social, legal, and political issues. Cities in Mexico show a continuously increasing demand of water supply. This is the case of the city of San Luis Potosí, in northeastern Mexico (Figure 1). Moreover, the surrounding irrigated agriculture zones and industrial developments in the region have caused a significant drawdown of the potentiometric surface of the middle aquifer.

As urban population grows, a combined use of surface and groundwater is likely to become increasingly common, and water management is required (Gossell *et al*., 1999; Aldrick *et al*., 1999). Even when its quality makes it unsuitable for drinking, groundwater can be used after treatment for alternative purposes. This could reduce the demand for high-quality water. Hydrogeological main flow and transport processes, and water supply infrastructure affecting urban groundwater are not essentially different from rural regions, but the time and space scales involved are significantly different (Vázquez-Suñe *et al*., 2005).

The aim of this paper is to provide a numerical model of transient flow of San Luis Potosí aquifer in order to contribute to the sustainable management of the aquifer, based on different extraction conditions. We have analyzed the hydrogeological system of San Luis Potosí in multidisciplinary studies conducted in the area; those studies provide the appropriate boundary conditions, geological layers, their geophysical properties and the hydrological parameters. The changes in potentiometric levels over the past 30 years have been analyzed and the results are presented in this report. This study also seeks to model the future water level decline from increasing water extraction as the rate of population grows until 2015. A three-dimensional numerical flow model was created using Visual MODFLOW software (McDonald and Harbaugh, 1988), version 3.1.

Geological setting and hydrogeology of San Luis Potosí Valley

The San Luis Potosí Valley (SLPV) is located in the Mexican Central Plateau physiographic province between the Sierra Madre Oriental and the Sierra Madre Occidental. It has an approximate altitude of 1,850 m above mean sea level (msl) and has an extension of 1,980 km^2. The SLPV coincides with the San Luis Potosí Graben, the most important geological feature in the area. It is bounded to the west by the Sierra de San Miguelito, to the east by the Sierra de Álvarez, and to the northwest and southwest by a series of isolated hills (Figure 3a).

The lithology of the SLPV used for this study was inferred from boreholes and geoelectrical studies already published. The geological and hydrogeological information has been recorded by Martínez-Ruiz and Cuellar (1979) and Labarthe *et al*. (1982). The vertical electrical soundings (VES) recorded by Castillo-Cruz (2003) and CNA (2002), and the lithological information

Figure 1. Location of the SLPV at the San Luis Potosi, Mexico. Dashed box indicates the flow model studied area in UTM co-ordinates.

of 130 wells (Castillo-Cruz, 2003) allowed to know the geological layers within the valley. This information was reinterpreted by Cardona (2007) to generate the stratigraphic column shown in Figure 2, composed by seven geological units described below, from the surface to the basement.

Unit U1 is composed of alluvial material of Quaternary age and consists of gravel, silt, sand and clay that fill the central portion of the area, which forms the SLPV. Its thickness varies between 60 and 350 m, according to the stratigraphic information of some deep boreholes. Within this unit are also gravel lenses of mixed composition. This suggests that their origin is due to rapid erosion of the nearby mountains, and and deposition by turbulent water currents, without prolonged weathering.

Unit U2 is constituted of clay and fine sand, and is identified as an aquitard with average thickness of 50 m. This unit is only located along the central part of the SLPV and gradually disappears towards the mountains.

Unit U3 has the same lithology as the unit U1 but the aquitard constituted by U2, between these two units make a separation of them. Moreover, the unit U1 is considered the shallow aquifer while the unit U3 is considered part of a deeper aquifer.

Unit U4 consists of rhyolites, ignimbrites, basalts and tuffs of the Oligocene epoch. The mean thickness of this unit is 210 m. The tuff is slightly reddish cream colored, laminated with layers of 5-30 cm thickness. The ignimbrite crops out over a wide area of the eastern part of Sierra de San Miguelito, it has colors ranging from light red to pink and pinkish gray in other cases, with 10-15% of quartz crystals content.

Unit U5 has a mean thickness of 340 m and is composed of rhyolites, ignimbrites and tuffs, also Oligocene in age. This unit outcrops in small areas in the lower part of the Sierra de San Miguelito with grayish brown rhyolites. The ignimbrite is pinkish-gray with 30-40% quartz crystals.

Unit U6 consists of rhyolites, sandstones, ignimbrites, clay and silt, of Paleocene-Eocene age, and has an average thickness of 130 m. It is the bottom layer of the volcanic series of the SLPV.

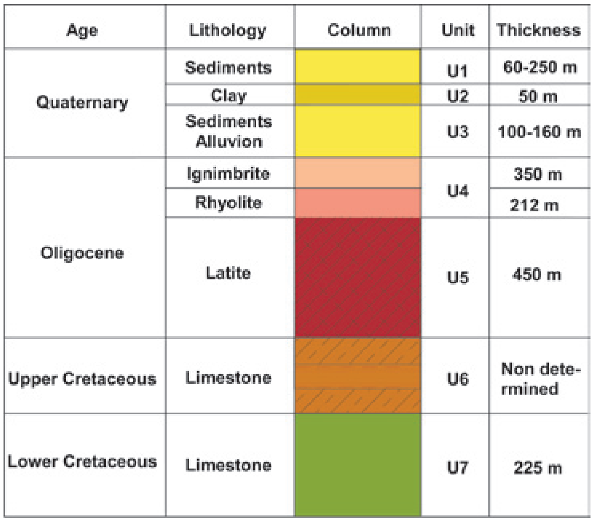
Unit U7 corresponds to the basement and is composed of limestone and clay. The whole unit is tightly folded so it is difficult to measure its thickness. The assigned age is the Late Cretaceous (Turonian).

According to Labarthe *et al*. (1982) and Tristan (1986) the process of continental clastic sedimentation (filling of the graben) is considered to have succeeded simultaneously to the formation of the graben. The normal faults flanking the graben form several blocks of different depths that increases toward the central part, named "the valley of San Luis Potosí".

Figure 3b shows two geological cross sections with the configuration of the granular material, which clearly defines the presence of a deeper regional basement in the central area. The surface location of these sections is also illustrated in Figure 3a.

