Geofísica Internacional 47 (1), 27-40 (2008)

Numerical modeling of Etla Valley aquifer, Oax., Mexico: Evolution and remediation scenarios

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Received: February 19, 2007; accepted: November 13, 2007

Resumen

Se presenta un modelo geohidrológico evolutivo 3D a corto plazo (para los años 2001, 2005 y 2015) del acuífero somero del Valle de Etla, Oaxaca, sureste de México, basado en los parámetros disponibles de geología, geofísica, geoquímica e hidrología. Las simulaciones numéricas fueron realizadas en Visual MODFLOW. Estas simulaciones indican que, si el actual régimen de extracción es mantenido, el abatimiento de la superficie potenciométrica puede ser mayor en el SE del área de estudio (i. e. cerca de la ciudad de Oaxaca). La contaminación por fertilizantes y por las fugas de drenaje es favorecida por la dirección de flujo imperante en el acuífero (vaciándose en el río Atoyac)

De acuerdo a las simulaciones numéricas, existe una posible remediación de este proceso, relocalizando los pozos situados en la ciudad de Oaxaca en las zonas de recarga (i. e. en las faldas de la Sierra de Juárez). Este escenario de remediación permitiría una recuperación en el nivel de la superficie potenciométrica.

Palabras clave: Modelo 3D, flujo de agua subterránea, geohidrología, México.

Abstract

Short-term evolution (for 2001, 2005 and 2015) for the shallow aquifer of Etla Valley, Oaxaca, southern Mexico, was simulated based in a 3D hydrological model elaborated from the available geological, geophysical, geochemical, and hydrologic parameters. The numerical simulations were based on Visual MODFLOW code. These simulations indicate that, if the actual extraction regime is maintained, the drawdown of the potentiometric surface will get worse to the SE of the study area (i. e. beneath Oaxaca city). The prevailing aquifer flow direction favors the ground water pollution by fertilizers and leakage from the sewage network (dumped to the Atoyac river).

According to the numerical simulation, remediation of this situation is possible if the wells located in the neigborhood of Oaxaca City are relocated at the recharge zones (i. e. at the feet from Sierra de Juárez). This remediation scenario will allow a recovery of the drawdown of the potentiometric surface.

Key words: 3D model, ground water flow, geohydrology, Mexico.

Introduction

In Mexico, at present, about 653 aquifers are in exploitation, contributing with up 60 % of the total all-purpose water supply. Over-exploitation, saline intrusion-contamination, domestic and industrial wastewater enhance the vulnerability to contamination of subsurface aquifers (CONAGUA, 2006). The Etla valley aquifer system is located in the central portion of the Oaxaca State, near the city of Oaxaca (Fig. 1), the State capital, with more than 250 000 inhabitants; its water requirements have increased considerably during the last twenty-five years. The number of wells used to extract water were increased from approximately 75 in 1984, to 190 in 1996, and 311 wells in 2001. These wells have been in constant giving over-exploitation has given rise to a drawdown of the potentiometric surface, which increases the pollution due to contamination sources (domestic and industrial wastewater, as well as soil fertilizers). Belmonte-Jiménez *et al.* (2003, 2005) have assessed the vulnerability to pollution from the aquifer of Etla and Zaachila Valleys.

Multidisciplinary studies (Belmonte-Jiménez *et al.*, 1998 a, b; Norzagaray, 1998; Flores-Márquez *et al.*, 2001; Campos-Enriquez *et al.*, submitted; Flores-Marquez *et al.*, submitted) have described the hydrolgy and geology of the area. In order to control contamination of the groundwater resources, the present study is focused on the effect of drawdown of the potentiometric surface on flow evolution. Over the last 25 years, the water-table level in the shallow aquifer has been monitored and the results are presented in this work. Several predictive scenarios are numerically simulated to determine the extraction rates for extraction–recharge balance. Numerical evolution models, based on the Visual MODFLOW Software (Waterloo Hydrogeologic Inc., Canada 2005), were computed for an integrated three-dimensional geological model constrained by geophysical, geological and geochemical studies. Ground water flow and transport models simulate the evolution of the potential future extraction regimes until the year 2015. We propose new locations for the extracting wells in order to diminish the drawdown of the potentiometric surface.

