Study of geothermal water intrusion due to groundwater exploitation in the Puebla Valley aquifer system, Mexico

**E. Leticia Flores-Márquez · Gabriel Jiménez-Suárez ·
Raymundo G. Martínez-Serrano · René E. Chávez ·
Daniel Silva-Pérez**

Abstract Significant intrusion of geothermal water into fresh groundwater takes place in the Puebla Valley aquifer system, Mexico. The decline in the potentiometric surface due to the overexploitation of the groundwater induces this intrusion. This hydrological system comprises three aquifers located in Plio-Quaternary volcanic sediments and Mesozoic calcareous rocks. The hydraulic balance of the aquifer shows that the annual output exceeds the natural inputs by 12 million m^3. Between 1973 and 2002, a drop in the potentiometric surface, with an 80 m cone of depression, was identified in a 5-km-wide area located southwest of the city of Puebla. Chemical analyses performed on water samples since 1990 have shown an increase in total dissolved solids (TDS) of more than 500 mg/L, coinciding with the region showing a cone of depression in the potentiometric surface. A three-dimensional flow and transport model, based on the hydrogeological and geophysical studies, was computed by using the MODFLOW and MT3D software. This model reproduces the evolution of the aquifer system during the last 30 years and predicts for 2010 an additional drawdown in the potentiometric surface of 15 m, and an increase in the geothermal water intrusion.

Résumé Le système aquifère de la Vallée de Puebla, Mexique, montre une importante intrusion d'eau géothermique. Le rabattement du niveau piézométrique est du à la surexploitation de l'aquifère, produisant cette intrusion. Le système hydrologique est composé de trois aquifères localisés dans des sédiments volcaniques du Plio-Quaternaire et des roches calcaires du Mésozoïque. Le bilan hydrologique de l'aquifère montre que le pompage excède les infiltrations naturelles par 12 millions m^3. Entre 1973 et 2002, il a été observé une chute du niveau piézométrique, avec la formation d'un cône de dépression de 80 m de profondeur et 5 km d'aire en surface, localisé au SW de la Ville de Puebla. Des analyses chimiques réalisées sur d'échantillons d'eaux, depuis 1990, ont présenté une augmentation des quantités de solides totaux dissous de plus de 500 mg/L, dans la région qui montre le cône de dépression piézométrique. Un modèle tridimensionnel de flux et transport, basé sur des études hydrogéologiques et géophysiques, a été réalisé en utilisant les logiciels MODFLOW et MT3D. Le modèle reproduit l'évolution du système aquifère pendant les derniers trente ans et propose, pour l'année 2010, une chute additionnelle du niveau piézométrique d'environ 15 m, en plus d'une augmentation de l'intrusion géothermique.

Resumen El sistema acuífero del Valle de Puebla, México, presenta una importante intrusión de agua geotérmica. El abatimiento de la superficie potenciométrica debido a la sobreexplotación del acuífero produce dicha intrusión. El sistema hidrológico está compuesto por tres acuíferos contenidos en sedimentos volcánicos Plio-Cuaternarios y en rocas calcáreas del Mesozoico. El balance hidráulico del acuífero muestra que la extracción anual excede en 12 millones de m^3 a las recargas. Entre los años 1973 y 2002 el nivel potenciométrico ha mostrado un importante cono de abatimiento de 80 m de profundidad y 5 km de área, al suroeste de la Ciudad de Puebla. Análisis químicos de muestras de agua, realizados desde 1990, han mostrado un incremento en las cantidades de sólidos totales disueltos (STD) de más de 500 mg/L, coincidiendo con la región que muestra el cono de abatimiento. Se realizó un modelo tridimensional de flujo y transporte, basado en estudios hidrológicos y geofísicos, utilizando los códigos computaciones MODFLOW y MT3D. Este modelo reproduce la evolución del sistema acuífero durante los últimos treinta años y predice para el año 2010 una disminución adicional del nivel potenciométrico de 15 m y un incremento de la intrusión de agua geotérmica.

Keywords Simulation · Groundwater flow · Transport · Geothermal water intrusion · Puebla aquifer

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Received: 27 January 2005 / Accepted: 30 January 2006

E. L. Flores-Márquez (✉) · R. G. Martínez-Serrano ·
R. E. Chávez · D. Silva-Pérez
Universidad Nacional Autónoma de México, Instituto de Geofísica,
Ciudad Universitaria,
Circuito Exterior, Mexico, DF 04510, Mexico
e-mail: leticia@tonatiuh.igeofcu.unam.mx

G. Jiménez-Suárez
Benemérita Universidad Autónoma de Puebla,
Facultad de Ingeniería,
Ciudad Universitaria, Puebla, Mexico

Hydrogeology Journal (2006) 14: 1216–1230 DOI 10.1007/s10040-006-0029-0

Introduction

Significant intrusion of geothermal water into fresh groundwater takes place in the Puebla Valley aquifer system. The decline in the potentiometric surface is due to the overexploitation of groundwater in the area. This overpumping induces an uprising of salty geothermal water from deep aquifers into the fresh water aquifer. This study seeks to model the intrusion by using numerical simulations based on the integrated model from geological, geoelectrical and hydrogeological data.

The urban and industrial development of the main cities of Mexico has exerted an adverse influence on the quality of fresh water. The random number and distribution of pumping wells, sometimes in unauthorized areas, have often resulted in the deterioration of the quality of the groundwater and in the depletion of the aquifer. Puebla is the fourth largest city in Mexico, and is a good example of this problem. The demand for water has considerably increased in the last 50 years. The water supply has been overwhelmed by demography and industrial growth, which has led to a considerable fall in the water-table level.

The presence of geothermal waters with high concentrations of total dissolved solids (TDS) has impaired water quality. Since the end of the nineteenth century, the local inhabitants have employed geothermal water for health reasons. Unfortunately, the fall in the potentiometric surface has resulted in the intrusion of geothermal water into the shallow aquifer, spoiling the quality of the drinking water. Today, a large number of wells in the city are now extracting geothermal water.

The hydrological system of Puebla has been assessed by an integrated multidisciplinary study. The evolution of the water-table levels in the shallow aquifer over the last 30 years has been studied and the results presented in this report. Also, the evolution of TDS in these waters over the last 14 years was investigated. This study also seeks to improve understanding of the water flow in the aquifer and to furnish some predictive models to estimate an extraction rate which would diminish geothermal water intrusion. Numerical models, using the Visual MOD FLOW Software (Waterloo Hydrogeologic Inc., Canada 2005), were computed on a three-dimensional geological integrated model constrained by previous geophysical, geochemical and geological studies.

Integrated model

Hydrogeology of the Puebla Valley

The city of Puebla, capital of the state of Puebla, is located in the central part of the Trans-Mexican Volcanic Belt, which includes most of the active volcanoes in Mexico (Demant 1978). The area lies about 120 km to the southeast of Mexico City. The study area is located at 18°58′–19°20′N (2,095,000–2,145,000N UTM) and 98°28′–98°06′W (550,000–592,000E UTM), and has a mean altitude of 2,160 m above sea level (m a.s.l.). This area corresponds to the intermontane basin of Puebla, which is shared by two political states: Tlaxcala and Puebla. The Malinche stratovolcano bounds the study area to the east; the Sierra Nevada, formed by the Iztaccíhuatl and Popocatépetl Plio-Quaternary stratovolcanoes, flanks the study area to the west and northwest; and the Sierra del Tentzo forms a boundary to the south (Fig. 1; Morán-Zenteno 1984). The climate is temperate with moderate precipitation in summer. The mean annual temperature is 16.6°C, with a maximum of 21.3°C in May and a minimum of 10.8°C in February. The main recharge zones are located within the major volcanic edifices to the east and west of the basin with an average annual rainfall of 1,000 mm/year. The annual precipitation in the basin ranges between 650 and 900 mm/year.

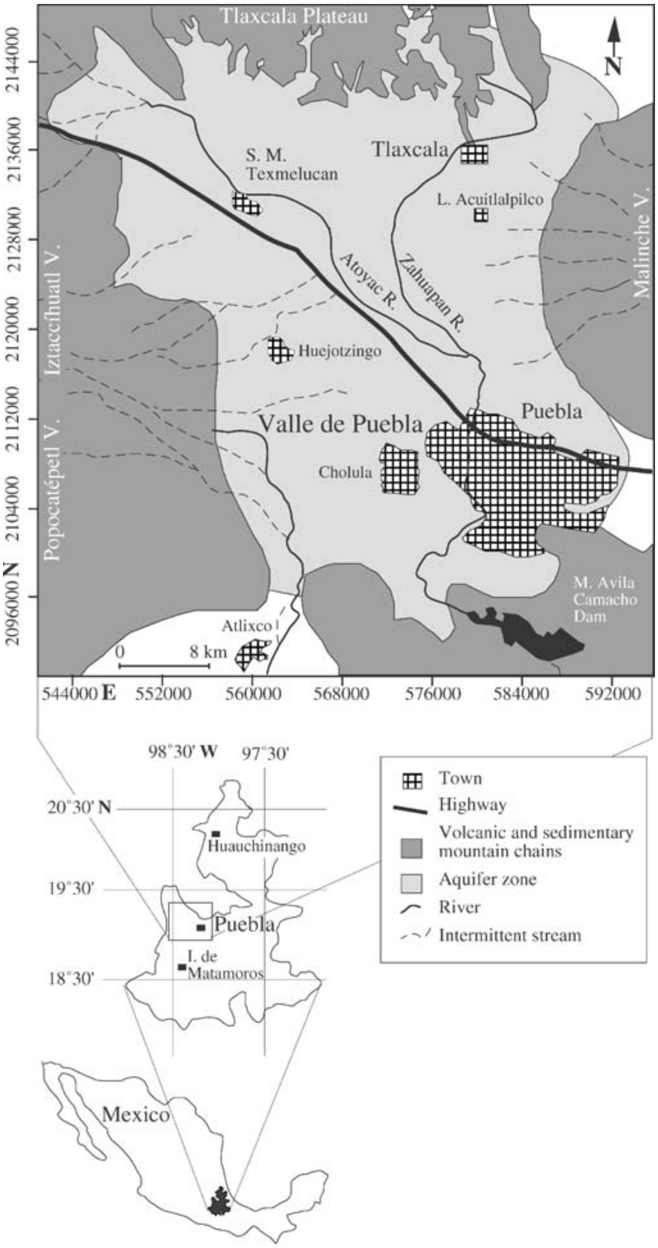

Fig. 1 Location of the state of Puebla. Delimitation of the Puebla Valley aquifer and its natural hill boundaries are depicted