Hydrogeology

The average annual rainfall in SLPV is 378 mm/year, where most rain occurs in the Sierra de San Miguelito and the Sierra de Álvarez (Tecnología ASSUL, 2005). The rainy season begins in May with most rain occurring from June to September. The mean annual temperature, based on measurements at a single weather station from 1979 to 2001, is 17.6 °C. The hottest month is May, after which the temperature drops gradually until December and January, which have the lowest temperatures. The annual average potential evaporation ranges from 1,950 mm in the eastern part of the SLPV to 2,250 mm in the foothills of the Sierra San Miguelito, an average of about 1,990 mm for the entire valley of San Luis Potosí (Sabinfosistem, 2005).



Age	Lithology	Column	Unit	Thickness
Quaternary	Sediments		U1	60-250 m
	Clay		U2	50 m
	Sediments Alluvion		U3	100-160 m
Oligocene	Ignimbrite		U4	350 m
	Rhyolite			212 m
	Latite		U5	450 m
Upper Cretaceous	Limestone		U6	Non determined
Lower Cretaceous	Limestone		U7	225 m

Figure 2. Stratigraphic column of the studied area (modified from Nieto–Samaniego *et al*., 2005).

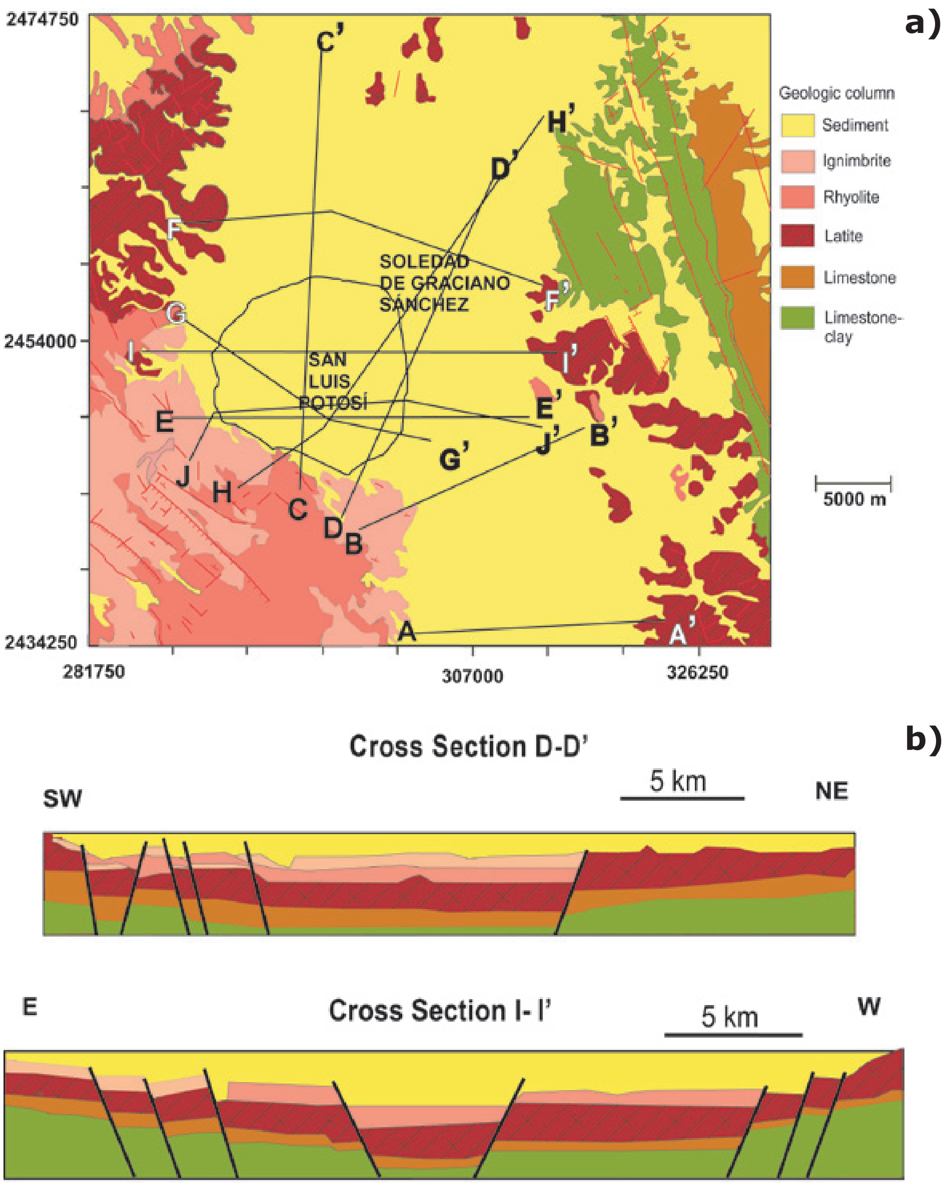


Figure 3. a) Surficial geology in the region and location of ten geological cross sections. b) Two geological sections D-D' and I-I' (modified from Cardona, 2007).

The rainfall runoff from the flank ranges (the Sierra de San Miguelito and the Sierra de Álvarez) feeds several intermittent rivers: the Santiago, which is the main collector of the basin; and the Españita, Paisanos, and La Parada, which are currently piped and do not contribute to the infiltration of the upper aquifer.

One important demand of water supply is due to the irrigated agriculture, extensively used in the central portion of the SLPV, where the main crops are nopal (cactus), corn, tomato, oats, chili, bean and replanted grassland. The remaining area on the valley floor consists predominately of natural vegetation: composed of chaparral and natural grassland, and in the hills dominated by scrub, desert scrub and thorny scrub (CNA, 2004).

The groundwater overexploitation is also due to the increased population of the region. According to the results of the last population census implemented in 2005, the population of the state of San Luis Potosí was 2,410,414. The populations of the municipalities located within the study area are shown in Table 1.

Table 1. Total population of the municipalities located within the study area (INEGI, 2005).

Municipalities	Total population
San Luis Potosí	730,950
Soledad de Graciano Sánchez	226,803
Mexquitic de Carmona	48,484
Cerro de San Pedro	3,278

The drinking water demand for the year 2001 was of 82.9 Million m^3 (Mm^3), corresponding to the average volume supplied to the conurbation of Cerro de San Pedro, San Luis Potosí and Soledad de Graciano Sanchez. The water supply increased to 90.7 Mm^3 for the year 2003; corresponding to an overall average of 226.95 liters/capita/day. In 2004, 92.6% of the water supply came from groundwater and 7.4% came from the "San Jose" and "El Peaje" reservoirs. The useful capacity of these reservoirs is 5.1 Hm^3 and 6.7 Hm^3, respectively. They are located in the Sierra de San Miguelito and are used to supply drinking water for the conurbation of the city of San Luis Potosí (Tecnología ASSUL, 2005).