Integrated model

Geological setting

The Sierra Madre del Sur extends from southern Jalisco to the Isthmus of Tehuantepec. This range contains several intermountain valleys with associated potential aquifers. The city of Oaxaca (Fig. 1) is located at the junction of three valleys: Etla to the northwest, Tlacolula-Mitla to the southeast and Zaachila to the south (Fig. 1). The study area constitutes an elongated valley with a NW-SE orientation, and bordered to the SW by metamorphic rocks of the Oaxaca complex (Grenvillian age) and to the NE by Mesozoic folded sedimentary rocks of the Juárez terrane (Sierra de Juárez) (Pantoja-Alor, 1992). The mountains bordering the Etla valley constitute the main recharge zones of the aquifer system.

Grenvillian metamorphic rocks of the Oaxaca complex or Zapoteco terrane (Campa and Coney, 1983; Sedlock *et al.*, 1993; Ortega-Gutiérrez, 1993; Ortega-Gutiérrez *et al.*, 1995) and Mesozoic sedimentary rocks and mylonites of the Juárez terrane (Ortega-Gutiérrez *et al.*, 1990; Sedlock *et al.*, 1993) constitute the basement of the region. The Oaxaca fault system with a NW-SE orientation constitutes the limit between these terranes. This fault system exhibits a complex history of displacements beginning in the Paleozoic, followed by left-lateral motion during the Jurassic and most recently normal fault motion in the Late Cenozoic with down-thrown block to the west (Alaniz-Alvarez *et al.*, 1996; Centeno-García *et al.*, 1990). Some isolated outcrops of Mesozoic sedimentary rocks and granites are distributed along the eastern border of the valley. Some proterozoic granites are also described on the west border of this basin (Solari *et al.*, 2004). The Cenozoic sequences are mostly Miocene in age and unconformably lie over rocks of the regional basement with a thickness of approximately 900 m (Ferrusquía-Villafranca, 1992). Based on gravimetric studies in the central part of the valley, Flores-Márquez *et al.* (2001) and Campos-Enriquez *et al.* (submitted) propose a maximum thickness of 730 m for these sequences.

Two sequences constitute the Cenozoic filling of the valley. The first one is made up of conglomerates and early Cenozoic andesitic–latiandesitc rocks (Wilson and Clabaugh, 1970; Ferrusquía-Villafranca, 1992). The second is mainly represented by a thick Miocene sequence that includes the Suchilquitongo Formation and the Telixtlahuaca unconsolidated conglomerate (> 400 m thick). The Suchilquitongo Formation contains lacustrine deposits (sandstone, shale, and limestone), silicic tuffs, ignimbrites and epiclastic tuffs (Wilson and Clabaugh, 1970; Ferrusquía-Villafranca, 1992). The recent deposits comprise Quaternary alluvium and soil that rest in concordance upon Neogene rocks. These alluvial materials are sufficiently permeable to allow ground water flow in a shallow aquifer.

Hydrogeology of the Etla Valley

The Etla valley aquifer comprises an area of about 400 km^2 with a mean altitude of 1660 m a.s.l. The main streams draining the valley are Atoyac, Mazaltepec, San Agustín, San Gabriel and San Pablo rivers (Fig. 1b). Rainfall in the Sierra de Oaxaca feeds the Mazaltepec and San Pablo rivers. The San Agustín and San Gabriel rivers on the eastern flank of the valley are fed from the Sierra de Juárez. These rivers join the Atoyac River, of 26 x 10^6 m^3/yr approximately, increasing to 52 x 106 m^3/yr in rain seasons (1.67 m^3/s). According to INEGI (1991), Belmonte-Jiménez *et al.* (1998 a , b), Flores-Márquez *et al.* (2001), Flores-Marquez *et al.* (submitted), and Campos-Enriquez *et al.* (submitted), the hydrological system is composed of two aquifers: a shallow one 20 to 60 m thick, and another one at depths below 60 m. The upper aquifer is in Neogene-Quaternary sand and gravel sediments containing water of good quality, whereas, the second aquifer is probably made up of Cenozoic lacustrine sediments, epiclastic tuffs and fluvial deposits with a thickness of some hundreds of meters. Mesozoic–Precambrian rocks underlay the aquifer system. A clay body between both aquifers, with an average thickness of 36 m constitutes an aquitard. This aquifer system provides about 80 % of total water for domestic and agricultural uses. By 1984, 75 wells, approximately, were used to extract fresh water for agricultural and human uses. Later more than 125 wells were drilled next to the city of Oaxaca and other small towns in the valley, mainly for domestic use.