The main rivers draining the intermontane basin of Puebla are: the Atoyac, the Zahuapan and the Alseseca (Figs. 1 and 2). The rainfall running down the Iztaccíhuatl volcano feeds the Atoyac River. The same process occurs with the Alseseca River on the western flank of the Malinche volcano as well as with the Zahuapan River, which is fed by the Tlaxco range (Tlaxcala Plateau).

The aquifer of the Puebla Valley occupies an area of about 1,300 km^2 in the basin. The lithology of the wells and the results of the geoelectrical studies (Geotecnología 1997) suggest that this hydrological system comprises three aquifers: shallow, middle and deep (Fig. 3c). The fresh water shallow aquifer is constituted of Plio-Quaternary volcanic sediments (sands and gravels) with a mean thickness of 130 m. It has a high permeability and retains water of good quality. The second aquifer is made up of fractured Neogene andesites, some pyroclastic deposits and conglomerates with a mean thickness of 200 m, and is bounded at the bottom by Mesozoic carbonate rocks and Pliocene lacustrine deposits on top. Such rocks are found throughout most of the basin, reaching thicknesses of more than 200 m towards the northern border of the basin, but in some places are absent. These deposits have a low permeability and function as an aquitard, but in the fractured areas, allow the vertical hydraulic connection between the shallow and deeper aquifers (EXXICO 1990). The deep aquifer is constituted of Mesozoic carbonate rocks with undefined thickness and retains water with high concentrations of dissolved salts.

By 1973, more than 234 wells had been drilled to extract fresh water for human and agricultural use. This number reached 646 by the end of 1981. Ten years later, the number of registered wells reached 1,189. The number remained almost constant between 1996 and 2003, but the rate of extraction in some wells increased. This produced a considerable decrease in the groundwater level. The

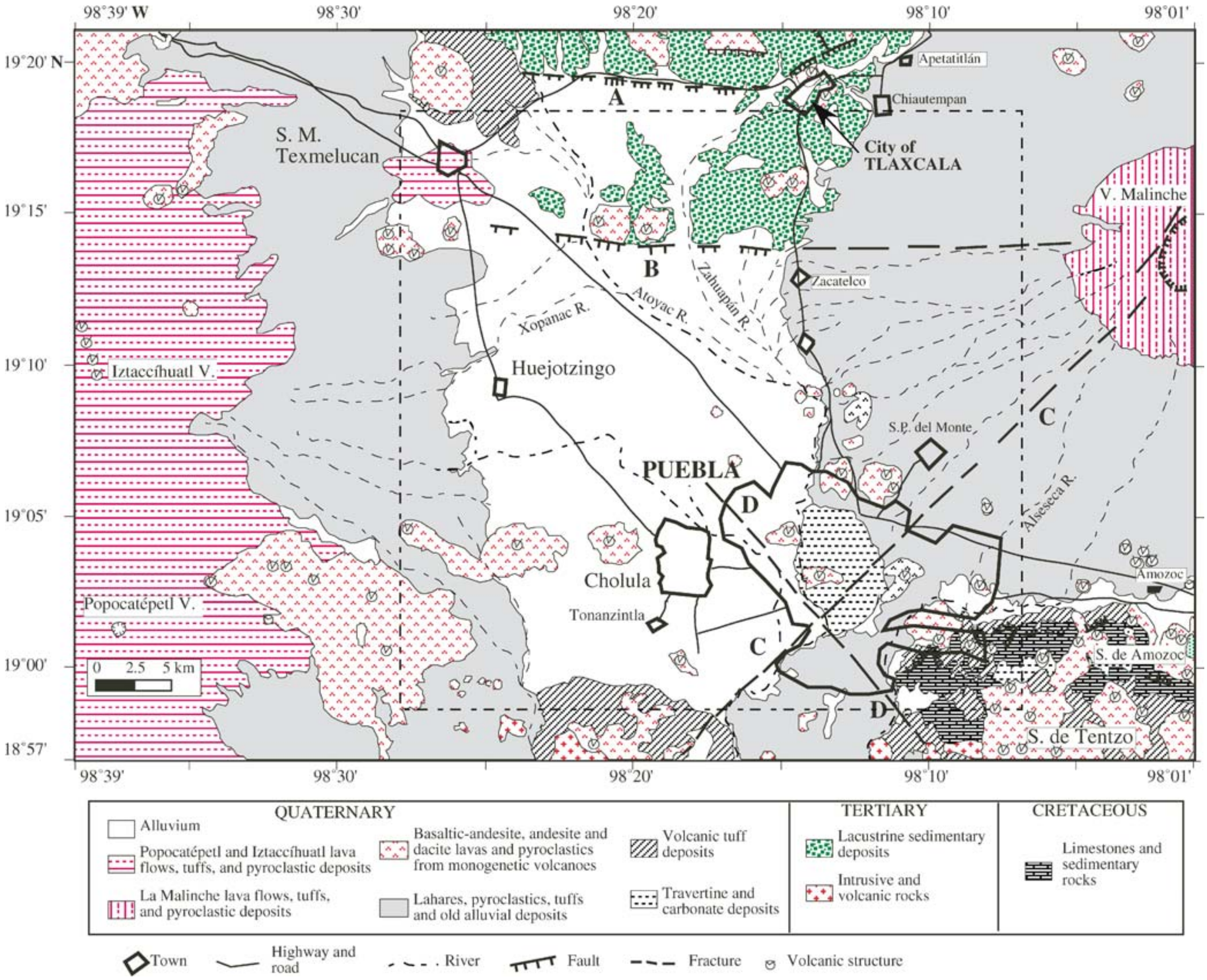

Fig. 2 Geological map of the intramontane basin of Puebla (after Mooser et al. 1996). Main faults and fractures (after Mooser 1972) are indicated by: (**a**) E–W Tlaxcala normal fault, (**b**) E–W Tetlatlahuca normal fault, (**c**) NE–SW Malinche fault and (**d**) NW–SE Valsequillo fracture. The alignment of some Quaternary volcanic structures suggests an E–W fault pattern in the Puebla Basin. *Rectangle* indicates the area modeled