Groundwater level decline

Potentiometric measurements of the aquifer system at San Luis Potosí used for this study were compiled from Cardona (1990), Martínez-Banda (2005) and Sabinfosistem (2005).

The extraction of groundwater from the deep aquifer began in the late forties, but the hydrogeological information available for that time was scarce and of poor quality, therefore we could not make conclusions about the management of the aquifer at that time. From the beginning of extraction to 1972, we estimated that the water level elevations in wells decreased at a rate of 0.9 m per year, while for the period 1977-1990 the mean decline rate was estimated at 1.3 m/year. The estimated extraction from the deep aquifer between 1972 and 1990 was increased around 330% (from 0.78 to 2.6 m^3/s). It should be mentioned that measurements of static levels for the years 1972, 1986, 1987 and 1997 are scarce, but show an average static levels of 1760, 1744, 1746 and 1730 m above sea level respectively.

Figure 4 shows the historical potentiometric levels of the deep aquifer for the years 1977, 1992, 1999, and 2003. We can notice that, for the year 1977 there is not drawdown of the potenciometric level, and the natural gradient shows water flows from the southeast to northwest. For the years 1992 to 1999, an important increase in demand of water produces a zone of drawdown at the city of SLP and the gradient of water inverted its flowing direction from the north of the aquifer to the south. The measurements for the years 1995 and 2005 were used to calibrate the flow model, because of the availability of a greater number of static level measurements recorded for those years. The static level depth was subtracted from the interpolated elevation in order to calculate the static level rise. The elevation of the static level through these years is shown in Figure 5.

Visual inspection of the potentiometric levels especially for the area delimited by the 1,720 m isoline, shows an increase in elevation. During the period from 1995 to 2005, this area increased from 88.6 km^2 to 274.2 km^2.

Groundwater flow model

The employed model to simulate the groundwater flow in the San Luis Potosí study region includes digital topography, natural boundaries of the aquifer system (i.e. ranges, borders with others aquifers, geological structures), definition of stratigraphic layers, and their corresponding hydraulic properties. The topographic data were taken from the Mexican digital topographic geodatabase from INEGI. The model was built relating the hydrogeological information and the lithological columns from wells drilled in the zone (Cardona, 2007). Hydraulic properties were assigned according to the lithology corresponding to the seven geological layers inferred from geophysical studies and lithological description from 130 wells, and also considering the surface geology and the deduced and measured local hydrologic properties already published (Gelhar *et al*. 1992; Bear 1972; Bear and Bachmat 1991 and De Marsily, 1986). Hydraulic transmissivity was inferred from local studies (i. e., pumping tests) performed in different wells along the basin (CNA, 2002; Sabinfosistem, 2005).

The model area was limited from 2,434,250 to 2,474,750 m North UTM coordinates and from 281,750 to 326,250 m East UTM coordinates (Figure 6a). It covers a total area of 1,802.3 km^2, with a grid of 90 columns and 82 rows representing the aquifer in the x-y plane, that is equivalent to 7,380 cells per layer, each cell measures 500 x 500 m. As we already mentioned, seven layers characterize the domain in the z-direction, with variable thickness corresponding to the interpreted geological units (Castillo-Cruz, 2003). Frontal and tributary recharges were treated in the model as specific flow boundaries that is a Neumann boundary condition (McDonald and Harbaugh, 1988).

Figure 6b shows the mesh of the model area. The inactive cells (green) represent the mountains surrounding the valley of San Luis Potosí, and they are not considered to solve the flow equations, while the white area represents the active cells of the model.

In agreement with the lithology of the area (shown in Table 2; Cardona, 2007), the hydraulic conductivity, for each layer in depth (the z-direction), was assigned as is illustrated in the cross section of the model (Figure 6c) in VISUAL MODFLOW software by different colors.