3D model based on geophysical studies

Geophysical studies by the Instituto Politécnico Nacional (Centro Interdisciplinario Investigación para De-

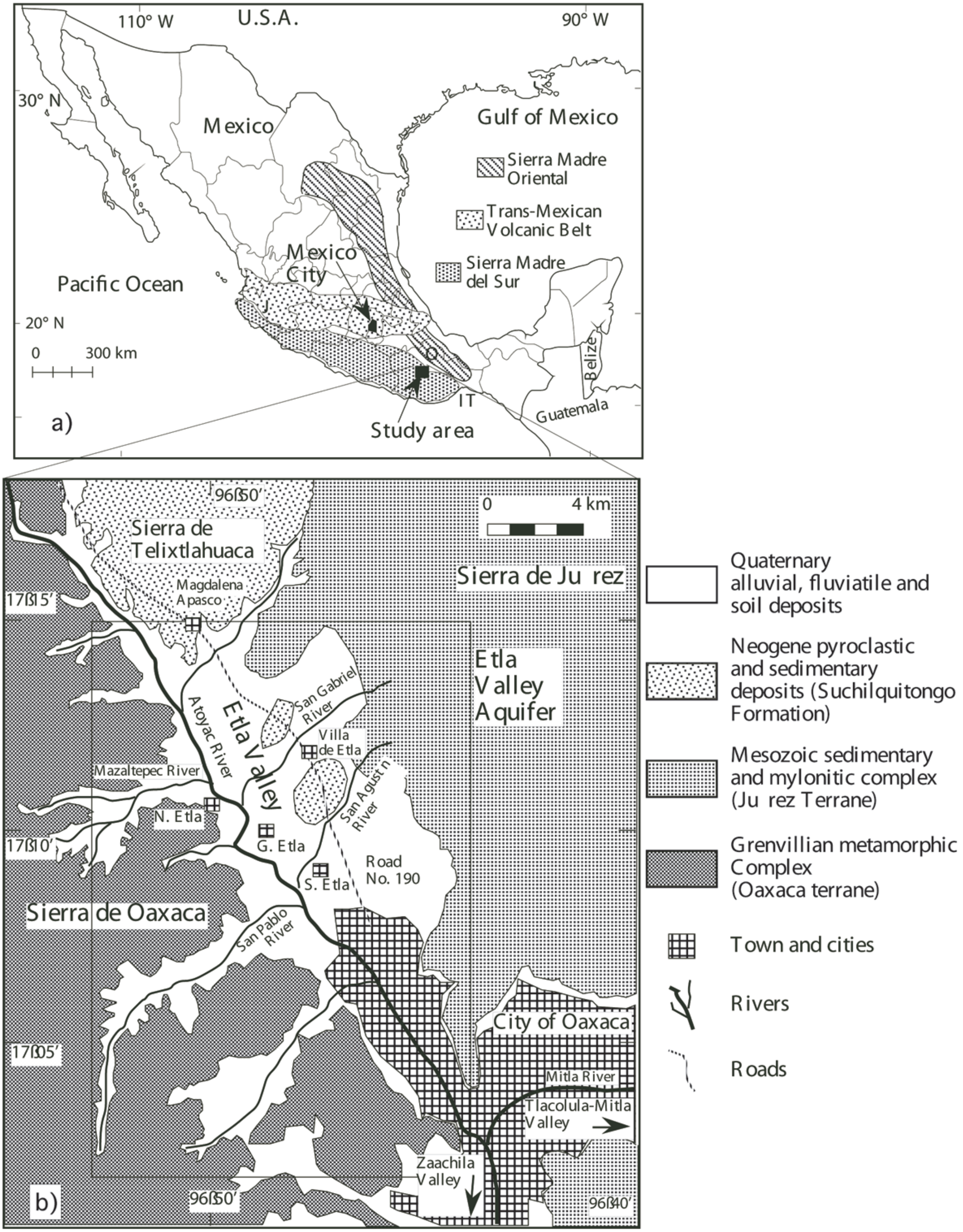

Fig. 1. a) Location of the study area at the Sierra Madre del Sur (J: State of Jalisco, O: state of Oaxaca, IT: Isthmus of Tehuantepec). b) Delimitation of the Etla Valley aquifer and its natural boundaries, and simplified geology.