DOI 10.1007/s10040-006-0029-0

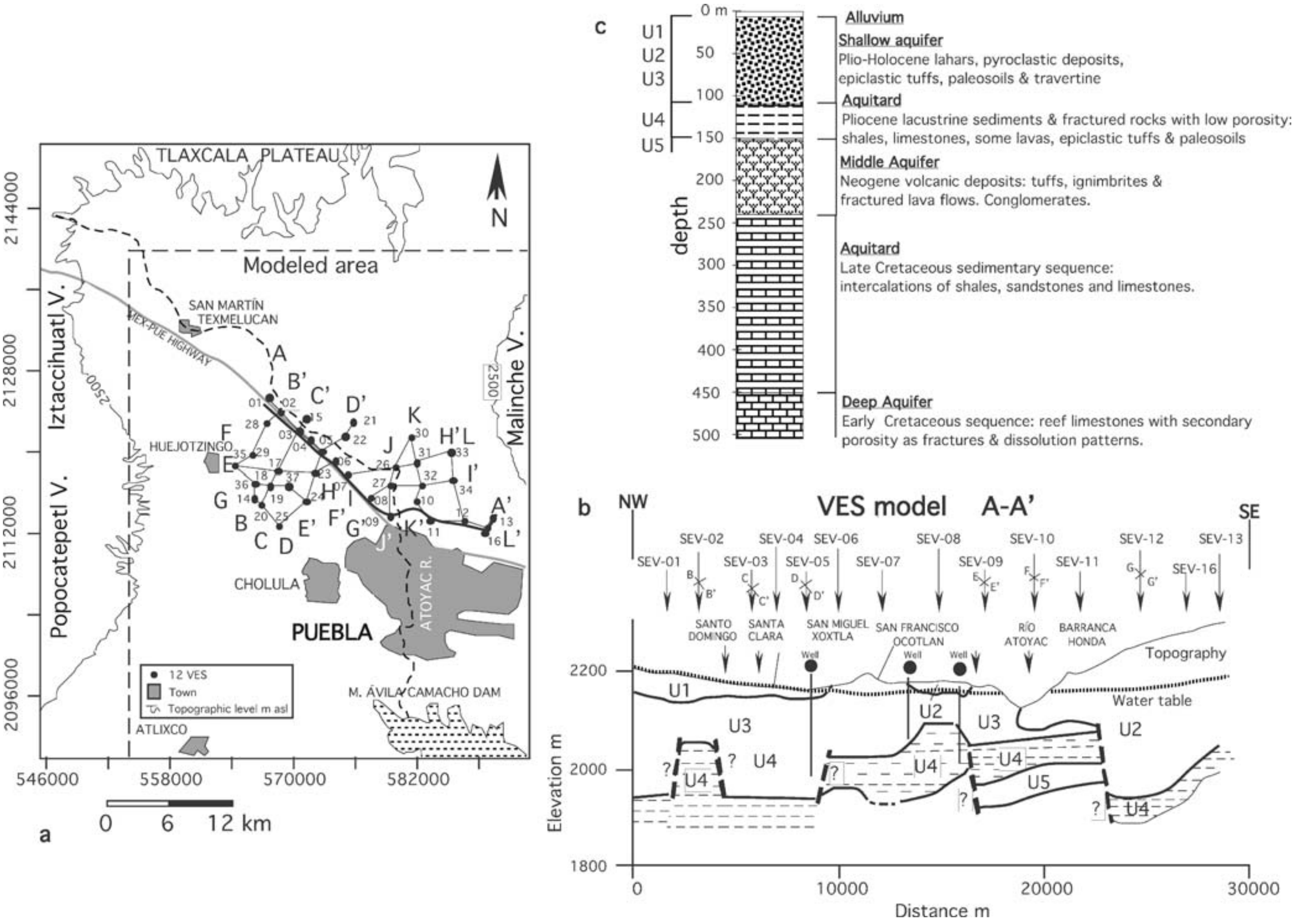

Fig. 3 **a** Location of the vertical electrical soundings (VES) carried out in the basin; the modeled area is also displayed. One of the reinterpreted geoelectrical profiles is shown in **b** Profile A-A' (this two-dimensional resistivity model was performed with the one-dimensional inverted sections of 14 VES); **c** Stratigraphic column obtained from the lithology of the wells and the correlation with the geoelectrical units found in the VES (units *U1–U5*)

annual pumping extraction in 1995 was calculated at 316 million m^3 (Mm^3), of which 56% was dedicated to human use, 26% to agriculture and 20% to industry. Today, percentages are about the same.

Geological setting

The intermontane basin of Puebla (Fig. 2) is surrounded by Neogene–Quaternary stratovolcanoes and mountain ridges of Upper Cretaceous limestone. It is filled with volcanic tuffs, lahars, lava flows, cinder cones, lacustrine fluvial deposits and reworked glacio-fluvial materials from the higher elevations. This basin lies on an old basement composed of Paleozoic metamorphic rocks of the Acatlan Complex and Mesozoic terrigenous and calcareous rocks (Ortega-Gutierrez 1978, 1993; Mooser et al. 1996; Erffa et al. 1977). Some outcrops of these old rocks are located in the southeastern portion of the basin, at the Sierra del Tentzo and the Serrijon de Amozoc (Fig. 2). The Mesozoic calcareous rocks in the southern area of the basin are considered to be part of the deep aquifer. Mooser et al. (1996) suggested that the Neogene sequence of lava flows, tuffs and conglomerates is more than 1,000 m thick. It is considered that the fractured lava flows and some volcanic deposits from this sequence determine the hydrological characteristics of the middle aquifer (Fig. 3c). Pliocene lacustrine deposits, which are emplaced in most of the basin, reach a thickness of more than 200 m towards the northern limits of the Puebla Valley. These continental sediments are composed of shales, sandstones and continental limestones, which constitute an impervious layer separating the Plio-Quaternary shallow aquifer from deeper aquifers. An outcrop of this lacustrine sequence may be observed in the travertine formations of Puebla, and is evidence of geothermal activity. This continental calcareous formation displays an important fracture system and high porosity, producing a significant vertical permeability.

Eruptive events of the major Plio-Quaternary stratovolcanoes such as the Malinche volcano to the east, and the Iztaccíhuatl and the Popocatépetl volcanoes to the west in the Sierra Nevada (Siebe 1986) filled the Puebla Basin with abundant volcanic materials. Although the thickness of volcanic materials (lava flows, ignimbrites, tuffs, lahars), paleosoils and reworked glacio-fluviatile sediments is unknown, it has been estimated to be more than

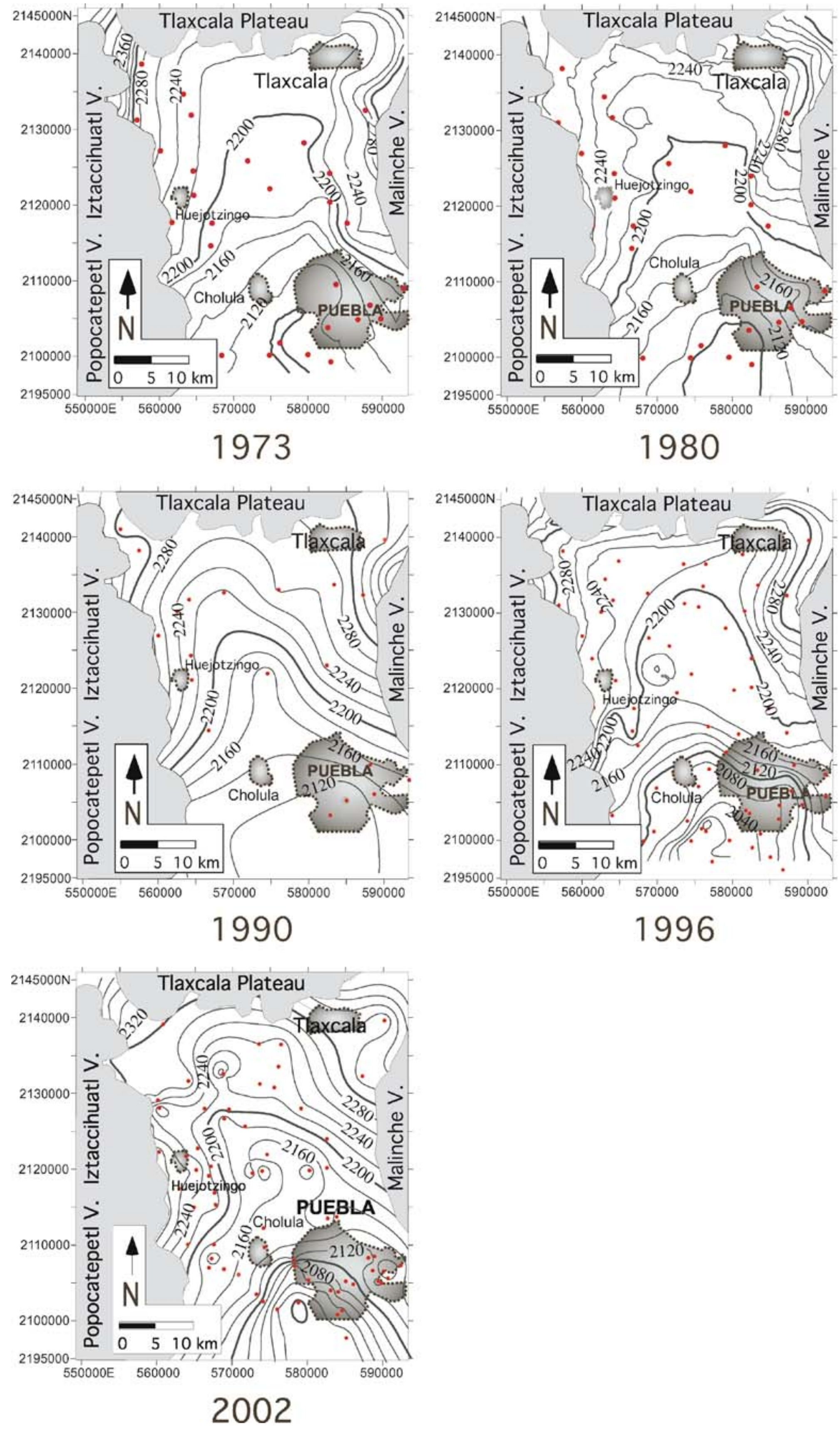

Fig. 4 Evolution of the water-table elevation (1973–2002). Numerical interpolation was computed based on original data provided by SOAPAP and CNA reports for the following years: 1973, 1980, 1990, 1996 and 2002. *Dots* are observed wells. Contours are in meters above sea level. *Dark shaded areas* indicate towns

250 m. These recent materials constitute the shallow aquifer (Fig. 3c) that supplies Puebla with fresh water. Some andesitic monogenetic volcanoes with an E–W orientation are present in several zones within the basin, producing inhomogeneities in the layers containing the aquifer system.

Structural studies (Mooser 1972; Geotecnología 1997) undertaken in the area reported three important structures. The E–W Iztaccíhuatl-Malinche graben that is bordered to the north by the Tlaxcala fault (Fig. 2a) and the Tetlatlahuca fault to the south (Fig. 2b). A second structure is the NE–SW Malinche fault (Fig. 2c) that begins in the volcanic edifice of that name and crosses Puebla, and finally, the NW–SE Valsequillo fracture (Fig. 2d) that also crosses the urban zone. Mooser et al. (1996) also described a graben with a NE–SW orientation, called Fosa Atlixco, that extends southwest from Puebla to Atlixco. The position and features of these main structures probably control the thickness and distribution of the volcanic and sedimentary sequences in the basin.