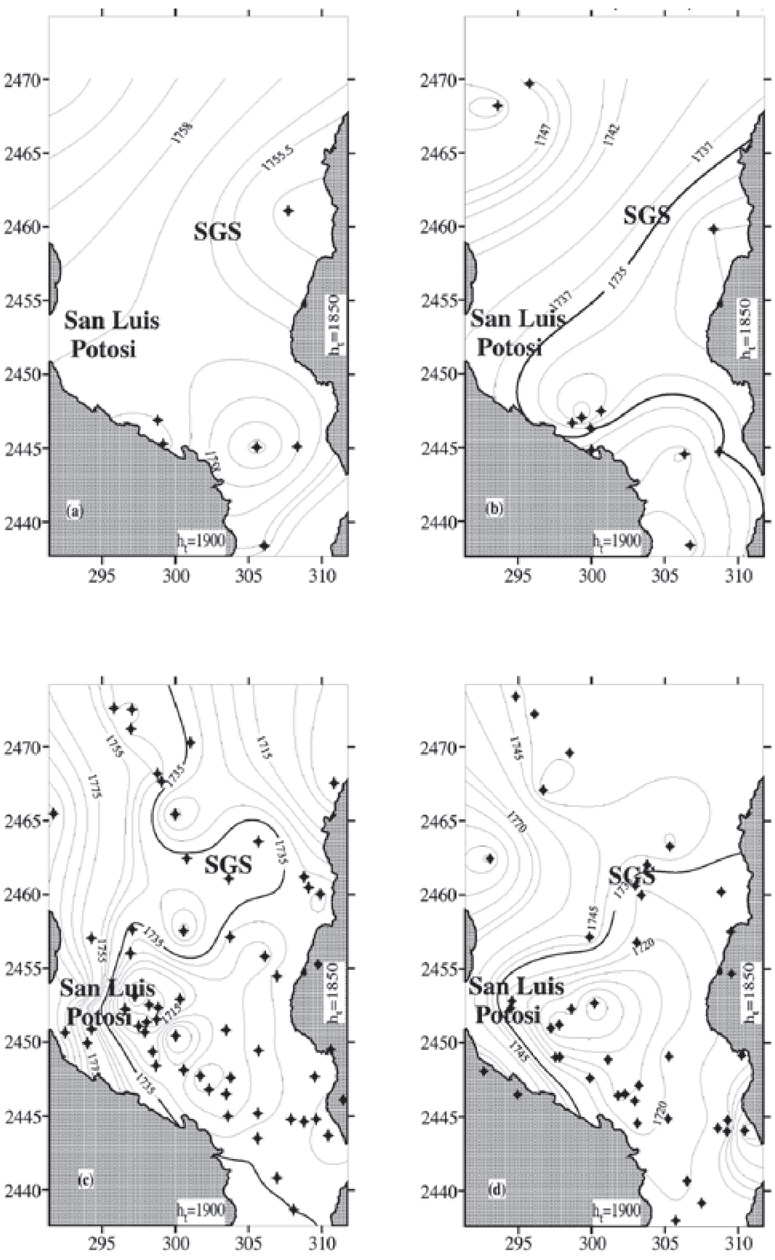


Figure 4. Historical potentiometric levels of the deep aquifer for the years (a) 1977, (b) 1992, (c) 1999 and (d) 2003. Well locations are also shown.

Table 2. Lithological layers merged to the model (see fig 6c).

Layer	Lithology	Thickness mean (m)	Color
1	Gravel, sand, silt and clay	60-250	Yellow
2	Aquitard: clay and fine sand	50	Dark Yellow
3	Gravel, sand, silt and clay	100-160	Yellow
4	Rhyolite, ignimbrite, basalt and tuff	350	Peach
		212	Dark pink
5	Rhyolite, ignimbrite and tuff	450	Dark Red (Dashed)
6	Rhyolite, sandstone, ignimbrite, clay and silt	130	Orange
7	Limestone and clay	225	Green

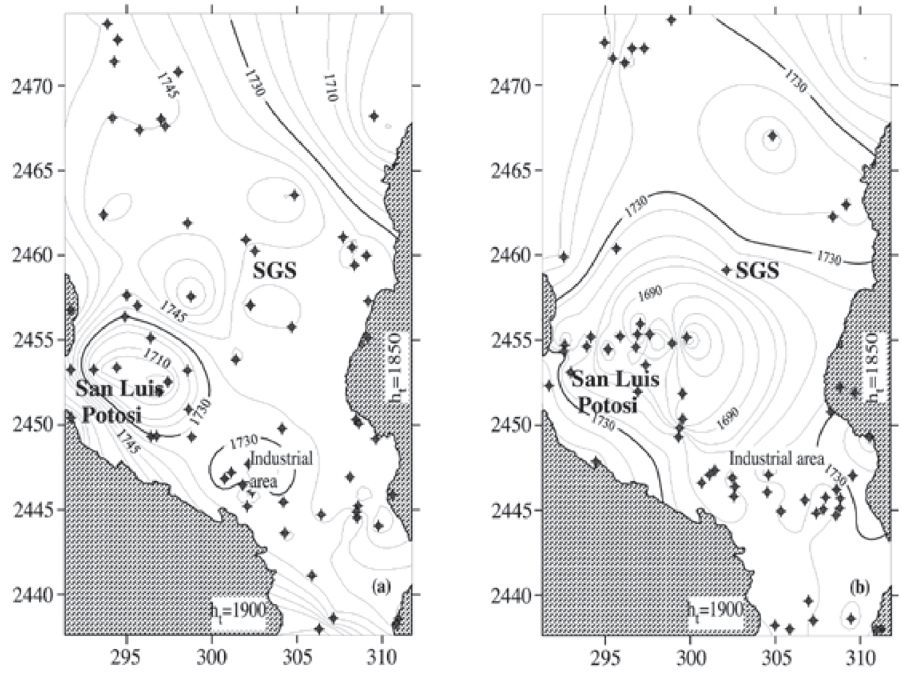


Figure 5. Historical potentiometric levels used to make the calibration of the flow model for the years (a) 1995 and (b) 2005. Well locations are also shown.

The hydraulic conductivity, specific storage, specific yield and total porosity were obtained from already published data (Domenico and Schwartz, 1990; Sanders, 1998 and Walton, 1989; Sabinfosistem, 2005; Flores-Márquez *et al*., 2006; Cardona, 2007); these parameter values were fitted during the model calibration (Table 3).

Boundary conditions used along the East, West and North sides of the model correspond to areas of natural recharge of the aquifer. The boundary conditions to the east and west were assigned along the ranges San Miguelito and Álvarez ranges, just after the inactive cells. The north border represents the exchange of water flow between the SLP aquifer and a portion of the aquifer to the north. A free boundary was assigned in south border because of the structural closure of the basin. All boundary conditions are taken as Neumann boundaries, which assume a constant flow (Table 4).

The recharge corresponding to rainfall was preset at 1x10^{-5} m/d (3.08 hm^3/year) for the total area of the valley, 844 km^2, without the hills. It is consistent with the values of precipitation reported in the zone (CNA, 2002; Tecnología ASSUL, 2005).

Evapotranspiration was fixed at 0.918x10^{-3} m/d, with an extinction depth of 5 m. These values were defined based on climate, vegetation of the region and previous studies.

Table 3. Hydrological parameters for each layer.

Layer	(K_x) Hydraulic conductivity (m/d)	(K_z) Hydraulic conductivity (m/d)	(Ss) Specific storage (m^{-1})	(Sy) Specific yield	Total porosity (%)
1	3.00	3.00	2x10^{-5}	0.09	0.28
2	0.15	0.15	8x10^{-5}	0.11	0.33
3	3.00	3.00	2x10^{-5}	0.09	0.28
4	6.33	12.00	7x10^{-5}	0.11	0.22
5	0.68	6.00	9x10^{-5}	0.14	0.20
6	0.36	0.36	6x10^{-5}	0.11	0.22
7	1x10^{-5}	1x10^{-5}	7x10^{-5}	0.05	0.28