sarrollo Integral Regional-IPN-Oaxaca), Universidad Nacional Autónoma de México (Instituto de Geofísica), Centro de Investigación Científica y Educación Superior de Ensenada (CICESE), were integrated to establish the basement morphology of the intermountain Etla Valley and characterize its sedimentary infill constituting the aquifer system. Two approaches were followed. The first one established the structure of the shallow aquifer and the other defined the morphology of deeper layers. Gravimetric and magnetometric studies helped to define the geometry of the basement and its main structural features (Belmonte-Jiménez *et al*., 1998 a, b; Norzagaray, 1998; Flores-Márquez *et al*., 2001; Flores-Marquez *et al*., submitted; Campos-Enriquez *et al*., submitted).

On the basis of these studies we constructed the 3D geometrical model shown in Fig. 2. The basement, with a graben morphology, is at least 730 m deep at Etla city, and is bounded by the Oaxaca and Etla faults. The sedimentary infill can be represented by six layers of different physical properties, inferred from the lithology described above. The Etla valley aquifers located in Quaternary deposits are 1) an upper unconfined aquifer, irregularly distributed with increasing thickness from the borders to the center of the valley (from 35 to 45 m), and 2) a second aquifer at depths of more than 50 m, following the same tendency. In some electrical profiles a sand and clay bed was detected at depths of 45 m that can behave as an aquitard between these aquifers. However, the continuity of this aquitard under the rest of the valley is not confirmed by geoelectric studies because of the irregular thickness of the upper sediments. The topography was obtained from the digital topographic geodatabase MDE (Mexican Digital Elevations), compiled by INEGI (2005).