Geoelectrical interpretation

A series of vertical electrical soundings (VES) were carried out by Geotecnología (1997) within the central portion of the Puebla Valley, to the northwest of Puebla. The survey consisted of 37 VES spaced about 2 km apart, and distributed along 12 pseudo-profiles in three areas: Puebla, Xoxtla and Barranca Honda. The original data was re-interpreted in this research employing a standard inverse algorithm and assuming a one-dimensional stratified earth (Das and Ghosh 1974). Profile A-A’ was computed (Fig. 3b) in a NW–SE direction, after integrating the inverted one-dimensional sections corresponding to the VES shown in Fig. 3a. The first three resistive units (U1–U3) correspond to the presence of Plio-Quaternary lahars, pyroclastic deposits, epiclastic tuffs, paleosoils, and travertine, which is where the main aquifer is found. Resistivities for these geological units range from 40 to 140 ohm/m, with a thickness ranging from 100 to 200 m (Fig. 3c). Unit U4 corresponds to Pliocene lacustrine sediments and fractured rocks of low resistivity (3–20 ohm/m), with a variable thickness from 50 to 150 m, which constitutes the aquitard. Neogene volcanic deposits form the middle aquifer (unit U5; 100–300 ohm/m), which has an unknown thickness. The geoelectrical surveys performed in Puebla distinguished four geoelectrical units. The first three units had the same geological composition as those observed in the basin. However, the travertine is widespread and represents about 60% of the city area. In this case, the deeper geoelectrical layer corresponds to calcareous rocks, with an undetermined thickness.

The geoelectrical characterization was employed to construct a three-dimensional geological model, which is used to calibrate the hydrological parameters employed in the flow model. The physical properties of the rocks encountered in the region were estimated based on previous geological studies done in the area (Ortega-Gutierrez 1978, 1993; Mooser et al. 1996; Erffa et al. 1977).

Groundwater level decline

The groundwater level in the shallow aquifer seems to decline with time. In order to determine the level variations, the piezometric data collected by CNA (Comision Nacional del Agua) and SOAPAP (Sistema Operador de Agua Potable y Alcantarillado de Puebla) from 1973 to the present time were used. Several numerical interpolations were calculated for the following years: 1973, 1980, 1990, 1996 and 2002. The corresponding interpolations of the water-table elevations for the observed wells are displayed in Fig. 4. The water-table measurements were carried out between the months of October and November for the corresponding years. It is important to point out that not always the same wells were monitored during the years mentioned. Therefore, care has been taken to avoid false effects due to this problem and to produce reliable results. It is observed that the northern portion of the basin has remained almost unchanged over the last 30 years, whereas the southern part has undergone a considerable drop in the water-table level. This pattern is probably due to the increased number of wells drilled and to the intensive extraction rates in the wells located near Puebla.

In order to quantify the total effect of the decline in the potentiometric surface, the difference between the water-table level observed in 1973 and 2002 was calculated, i.e., the first and the last monitored years when the major changes were observed. Figure 5 displays a cone of depression of 80 m and 5 km wide towards the SW of Puebla. In the middle part of the valley, a depression of 30 m in the potentiometric surface is also observed. Our calculations suggest that the water-table level dropped at a rate of more than 2 m/year over a 30-year period. On the other hand, the northern portion of the basin remained practically unchanged within the same period.

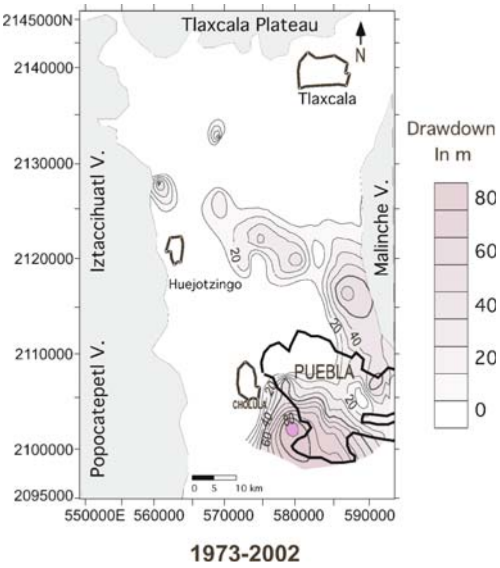

Fig. 5 Difference in measured water-table levels from 1973 to 2002. Significant drawdown has been observed in the southern portion of the basin (about 80 m) towards the southwestern portion of Puebla

The hydraulic balance of the aquifer system shows that the total input can be quantified at 1,398 Mm^3, considering the following data: the average annual precipitation (1,150 Mm^3), and the volumes of underground inflow (84 Mm^3), return water from agriculture (40 Mm^3), and inflow from rivers (124 Mm^3). These values have remained nearly constant since 1973. Nowadays, the total volume outflow from the aquifer is estimated at 1,410 Mm^3. This estimation takes into account the amount of outflow from the following sources: underground (19 Mm^3), evapotranspiration (737 Mm^3), river outflow (315 Mm^3) and the extraction of 1,200 wells (339 Mm^3). This global balance for the aquifer indicates an imbalance between input and output water. The annual output exceeds the natural inputs by 12 Mm^3. The effect of this imbalance is evident from the observed cone of depression of 80 m observed to the SW of Puebla (Fig. 5). That means that the depleted water volume of the groundwater storage is equivalent to about 188 Mm^3. The observed drawdown is significant and there is no evidence of aquifer compaction. However, some groundwater depletion is irreversible.

Therefore, in this investigation special attention was accorded to the southwestern sector of the city, where the observed drawdown is greater. It should be pointed out that the minimum cone of depression ranged from 60 m in 1996 to 80 m in 2002, indicating that the water level dropped 3 m/year over a 6-year period.

Groundwater quality

Since the nineteenth century, the inhabitants have used thermal springs located in Puebla for health reasons. Some of them have been commercially exploited. Nowadays, some of these natural artesian springs have lost pressure and they have been transformed into pumping wells. These geothermal sources are located in the western section of the city. Temperatures of extracted waters are around 29°C. The local inhabitants refer to this region as the “sulfur water zone” (SWZ).

In order to characterize the groundwater quality, chemical analyses of water samples obtained from 60 wells in the Puebla Basin were carried out by CNA and SOAPAP in 1990 (CNA and SOAPAP, 1990, personal communication). Later, water samples from 78 pumping wells underwent physical-chemical analyses in 1997. From these chemical data, it may be observed that the TDS content in the north of the basin did not experience any considerable change from 1990 to 1997 (Fig. 6). However, significant changes in the TDS contents have been observed in the region comprising the cities of Cholula, from 500 to 600 mg/L, and Puebla, from 500 to 2,000 mg/L.

Subsequent chemical analyses of water samples were performed in the region encompassing the cities of Cholula and Puebla (CNA and SOAPAP, 1990, personal communication). Figure 7 shows the location of natural geothermal springs sources (triangles), which correspond to the SWZ. The wells exploiting geothermal water (dots 1, 2, 3) at present are also indicated. Figure 7a displays the interpolation of 54 well TDS measurements performed in 1990. The evolution of the TDS content for the years 2000–2002 is shown in Fig. 7b. In both cases, the natural spring sources and the geothermal wells were not included in the interpolation. The TDS map depicts an increase in the TDS content in the SWZ of about 500 mg/L in 10 years. Another important effect is the growth, from about 12 km^2 in 1990 to 40 km^2 in 2002, of the contaminated region exceeding 2,000 mg/L (see isoline 2,000 mg/L in Figs. 7a and b). It is possible to observe that the increment in the TDS values coincides with zones displaying a maximum drawdown in the potentiometric surface (Fig. 5). The TDS content could have a number of sources: geothermal activity, dissolution of carbonates from the calcareous rocks, leakage of the sewage network, fertilizers and other causes attributed to drains. However, it is assumed that most of the TDS content (up to 80%) is due to geothermal water intrusion and dissolution of carbonates. Chemical analyses of waters in this area show slight enrichment of boron (from 1 to 3 mg/L), fluorine (>1.5 mg/L), and sulfide (>8.5 mg/L), and the temper-

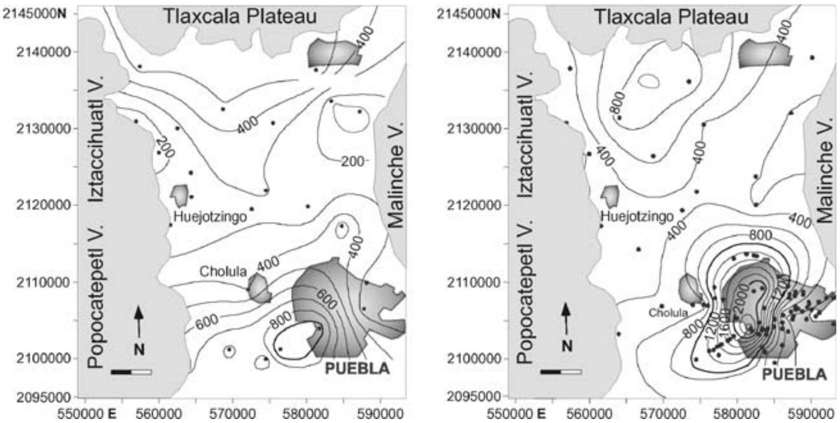

Fig. 6 Evolution of TDS in the Puebla Basin for 1990 and 1997. Numerical interpolation is based on geochemical analysis. *Dots* are the observed wells. Contours are in mg/L. *Dark shaded areas* indicate towns

atures measured were around 29°C, which is evidence of a geothermal effect. The region of higher TDS concentration coincides with the travertine outcrops. At present, it is observed that the natural spring sources in the travertine show a peculiar NW–SE alignment (Fig. 7) that could be related to the Valsequillo fracture (Fig. 2d). The location of the SWZ coincides with the maximum values of TDS (see isoline 2,000 mg/L in Fig. 7). Therefore, it could be assumed that both areas are equivalent. This implies a considerable reduction in the quality of water pumped from wells located in this region. Additionally, the depth of the wells that are targeting the middle aquifer aggravates this problem in that it enables the hydraulic connection between both shallower and middle aquifers.