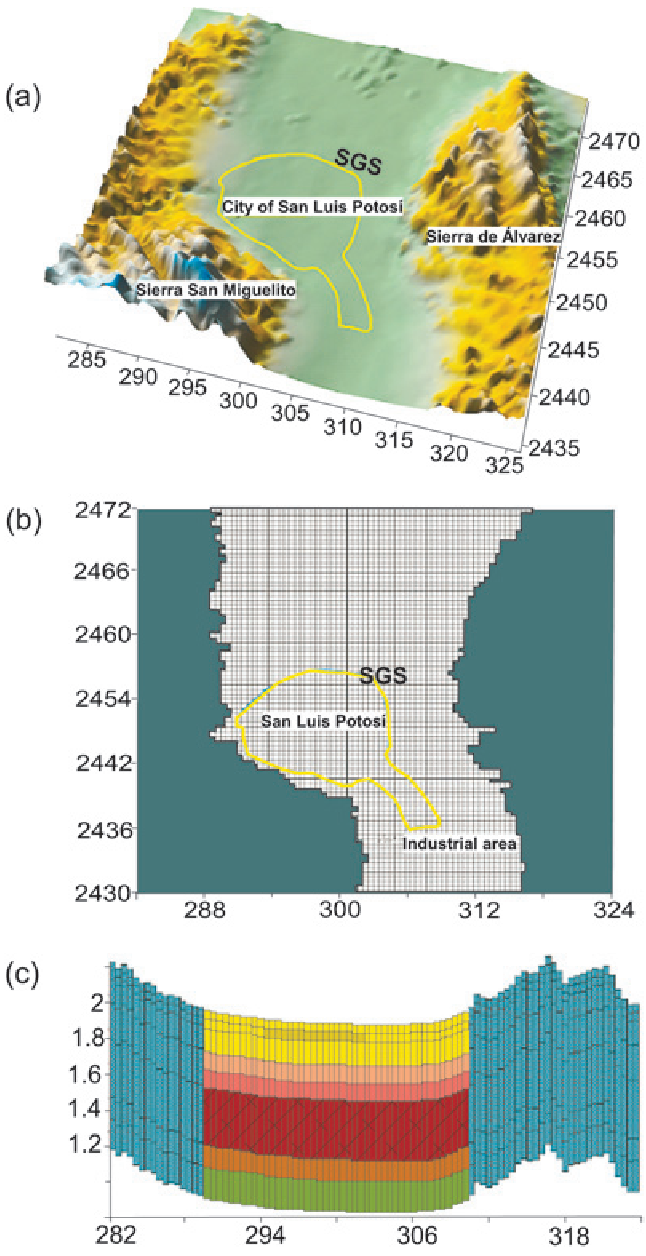


Figure 6. (a) Tree-dimensional view of Digital topographic elevation for the modeled area, contour of Luis Potosi city comprising southeast industrial area is in yellow (b) mesh used for the model and (c) layers in depth (km) used for the flow model.

The first stage of the numerical model was a stationary model that reproduces the observed hydraulic head configuration for the year 1995, which is considered the beginning of extensive exploitation.

Transient flow model

A transient flow model simulates the evolution of the aquifer due to total water extraction in the area and its evolution in time. A total of 1,273 exploitation wells have been registered within the San Luis Potosí aquifer, from them 785 wells extract water from the deep aquifer, and 488 exploit the shallow aquifer (Sabinfosistem, 2005). Nevertheless, just 48 wells had enough historical potentiometric measurements. In order to optimize this information in the model, the totality of exploited wells were only modeled by these 48 documented wells (Flores-Márquez *et al*., 2006). The position of each well was properly located on the model to agree with their real location, thus the amount of extraction water for each one represents the equivalent extraction of 25 wells approximately. Measured hydraulic heads of 29 observed wells were used for calibration of the model, and correlated with those computed by the model (Figure 7a). The initial head distribution, boundary conditions and hydraulic parameters were properly input in the model, agree with the natural boundaries of the aquifer described above.

The transient simulation of the aquifer starts at 1995, figure 7b shows the potentiometric surface generated by the model for that year. It can be observed the bigger drawdown is recorded by the equipotential of 1,710 m asl, which is located in the west part of the city of San Luis Potosí, indicating a cone of depression in this area. A second place showing a significant drop in the potentiometric surface is Soledad de Graciano Sanchez (SGS), an important industrial area close to the city of San Luis Potosí. In this region, besides to the water supplied for human consumption, there are several wells extracting water for agricultural purposes. A minor decline is located near to the Sierra de San Miguelito, which constitutes an important region of aquifer recharge. The comparison

Table 4. Boundary conditions of the model.

General head Boundary (GHB)	Boundary head (m)	Conductance (m^2/d)	Time (days)	Layers where allocated
North	1760	3164	21,900	1
East	1750	4082	21,900	1
West	1750	4082	21,900	1 to 7

between the potentiometric surface computed for the years 1995 and 2005 allows to confirm that the greatest drawdown remains at the same superficial position of the city of San Luis Potosí, which is featured by an increase of 5 m in depth of the drawdown. Moreover, figure 7c (the model for the year 2005) illustrates that the isoline 1,730 m asl, spans a wider surface area towards the SGS and the Cerro de San Pedro covers a larger region on surface.