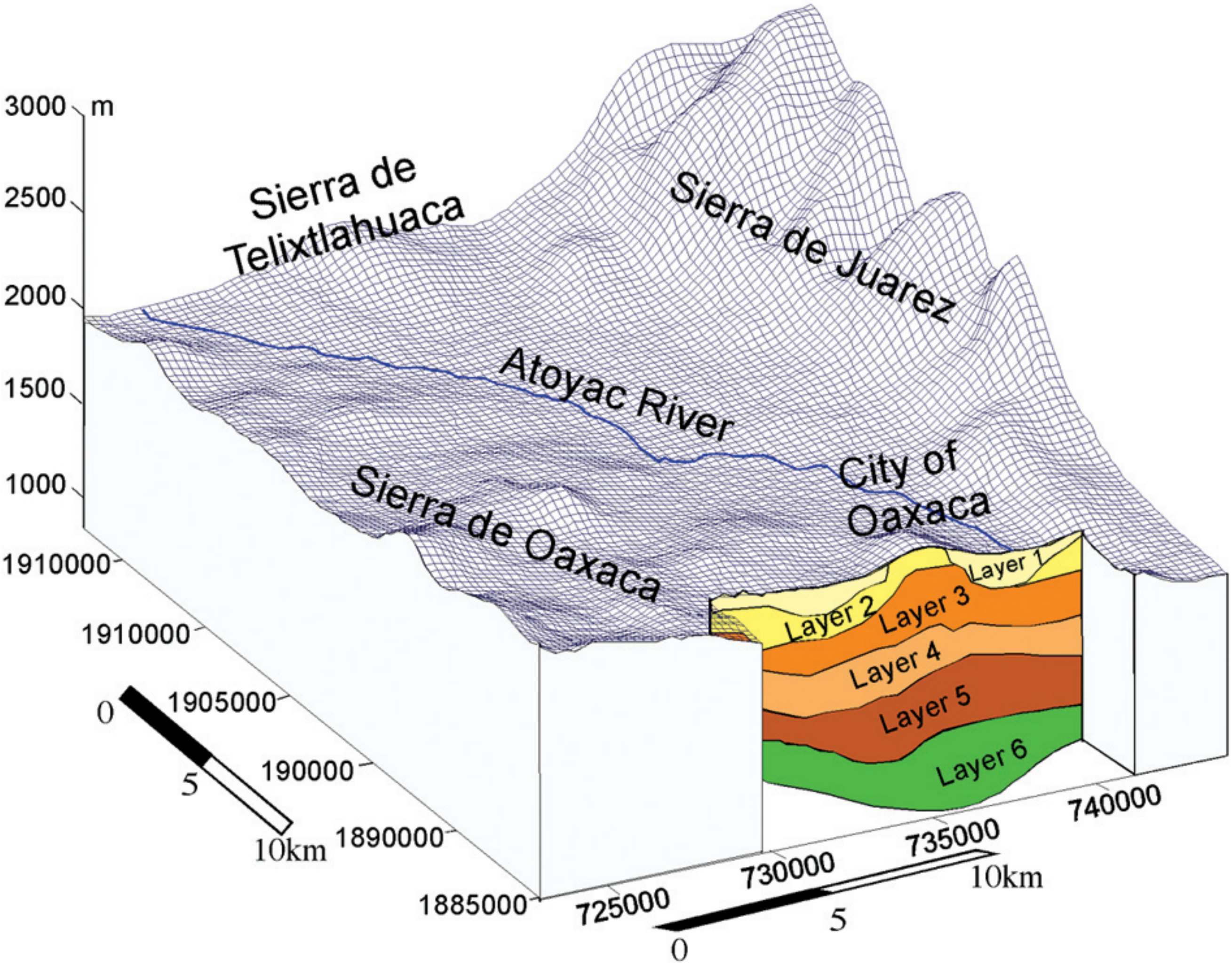

Fig. 2. Conceptual diagram of the large-scale three-dimensional model of the Etla Valley (parameters given in Table 1). The bottom of layers was inferred from the geoelectrical study. The basement of valley was inferred from gravimetric inversion studies. Topography is also shown.

Hydrological evolution

We describe the historical evolution of the water-table from 1984 through 2001. Numerical interpolation of water-table measurements for each period was carried out (Fig. 3). In 1984, the National Water Commission (Comisión Nacional del Agua, personal communication) monitored from January to July 60 extraction wells on the Etla valley aquifer. It was observed, that the ground water flows from NW to SE with a hydraulic gradient of 9 x 10^{-3}, following the pattern of the Atoyac River, and preserving the hydraulic gradient. The lateral contributions to the ground water flow came from the recharge zones in Sierra de Juárez and Sierra de Oaxaca. The first one with a hydraulic gradient of 10 x 10^{-3} to the northeast, but reducing its value to a 5.8 x 10^{-3}, towards the southeastern flank of the valley (where the ground water flow meets the Mitla-Tlacolula valley). The hydraulic gradient increases to 14.8 x 10^{-3} in rainy season at the northeast portion of the valley. The contribution of the Sierra de Oaxaca, near the middle part of the valley, amounts to 15.3 x 10^{-3}. However, the hydraulic gradient decreases to 5 x 10^{-3} towards the southwestern flank of the valley.

In 1996, geohydrological monitoring was carried out by the Instituto Politécnico Nacional (CIIDIR-Oaxaca; Belmonte *et al.*, 1998 a, b; Norzagaray, 1998). In February, March, April, August and December, 59 extracting wells were monitored. The interpolation of mean values of the corresponding water-table measurements is shown in Fig. 3b. Between these two periods, the observed hydraulic gradients from the Sierras remain fairly constant in some regions; the center and SE of the valley presented drawdown of the water-table elevations.

The 2001 geohydrological survey was carried out by the Comision Nacional del Agua (CNA, 2001). 311 extraction wells were in use, but only 80 extraction wells were monitored during the months of October and December. Interpolation of the mean values of the water-table measurements is shown in Fig. 3c. From 1984 to 2001 no major changes in the hydrological flow pattern are observed. There were no major changes in hydraulic gradients from the ranges in the main NW-SE flow direction along the valley with nearly the same hydraulic gradient, and in the flow of the rivers; but the number of extraction wells increased, and the water-table dropped at the center and to SE of the valley.