Groundwater flow model

The model employed to simulate the groundwater flow and transport in the intermontane basin of Puebla consists of two linked models using different scales. Because of the different grid scales, some areas were treated with a higher resolution than others. This resulted in an increase in the spatial variability of the hydraulic properties. The conceptual design of the large-scale groundwater flow model is shown in Fig. 8. The block model displays the area, digital topography, natural boundaries of the aquifer system and stratigraphic layers. The topography was obtained from the digital topographic geodatabase MDE (Mexican digital elevations) compiled by the government

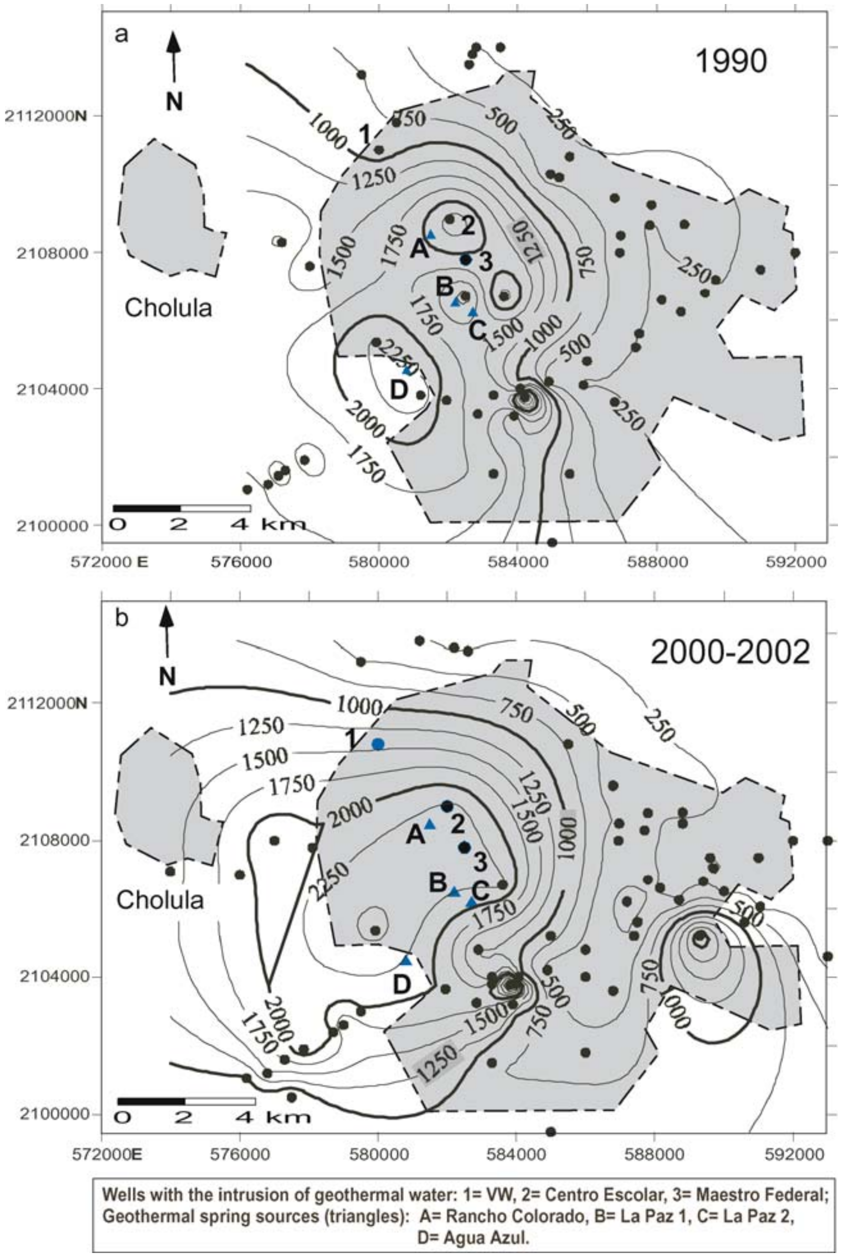

Fig. 7 Evolution of TDS in the Cholula and Puebla region (*shaded areas*). **a** TDS monitored in 1990 and **b** 2000–2002 (contours in mg/L). Numerical interpolation is based on original data. *Small dots* are observed wells. *Large dots 1*, *2* and *3* are wells exploiting geothermal water. The natural spring sources and the geothermal wells were not included in the interpolation

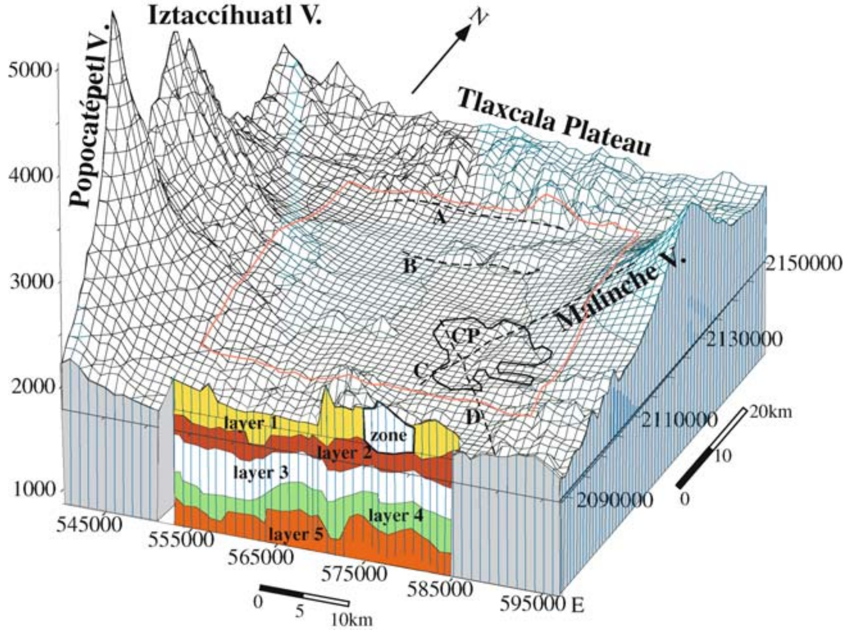

Fig. 8 Conceptual diagram of the large-scale three-dimensional model of the Puebla Basin. The bottom of layers was inferred from the geoelectrical study. Topography and faults (**a**) E–W Tlaxcala normal fault, (**b** E–W Tetlatlahuca normal fault, (**c**) NE–SW Malinche fault and (**d**) NW–SE Valsequillo fracture) are also shown (see Fig. 2). *CP* city of Puebla. The *grey line* shows the modeled area

institute INEGI (Instituto Nacional de Estadistica, Geografia e Informatica; INEGI 2005). The model was constructed taking into account the hydrogeological map of the area and the correlation between the lithological columns of 16 wells and the three inferred resistive horizons (Geotecnología 1997) described above. The integration of these data produces a five-layer model in a z-direction. The surficial layer (layer 1, see Table 1 and Fig. 9) of the model was divided into six different zones according to the surface geology and the deduced and measured local hydrologic properties (Gelhar et al. 1992; Bear 1972; Bear and Bachmat 1991and De Marsily 1986). The results of 49 pumping tests performed in different wells along the basin were taken into account to estimate the corresponding hydraulic transmissivity. The subsequent layers (layers 2–5) were also divided into horizontal zones in order to reproduce the lateral lithological variations and their hydrological properties. Table 1 summarizes the lithology, hydrological properties, and the zones assumed in the numerical model.

The model representing the aquifer comprises a rectangular grid of 105×112 cells (cell size area is 380 × 390 m) in the x-y plane. Five layers in the z-direction characterize the domain, with a variable thickness corresponding to the interpreted geology (Fig. 9; Table 1). The natural boundaries of the aquifer system are: the Malinche volcano to the east, Popocatépetl and Iztaccíhuatl volcanoes to the west and the Tlaxcala Plateau to the

Table 1 Hydrological properties assumed for the lithological units used in the numerical model

Hydrogeological unit	Lithology	Hydraulic conductivity (m/s)		*Ss* (m^{-1})	TP (%)
		K_x=K_y	K_z		
Layer 1					
Zone 1	Reworked glacio-fluviatile sediments	5.0E-06	3.0E-06	0.5	0.30
Zone 2	Fractured tuffs, lahars and pyroclastic deposits	4.0E-05	1.0E-06	0.01	0.18
Zone 3	Lava flows	5.0E-07	5.0E-07	0.005	0.18
Zone 4	Travertine and carbonate deposits	1.0E-05	3.0E-05	0.05	0.20
Zone 5	Lacustrine sediments	1.0E-07	5.0E-06	0.4	0.18
Zone 6	Tuffs, lahars and pyroclastic deposits	Recharge zones	Recharge zones		
Fractures	High permeability lines	1.0E-06	3.0E-05		
Layer 2	Pliocene lacustrine deposits: sandstones, shales and silicated limestones	7.0E-06	4.0E-06	0.00005	0.2
Zone 4	Travertine and carbonate deposits	1.0E-05	3.0E-05		
Layer 3	Igneous fractured rocks and andesitic lava flows	8.0E-06	5.0E-06	0.00005	0.2
Zone 4	Travertine and carbonate deposits	1.0E-05	3.0E-05		
Layer 4	Mesozoic carbonate rocks	5.0E-06	3.0E-06	0.0001	0.25
Layer 5	Metamorphic rocks: gneisses and schists	1.0E-07	1.0E-07	0.000001	0.01–0.02