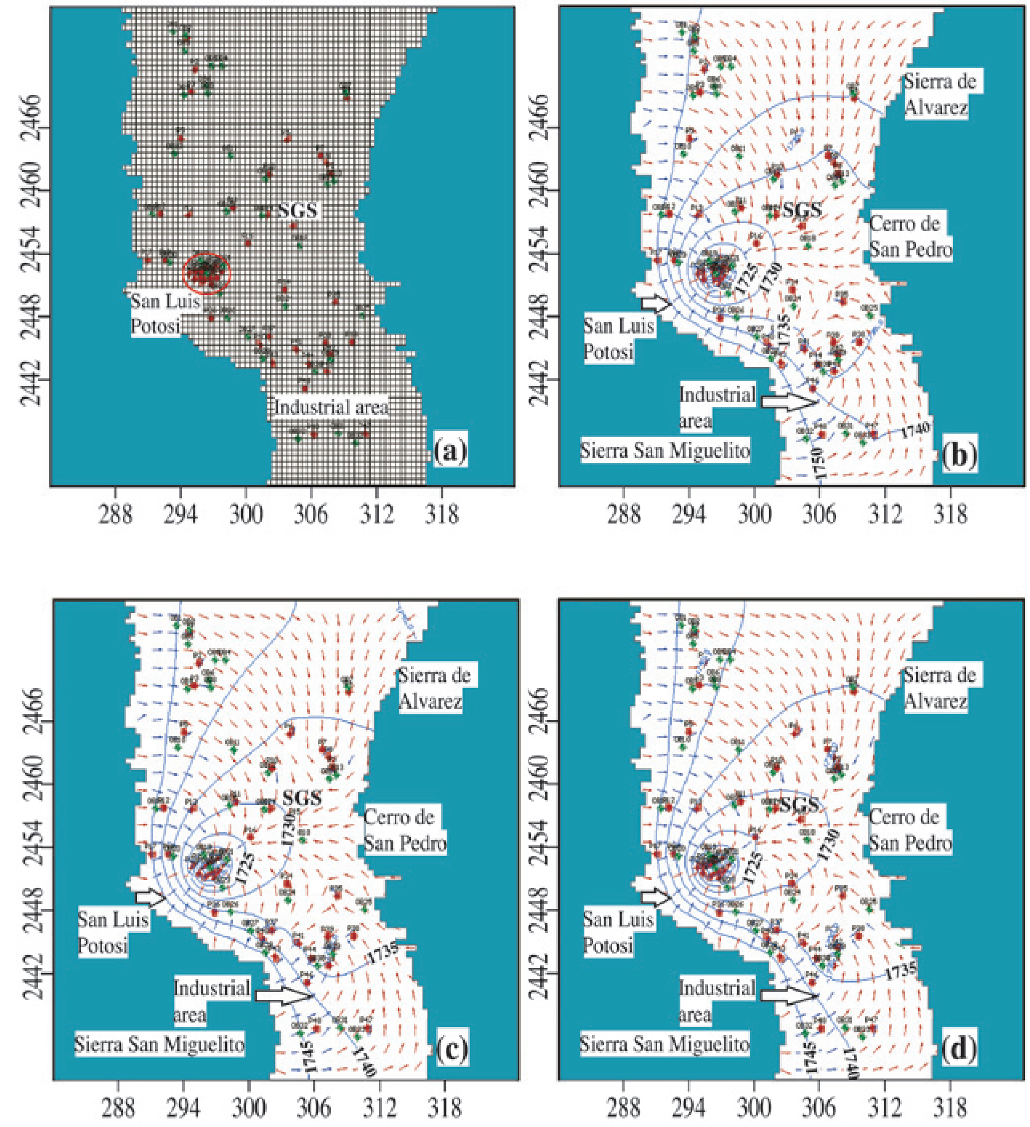
The linear correlation between observed and computed hydraulic heads for the years 1995 and 2005 can be observed in Figure 8 (a, b), with an associated RMS error of around 9%, which is acceptable for an aquifer in constant intensive exploitation.

Aquifer exploitation future scenarios

The first scenario simulated corresponds to the year 2015 (Figure 7d); it assumes the same volume of water extraction that was used for 1995 and 2005 simulations. It shows the evolution of the aquifer if the rate of extraction is constant till the year 2015. It is observed that the drawdown in the city of San Luis Potosí increases and is more widespread.

After this one, two types of simulated scenarios were analyzed: one predictive and the other for remediation. The predictive scenario of the aquifer was computed increasing the extraction flow in terms of four possible rates of population growth. The remediation scenario

Figure 7. a) Horizontal mesh of the model and well locations, the red points are extraction wells and the green points are observation wells, orange circle envelop the wells situated within the SLP city, from 19 to 33. Potentiometric surface generated by the model for the years: b) 1995, c) 2005 and d) 2015.



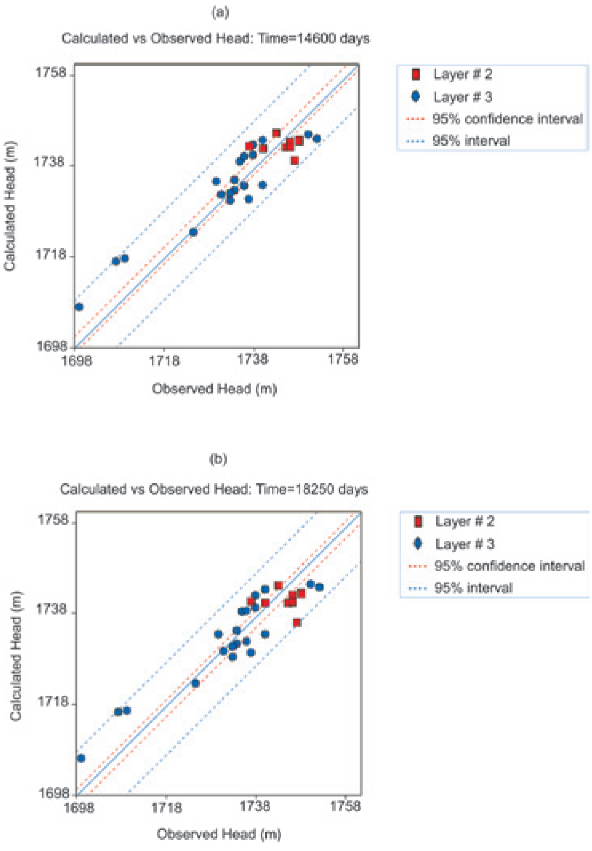


Figure 8. Scatter plot correlation for the corresponding model calibration for the years (a) 1995 and (b) 2005.

was simulated assuming a decrease of the total amount of extraction water and relocation of extraction wells to the recharge zones.

Predictive scenarios

For the four predictive scenarios, growth population rates were computed according to the last census performed by INEGI (2005) in the state of San Luis Potosí, assuming increases of population of: 1.0, 0.8, 0.6 and 0.4% respectively. The annual population growth rate that occurred between 2000 and 2005 was 0.8%, therefore we chose a higher rate than this percentage (1.0%), an equal rate (0.8%), and two lower rates (0.6 and 0.4%) in order to compute a reasonable population for 2015. Table 5 shows the existing population in 2005 in the area and the projected population in 2015 for each growth rate applied.

In Table 5 a water consumption of 226.95 liters per day per capita (Tecnología ASSUL, 2005) was used to compute the additional extracting volume and the total water supply for 2015. Finally, depending on the rate of population growth, the additional amount that would extract each well (in m³/day) was computed. Four predictive models were obtained, each one corresponding to the different rates of population growth, they are shown in Figure 9: a) 0.4%, (b) 0.6%, c) 0.8% and d) 1.0%.

Table 5. Total population (in number of inhabitants) for 2005 and 2015, and the additional extraction need for each growth rate population.