The hydrogeological data collected by CNA and IPN-CIIDIR-Oaxaca allowed us to estimate the aquifer hydraulic balance. The total input can be estimated at 564.9 Mm^3 (1 Mm^3 = 1 x 10^6 m^3) considering an average annual precipitation of 30^2 Mm^3, an underground inflow volume of 8.5 Mm^3, return water from agriculture of 4.4 Mm^3, and an inflow from rivers of 250 Mm^3. These values remained nearly constant since 1984, except for rivers, whose flow has been diminishing. Total aquifer outflow volume changed. For 1984 the hydraulic balance between input and output flows had a surplus of 10,000 m^3; the 1996 balance showed a deficit of 17 Mm^3. In 2001, the outflow was estimated from an underground flow of 4 Mm^3, an evapotranspiration of 226 Mm^3, a river outflow volume of 282.7 Mm^3 and the extraction of 311 wells (70 Mm^3). Now annual output exceeded the natural input by 17.8 Mm^3. At present, the aquifer again registers an imbalance of nearly the same amount. There are depression cones in the valley to be described in the next section.

Ground water level declines

In order to quantify the potentiometric surface decline, the difference in the water-table levels in the periods 1984-1996 (Fig. 4a), and 1984-2001 (Fig. 4b), were obtained. Fig. 4a displays four depression cones in sites A (situated to the SE of Magdalena Apasco, Fig. 4b), B (to the N of Guadalupe Etla), C (to the S of Guadalupe Etla) and D (Oaxaca City), where a significant drawdown in the potentiometric surface is observed (from 5 to 20 m). For 1984-2001, increases in depth and extension of depression cones are observed as follows: 10 m for depression A; 5 m for the site B; site C presents an increase in extension of about 50%, but preserves its original drawdown of 10 m. Finally, the cone of depression in site D increased its depression by about 30 m with an extension of about 8 km^2; the ground water corresponds to a depleted water volume storage equivalent to about 3 Mm^3. The observed drawdown is significant, but its area and depth could be overestimated because in some wells the measurements were not made in a steady state regime. It should be pointed out that the depression cone changed from 10 m in 1996 to 30 m in 2001 for this region. The water table level dropped for the site D at a rate of 4 m per year in the period 1996-2001. This effect could be due either to extraction in this region, or to excessive extraction within the valley. Water-table level in portions of the basin nearest to the recharge zones (feet of the Sierras de Juárez and Oaxaca, and NW of the valley) remained practically unchanged for the same period.

Ground water quality

In addition to the drawdown, some contaminated regions of the upper aquifer were detected. Chemical analyses of water samples from 24 pumping wells in the Etla valley were carried out in 1996 by the CIIDIR-Oaxaca (Belmonte *et al.*, 1998 a, b; Norzagaray, 1998). For that year, the total dissolved solids (TDS) did not exceed 500