Ss specific storage, *TP* total porosity, *x* E–W direction, *y* N–S direction, *z* elevation

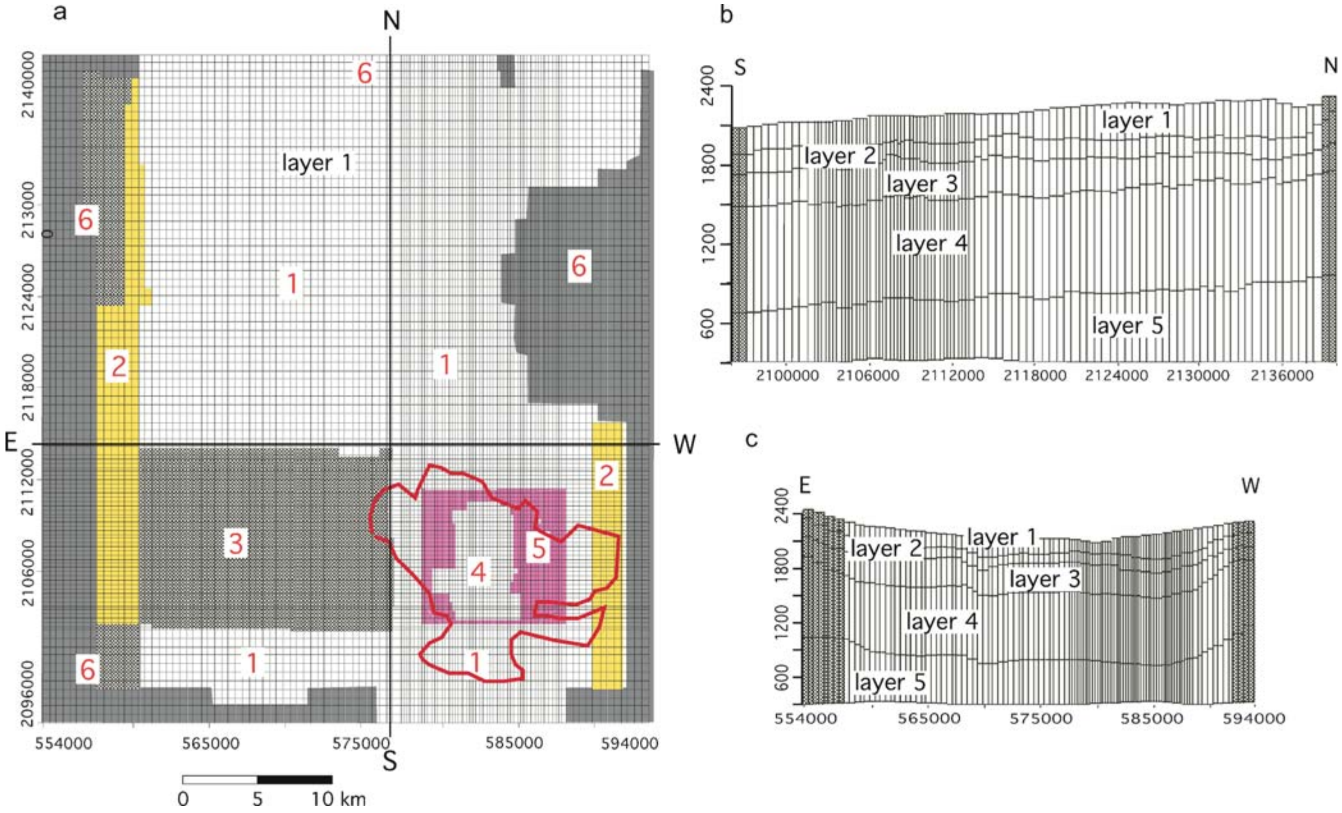

Fig. 9 Discretization of the study area. **a** The rectangular grid in the x-y plane comprised 105×112 cells (380 × 390 m cell size area); the refined grid area was 200 m. *Numbers from 1 to6* represent the six different zones into which layer 1 was divided according to the surface geology and hydrological properties (see Table 1). **b** S–N section showing the configuration of the five layers representing the hydrogeological units at depth. **c** E–W section is also shown

north (zone 6 in Fig. 9 and Table 1). The main discharge zone is found in the southern portion of the basin. The precise definition of the boundary conditions is essential for the accuracy of the basin simulation. The mountain front and tributary recharge were treated in the model as a specific flow boundary.

In this work, the annual volume of infiltration estimated for the aquifer was 200 mm/year. The infiltration volume depends on annual precipitation, mean temperature, evapotranspiration, hydraulic conductivity of soil, and saturation of soil and vegetation. Castany (1975) assumes the annual volume of infiltration is equivalent to 18±6% of the annual precipitation, while (Kessler 1965) estimates it could reach 60%.

The above-mentioned block model (105×112×5 cells) was carried out with the Visual MODFLOW software. A steady state calibration of the groundwater flow model was obtained using the module MODFLOW (McDonald and Harbaugh 1988) for the years monitored, which uses a finite difference method with a three-dimensional centered block. Thirty-five observation wells located in the basin were employed to compare the observed and computed hydraulic head. The mathematical boundary conditions imposed in the groundwater movement differential equation correspond to Neumann conditions. Table 2 displays the general head boundary (GHB) conditions introduced in the model, only maximum and minimum values are displayed. Rivers are considered internal boundaries with imposed hydraulic head following the observed data along each river. The input parameters of the model correspond to observations of the hydrologic balance. Figure 10 shows the potentiometric surface maps obtained with the module MODFLOW for the years monitored. The year 1973 was assumed to be the initial state of the system and the measured water table corresponding to that year is used in the model.

Table 2 The boundary conditions used for whole modeled area

Boundary	General head boundary (GHB)		Time (days)
	Minimum elevation	Maximum elevation	
North	2,250	2,430	12,045
West	2,370	2,100	12,045
East	2,385	2,230	12,045
South	2,200	2,080	12,045

Transient flow model

A transient flow model, simulating the total water extraction in the area of several wells and their evolution in time, constitutes the second step in the procedure. The simulation of water extraction of the 1,200 wells existing in the Puebla Basin is modeled by 80 wells. The location

DOI 10.1007/s10040-006-0029-0

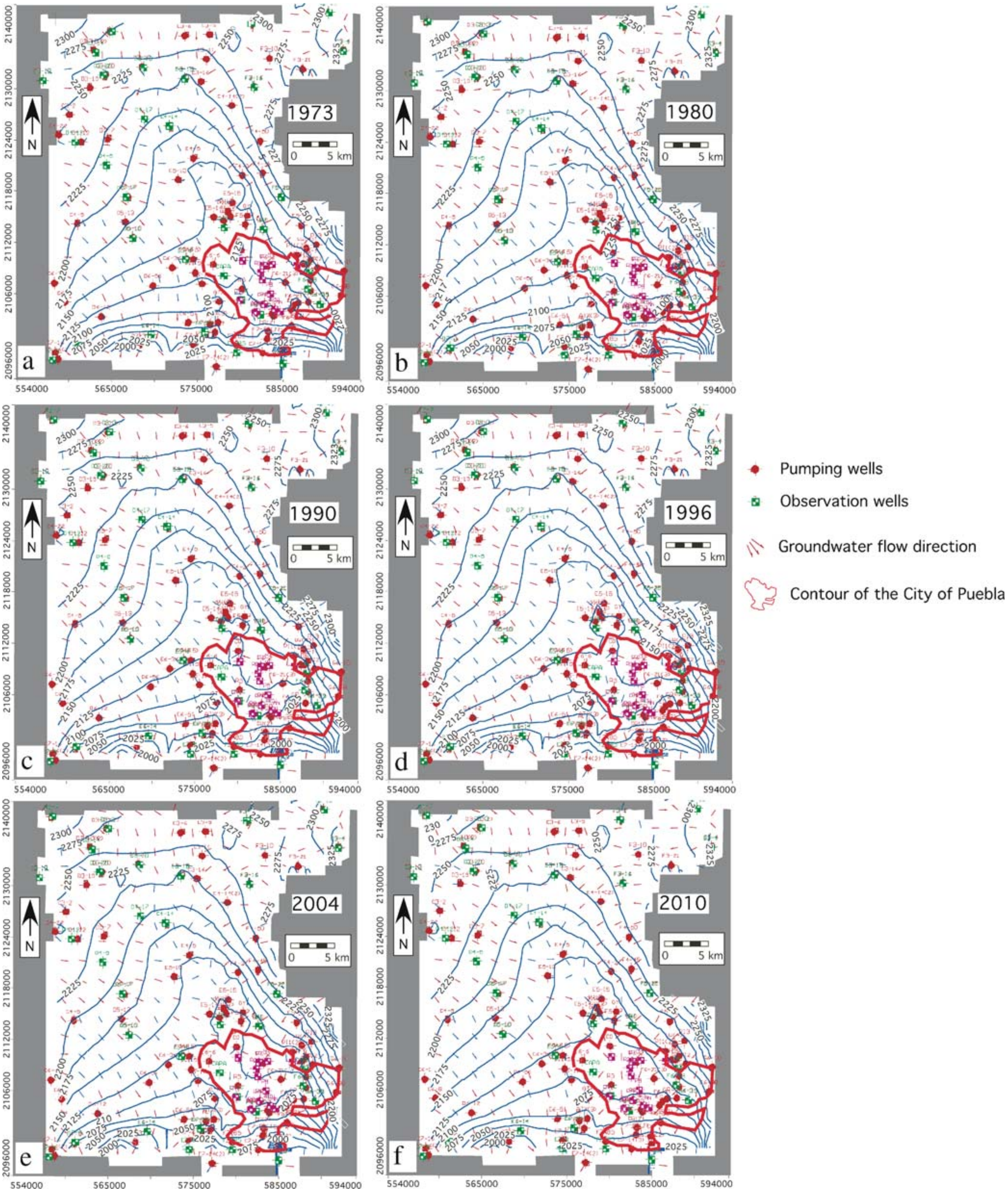

Fig. 10 The potentiometric surface maps from MODFLOW module. **a** Steady state regime (1973) and the evolution of the system for the years **b** 1980, **c** 1990, **d** 1996, **e** 2004, and **f** 2010 are shown. This model uses the hydrogeological parameters depicted in Table 1

of these wells properly agrees with the real location of the extracting wells, and the amount of the extracted water of each one represents the equivalent extraction of 15 wells. The evolution of the aquifer, assuming all the conditions of intensive exploitation, was simulated for the last 30 years. Figure 10 shows the outputs for the years