Population growth rate	Computed population for 2015	Additional extraction for each well (m³/day)
2005 year	1,011,520*	
0.4%	1,092,442*	383
0.6%	1,132,902*	574
0.8%	1,173,363*	765
1.0%	1,213,824*	957

*The inhabitants were considered for the municipalities of Cerro de San Pedro, Mexquitic de Carmona, San Luis Potosí and Soledad de Graciano Sanchez.

Remediation scenarios

Concerning remediation models, two possibilities of aquifer evolution till year 2015 were simulated. The first one was based on the previous model corresponding to the annual population growth rate of 1.0% and by assuming a 30% decrease (78,120 m³/day) of extraction water for the wells situated in the area of great drawdown (the wells situated in the SLP city, from 19 to 33). Remaining wells were taken with an unchanged extraction volume; Figure 10a shows the potentiometric surface generated by this model.

The second model assumes a relocation of wells; we propose four new extraction wells in one side of the Sierra San Miguelito, immediately west of the city of San Luis Potosí, which would extract the same volume of those reduced by decrease in extraction. The new extraction wells are called: R1, R2, R3 and R4 (Figure 10b, orange circles). This model was also based on the annual population growth rate of 1.0% and by assuming a 30% decrease of extraction water for the wells situated in the area with the greatest drawdown (the wells situated in the SLP city, orange circle of Figure 7a). Thus the extraction in the four wells, that is equivalent to the reduction extraction, does not significantly affect the response of the rest of the aquifer.

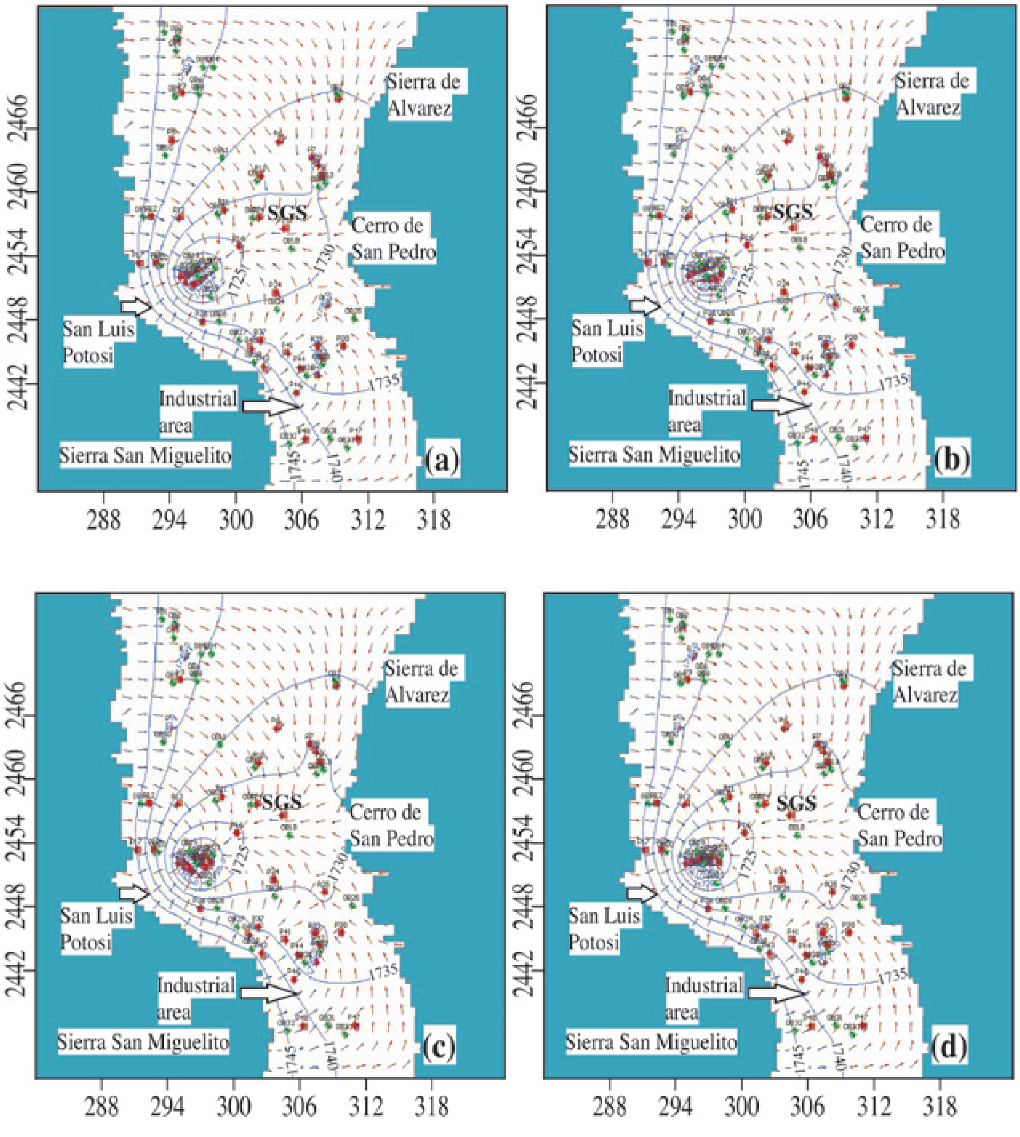


Figure 9. Four predictive models for 2015, assuming population growth rates of (a) 0.4%, (b) 0.6%, (c) 0.8% and (d) 1.0%.

Discussion

The transient model developed for this study simulates the evolution of the potentiometric surface of the aquifer system of the SLPV from 1977 to 2005. The model reproduces adequately the observed configurations of the potentiometric surface for the years 1995 and 2005 (Figure 5).

The results of the predictive models (Figure 9) show, that assuming any rate of growth population, for the year 2015 a larger drawdown in the city of San Luis Potosí, moreover, the equipotential value of 1,730 m asl increases the area to the east side, enclosing the wells 7, 8 and 9. In particular, it increases its area towards the Cerro de San Pedro. As it is expected, the greatest drawdown is observed in the model corresponding to 1% of population growth rate, increasing the area covered by the same equipotential value and through the industrial zone. In addition to this facts, the computed flow direction vectors, situated within the 1,730 m equipotential have opposite direction to Cerro de San Pedro, indicating the groundwater is flowing towards the city of San Luis Potosí.