1973, 1980, 1990, 1996, and 2004, in which a considerable drawdown in the potentiometric surface towards the western sector of Puebla is observed. This feature reproduces the observations displayed in Fig. 4; the general trend of the groundwater flow is from northwest to southeast, and the drop in the potentiometric surface is observed to the southwest of Puebla.

The hydraulic head measurements from a set of historical data from 35 wells were used for comparison with the computed hydraulic head data, which constituted the calibration of the model. Figure 11a shows the scatter plots obtained between the observed levels in the 35 wells and those computed by the MODFLOW module. The linear regression analysis shows a confidence interval of 95% with a standard error of 6 m. These results confirm the model confidence for the period simulated. However, some particular regions are out of this confidence interval. Figure 11b shows the spatial variation of the differences between observed and computed hydraulic heads within the modeled area for the years 1973, 1996 and 2002. The model presents an overestimation of the hydraulic heads south of the Tlaxcala Plateau and to the western side of Puebla. The subestimation of the hydraulic head levels, depicted in Fig. 11b, shows a more irregular distribution during these years. This could be due to the scarcity of monitored wells in these areas. Despite this fact, the model satisfactorily reproduces the hydrological balance and parameters. A future scenario corresponding to 2010 (Fig. 10) shows that the water-table levels would remain practically unchanged in the northern part of the basin, under a constant extraction regime. However, in Puebla, it can be predicted that the depth of the cone of depression will increase by 15 m in the period from 2004 to 2010.

Transport model

An intermediate scale model was also computed. It was focused on the area comprising the southern portion of the basin, which includes the cities of Cholula and Puebla. This region displays the most important sinking effect. A redefined grid (200×200 m) composed of fine cells represents this region (Fig. 9). This produced an increase in the spatial resolution of the area and consequently an increase in the spatial variability of hydraulic properties. In particular, the fine grid covers the region where the existence of geothermal intrusion is more evident. This model was also used to achieve transport simulation, using the module MT3D (Zheng 1990, 1992, 1993) of mass transport. The intrusion of geothermal water was simulated assuming a high salt content in the fluid, with a point-like distribution of TDS sources aligned with the Malinche fault and Valsequillo fracture situated in the deep aquifer at 1,300 m depth. The assumed concentration for the sources ranges from 3,500 to 7,000 mg/L. Four hypothetical sources were associated with the NW–SE Valsequillo fracture and six for the NE–SW Malinche fault. The combined effect of the cone of depression and the hydrodynamic dispersion coefficient due to water circulation (Newman 1990) produces an enlargement of the SWZ represented by the TDS isolines (Fig. 12). Zone 4 simulates the high vertical hydraulic conductivity of

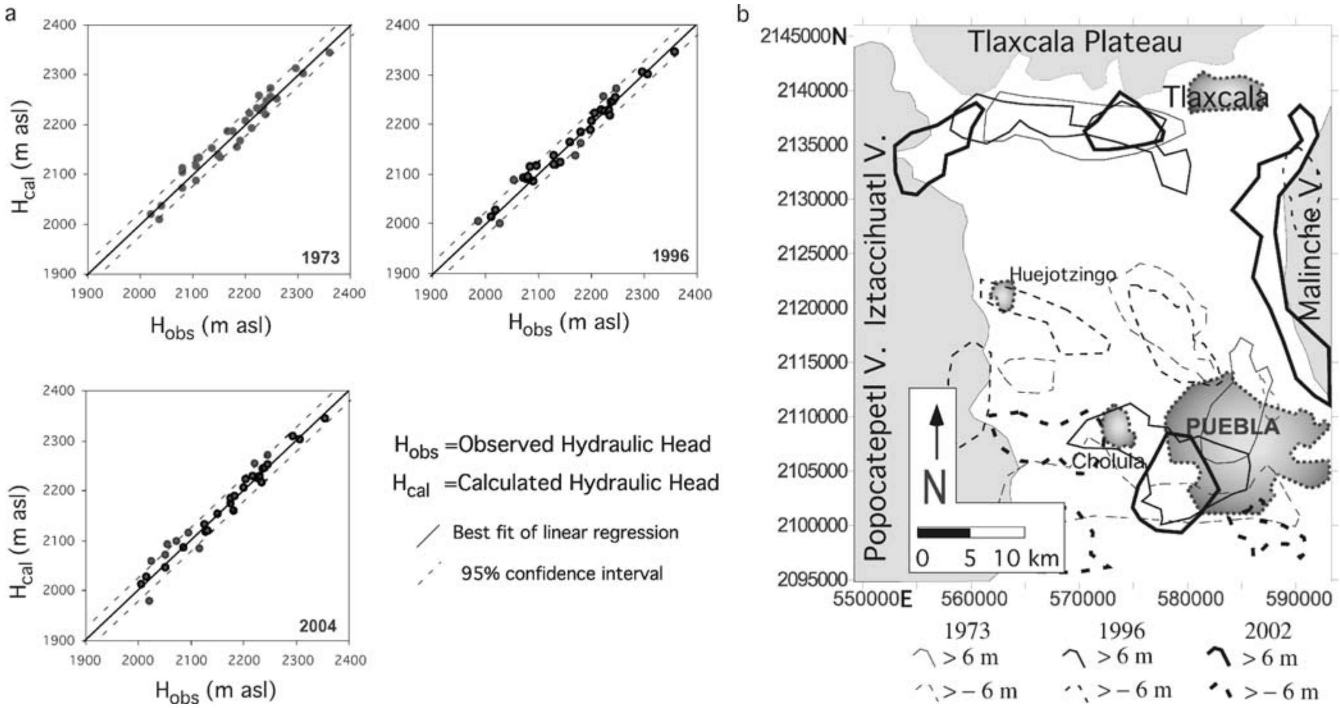

Fig. 11 Plots in which measured hydraulic head data are compared with the calculated (in meters). **a** Scatter plots show the correlation with observed data for the years 1973, 1996 and 2004. Linear regression analysis shows a confidence interval of 95% with an SE of 6 m. **b** Spatial variation of the differences between the observed and the computed hydraulic head levels for the years 1973, 1996 and 2002 are depicted

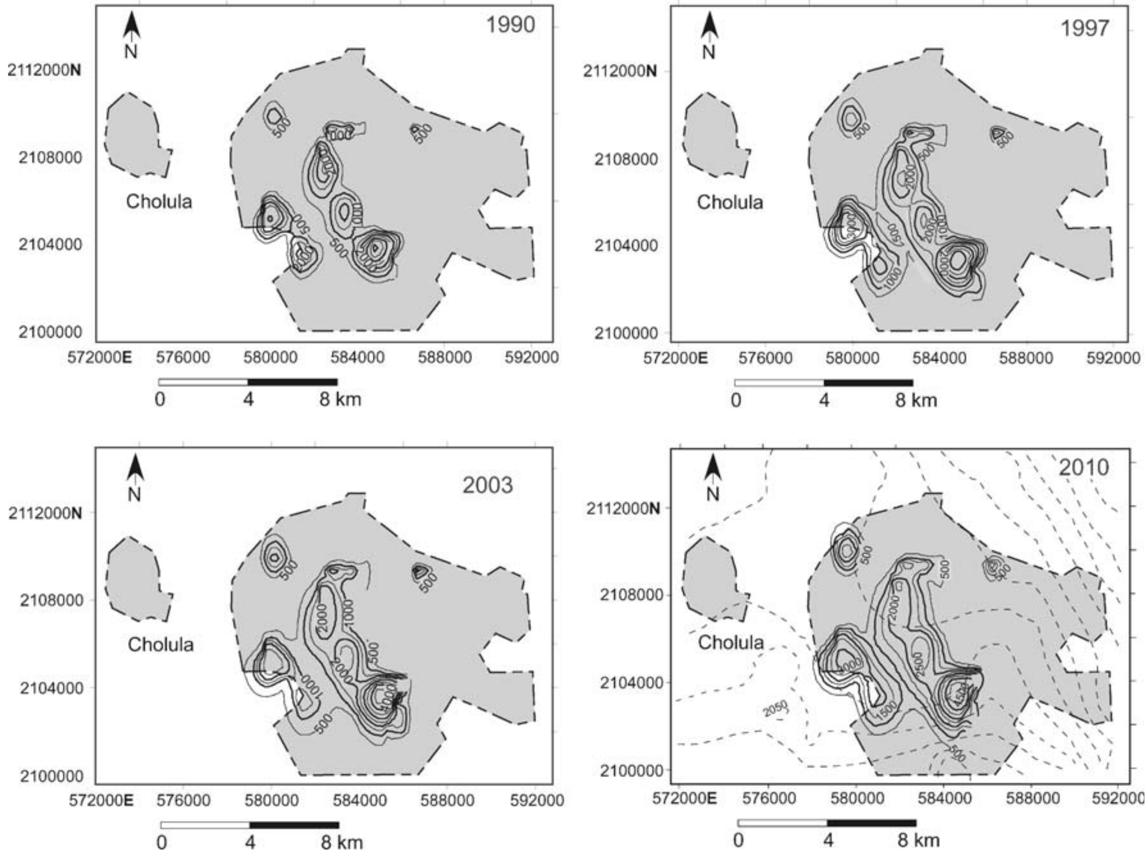

Fig. 12 Computed TDS maps for transport simulation (contour intervals 500 mg/L). The geothermal water is assumed to be at depth. Point-like distribution of TDS sources align with the Malinche fault and Valsequillo fracture. Evolution for the years 1990, 1997, and 2003 are shown. A possible future pattern for 2010 is also depicted. Potentiometric isolines are represented by *dashed lines* and the *dark shaded areas* represent towns

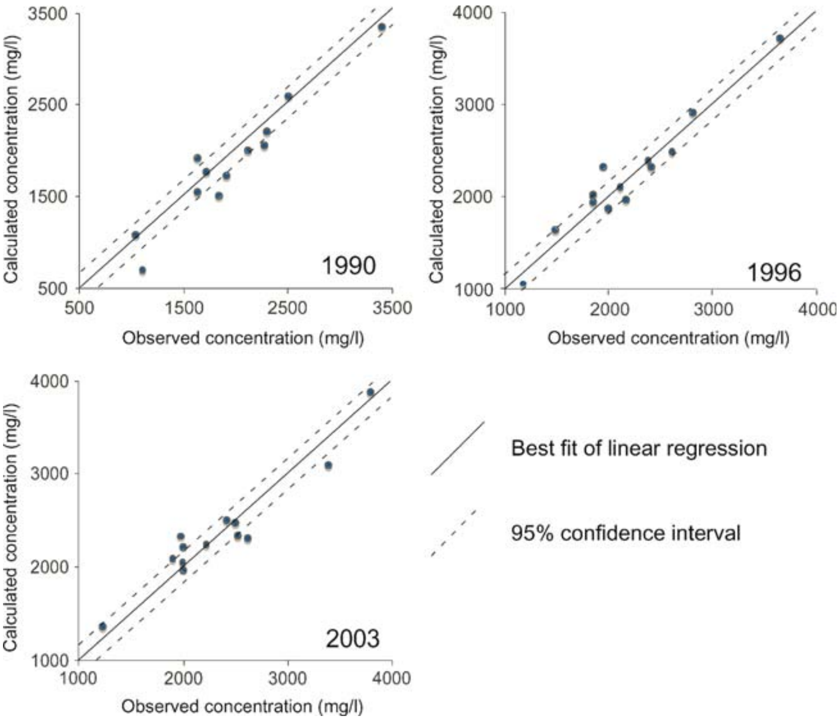

Fig. 13 Scatter plots of the observed and computed TDS data. The correlation was calculated for three years including **a** 1990, **b** 1996 and **c** 2003. Linear regression analysis shows a confidence interval of 95% with an SE of 100 mg/L

travertine in the modeling process (Table 1). Figure 13 shows the scatter plots obtained between the measured TDS in 12 wells and those computed by the MT3D module. Linear regression analysis shows a confidence interval of 95% with a standard error of 100 mg/L. The observed data are consistent with the computed data between 1990 and 2003. The TDS map in Fig. 12 for the year 2010 shows an increase in the SWZ, and is in agreement with observations in previous years.

Discussion

The transient flow models computed in this study were used to simulate the evolution of the potentiometric surface of the Puebla Valley aquifer system from 1973 to 2002. The model reproduces satisfactorily the observed potentiometric map for these years (Figs. 10 and 11). An important drawdown in the potentiometric surface is observed in the southern portion of the basin (Fig. 10). This result correlates with the observations (Fig. 4) recorded during that period of time. An important contribution to this pattern is the trend of the groundwater movement, from northwest to southeast. The Puebla Basin has two regions of water flow interchange, one to the north and the other to the south. To the north, the Atoyac, Zahuapan and Alseseca rivers are affluent providing approximately 8 m^3/s. The surficial and groundwater drains coming from the Tlaxcala Plateau also contribute to the positive flow of water into the aquifer system. The discharge zones are situated to the southeast of the basin, constituting an important tributary of the Valsequillo Dam. This reservoir is located to the southeast, outside of the limits of the aquifer system.

The transient flow model shows an important cone of depression located in the southwestern part of Puebla. The calculated model for 2010 indicates a drawdown of 95 m in the cone of depression at the same location. This means the potentiometric surface will fall by more than 15 m compared to the level now observed. The computed TDS concentration isolines are in agreement with the observed ones (Fig. 13). This model also indicates an enlargement of the high TDS concentration area of about 40% in Puebla in the last 18 years. The combined effect among the drawdown of the potentiometric surface, the dispersivity due to the water circulation (Newman 1990), and the high vertical hydraulic conductivity of travertine produces the expansion of the SWZ. The increasing number of wells drilled in the region of Cholula and Puebla (~50 new wells in the last 10 years) also contribute to the growth of the SWZ.

The artesian boreholes containing sulfur water provide evidence of the interaction between the middle and deep aquifers of the Puebla Basin and the geothermal system is probably associated with the Malinche volcano. Chemical evidence of the influence of geothermal waters in the aquifer is a slight enrichment of boron (from 1 to 3 mg/L), fluorine (>1.5 mg/L), sulfides (>8.5 mg/L) and TDS. Since the values of geothermal water reported in the literature (Henley et al. 1984) are higher than those encountered in the wells, it is assumed that the geothermal water is mixed with fresh water. This evidence seems to confirm the hypothesis that these contaminants infiltrate the upper aquifer through the fractured travertine and the new wells. It is important to point out that the dissolution of Mesozoic calcareous rocks produced by warm water also increased the TDS content. This area expanded from 16 km^2 in 1990 to 40 km^2 in 2002. A maximum TDS concentration of 2,000 mg/L was found in 1990 in four wells. Today, the maximum TDS concentration has increased to 2,500 mg/L in the same wells.

Conclusions

An integrated geoelectrical, geological and hydrogeological study was carried out in the Puebla Basin to appraise the aquifer system providing fresh water to Puebla. Two important findings were made: a significant drawdown in the potentiometric surface was identified towards the southern portion of the basin and hydrothermal fluid intrusion seems to have risen from the deeper aquifers to the shallow aquifer, producing a mixed fluid with relatively high concentrations of TDS.

The reinterpreted series of VES profiles in the central portion of the basin were used to define the thickness of geoelectrical layers. This model and the evidence encountered in the lithology of the wells were employed to construct a five-layer model that was used to simulate the evolution of the aquifer and to predict its future behavior under different extraction conditions. The computed evolution of the potentiometric surface from 1973 to 2004 shows that the northern portion of the basin remains practically unchanged. However, the region southwest of Puebla possesses a cone of depression of about 80 m. This depression increased 20 m in 6 years (from 1996 to 2002) and could increase an additional 15 m in the next 10 years.

The geological and structural features of the Puebla Basin play an important role in the hydrological patterns. The intersection of the Malinche fault and the Valsequillo fracture in the city of Puebla has allowed the development of a region of high secondary permeability due to fracturing. It is also relevant that at this location, the travertine is more widespread and occupies 60% of Puebla. This fractured region allows the exchange of water between the different aquifers existing in the valley. In addition, the overexploitation of the aquifer has led to an increase in geothermal water intrusion, giving rise to the so-called sulfur water zone (SWZ). The numerical simulation of pumping wells located in the city of Puebla shows that the intrusion process has also worsened due to the drawdown of the potentiometric surface.

A predictive trial run for a 15-year evolution until the year 2020 was performed, assuming a redistribution of the water-extracting wells. Those located in the region of the cone of depression were moved towards the recharge zones, and the remaining wells were left in their original position. This scenario was proposed to diminish the intrusion process and to observe the aquifer system recovery. However, such a scenario did not produce any recovery in the system, and, therefore, alternatives to remedy this situation must be investigated such as re-injection wells, water treatment, amongst others. Needless to say, the water extraction rate must be controlled and fresh water wells in the SWZ should be abandoned. The hydraulic balance of the aquifer shows a deficit of 12 Mm^3/year. This extraction rate must be diminished in order to equilibrate the total amount of recharge and extraction.

Acknowledgements This study was financed by the Direccion general de Personal Academico de la Universidad Nacional Autonoma de Mexico research projects IN107602 and IX103304. The authors are indebted to Sistema Operador de Agua Potable y Alcantarillado de Puebla (SOAPAP), and especially to engineers H. Muñoz, M. Osorio and F. Castillo (Director of SOAPAP) and to A. Ortiz from Gerencia Estatal de Puebla de la Comision Nacional del Agua (CNA) for providing some original data. GJS was supported by the Benemerita Universidad Autonoma de Puebla (Mexico) through a PhD research program. The authors would like to thank B. Martiny from Universidad Nacional Autonoma de Mexico for her English revision of the manuscript. The authors are indebted to the Associate Editor C. Zheng, Managing Editor M.-T. Schafmeister and the two anonymous reviewers for their helpful comments for improving the manuscript.

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