Results of the remediation models (Figure 10a) show the reduction of the extraction results in a shorter area covered by the equipotential of 1,730 m asl in comparison to Figure 9d. Furthermore, the minimum level of the cone of depression gets back 10 m depth (1,705 m asl). This fact is significant while the time elapsed

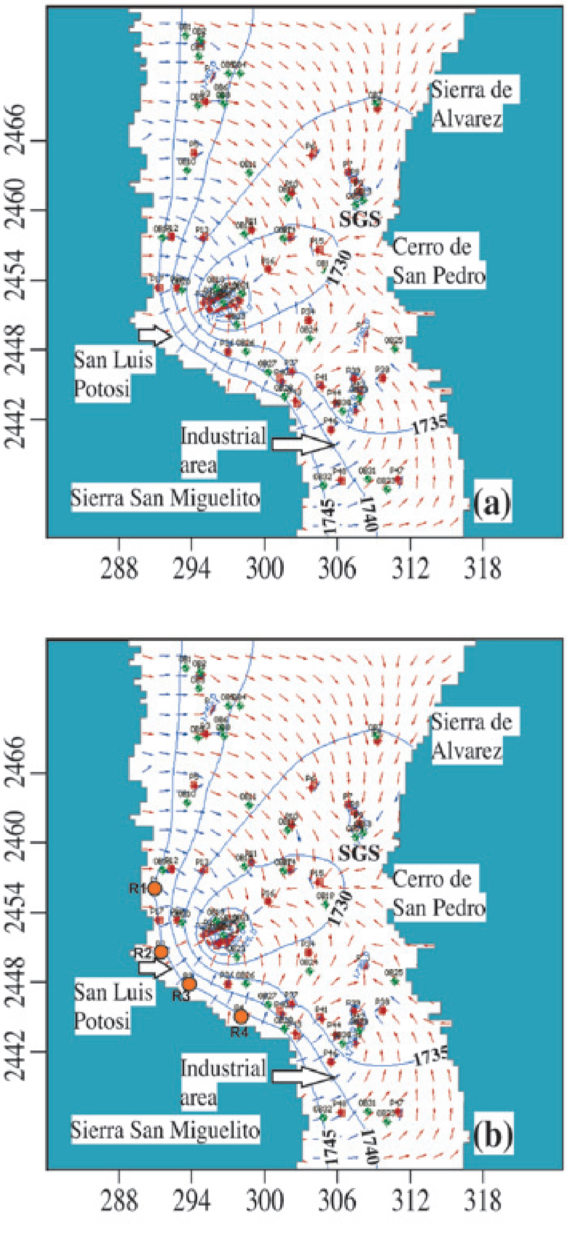


Figure 10. Potentiometric contours showing the remediation models for the year 2015. (a) "Decreased extraction", it assumes 30% decreased extraction in wells from 19 to 33. (b) "Relocation model" with the four new extraction wells (showed by orange circles R1 to R4) assigned near to the Sierra San Miguelito.

for this model is only of 7 years; that means a recovery of about of 1.43 m per year.

Modification of this model, by introducing four wells (R1, R2, R3 and R4) near of the Sierra San Miguelito, maintaining the reduction of extraction water in the already mentioned wells in SLP city, shows that there are no changes in the configuration of the equipotentials as it is shown in Figure 10. Then the extraction in the four wells, that is equivalent to the reduction amount, does not affect the response in the rest of the aquifer.

These results show that if the extraction is diminished by 30% in the wells at the area of the depression cone, transferring it to the four wells proposed (R1, R2, R3 and R4), over a 10 years period, reduces the impact of the extraction in the depression cone. It allows further extraction of water to supply the needs of the population, even with a growth rate of 1.0% per year in the population, without producing additional imbalance of the aquifer.

Conclusions

A hydrogeological characterization, based on previous geophysical and lithological studies, was carried out for the San Luis Potosí aquifer system to obtain its transient flow model. Important findings comprise: a significant drawdown in the potentiometric surface at the east part of the city; the model shows that the aquifer is very sensitive to the locations of extraction wells and therefore some remediation measures were simulated to propose some alternatives of extraction procedures in order to recover the aquifer system.

The historical hydrogeological information was compiled from previous studies performed from 1995 to 2005, this information enables us to predict the behavior of the aquifer system for the year 2015. The observed decline of the potentiometric level has an average rate of 2.0 m per year. The natural gradient in the aquifer was inverted in the groundwater of the city of SLP due to the excessive extraction.

Two kinds of possible evolutions of the aquifer for the year 2015 were simulated. The first kind was based on four growth rates of the annual population in SLP; it shows that assuming any rate of growth population for the year 2015 produces a greater drawdown in the city of San Luis Potosí. Specially, the potentiometric surface shows a larger drawdown to the east of the city, increasing its area until covering the industrial zone and rise to Cerro de San Pedro. If the management of extraction, supported the last 10 years, is maintained to the future, the depression cone would become larger and will pushed the authorities to drill deeper wells to exploit water and also new ones situated far from urban zone, increasing the cost of water.

The second type concern to remediation scenarios, propose a reduction of 30% the water extraction of wells, situated in the zone of the cone of depression. It is observed that this reduction produces that the minimum level of the cone of depression recovers 10 m of depth in a period of 7 years of simulation, even with a growth rate of 1.0% per year in the population. This represents a recovering of the water level at a rate of 1.43 m per year. To compensate the reduction of 30% of water extraction, four new wells are proposed in order to extract the same quantity of water. These wells are located near of the Sierra de San Miguelito (a recharge zone), it produces the best scenario of water exploitation without produce additional imbalance of the aquifer.

The results obtained by the remediation scenarios show that the model can significantly contribute to the proper management of groundwater in the valley of San Luis Potosí, and allow agencies of resource management to plan the exploitation of the aquifer under a sustainable framework and guide the use of water in an efficient manner. The treatment of the wastewater will also contribute to recover the natural balance of the aquifer, by providing water for agricultural irrigation, to not pollute the shallow aquifer. The increase of green areas in the city favored the percolating of the pluvial precipitation.

Acknowledgements

This study was partially sponsored by the Dirección General de Personal Académico de la Universidad Nacional Autónoma de México UNAM (Research Project IN-112906) and by the Instituto de Geofisica, UNAM. The authors are indebted to Sandra Edda Martínez and Oscar Escolero for their helpful comments and data, and particularly to Comisión Nacional del Agua (CONAGUA) for providing original data. Ingrid Kohn was supported by Consejo Nacional de Ciencia y Tecnología Scholarship Graduate Program.

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