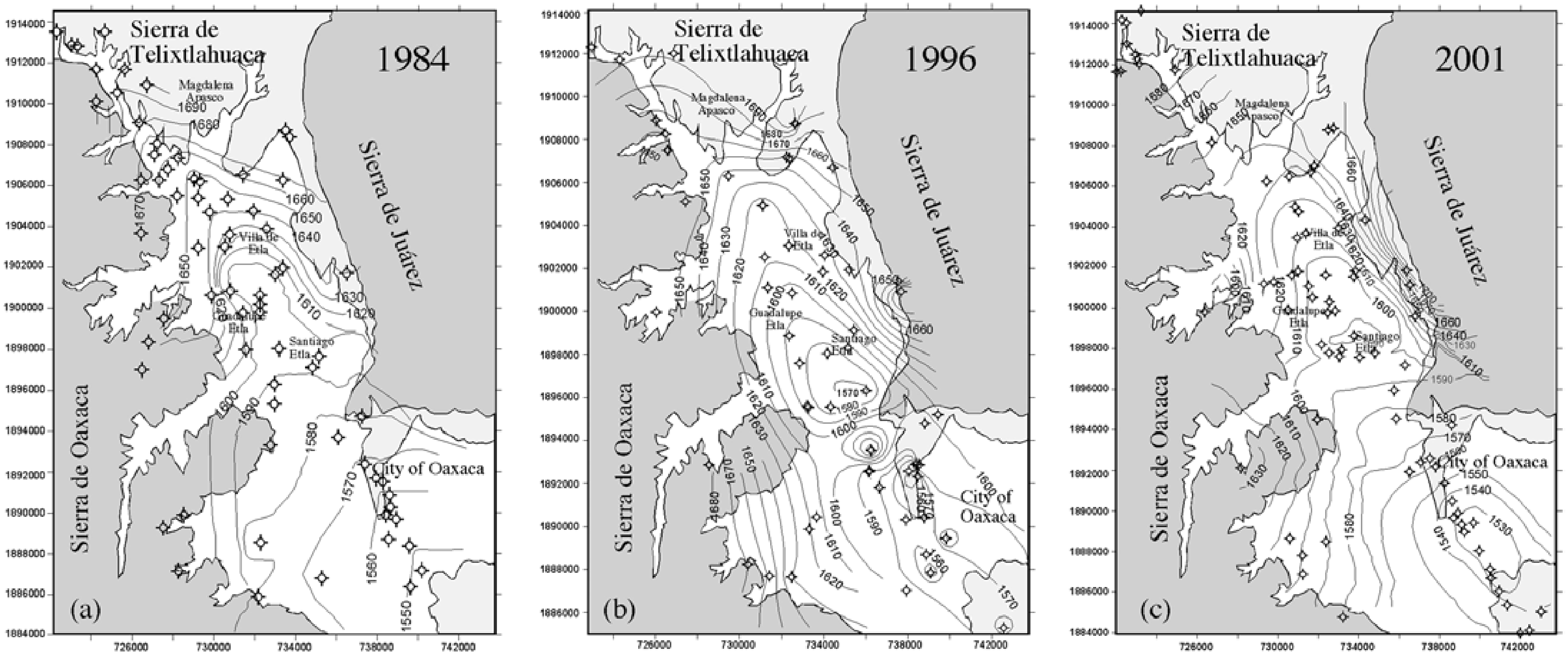

Fig. 3. Evolution of the water-table elevations of the Etla Valley for the years: a) 1984, b) 1996 and c) 2001, in meters. Numerical interpolations are based on original data provided by CIIDIR and CNA reports (see text). Monitored wells are also indicated.

mg/L (Fig. 5) which meets the Mexican official law for potable water (NOM-127-SSA1-1994: TDS ≤ 1000 mg/l). Samples from one borehole exceeded 3000 mg/L, and were not taken into account in the interpolation process, assuming it an outlier due to contamination of the samples. Recent chemical studies (CNA, 2001), indicated an average increase of 120 mg/L of TDS in some monitoring wells (Fig. 5); concentrations of about 620 mg/L of TDS were registered. These values are within the Mexican official law for potable water, but the increase in TDS indicates some contamination process. The economic activities in the valley comprise agriculture and some small industries; therefore, it was assumed that the main pollution sources are fertilizers, industrial sewage and some leakage of local sewage. Although the measurement period was only five years, there are signs indicating that care has to be taken in the management of fertilizers and the local wastewater leakage.

Ground water flow model

Numerical models are useful to predict the values of the hydraulic head which enables one to determine the impact of pumping wells on the water-table levels or to predict the direction and rate of ground water flow. MODFLOW (McDonald and Harbaug, 1988) was used to compute the ground water evolution for the study area, based on gravity inversion, represented as a non-flow condition. The block model (Fig. 2) shows the area extension, its topography, as well as the natural boundaries of the aquifer system and stratigraphic layers comprising it. The stratigraphic layers were constructed from the hydrogeological map of the area and the correlation between the lithological columns of 6 wells (CNA, 2001) and the inferred resistive horizons described in above-mentioned geophysical studies. From these data a six-layer model was elaborated (Table 1), with variable thickness (Fig. 2). The surficial layer (layer 1, see Table 1 and Fig. 2) was divided in four different zones according to the surface geology and the deduced and measured local hydrologic properties (Gelhar *et al.*, 1992; Bear, 1972; Bear and Bachmat, 1991; De Marsily, 1986). The results of 15 pumping tests performed in different wells along the valley (CNA, 2001) were taken into account to estimate the corresponding hydraulic transmissivity. The flow and transport model of the aquifer within the valley consists of a rectangular grid of 43 x 56 cells (cell size area is 500 x 500 m) in the x-y plane.

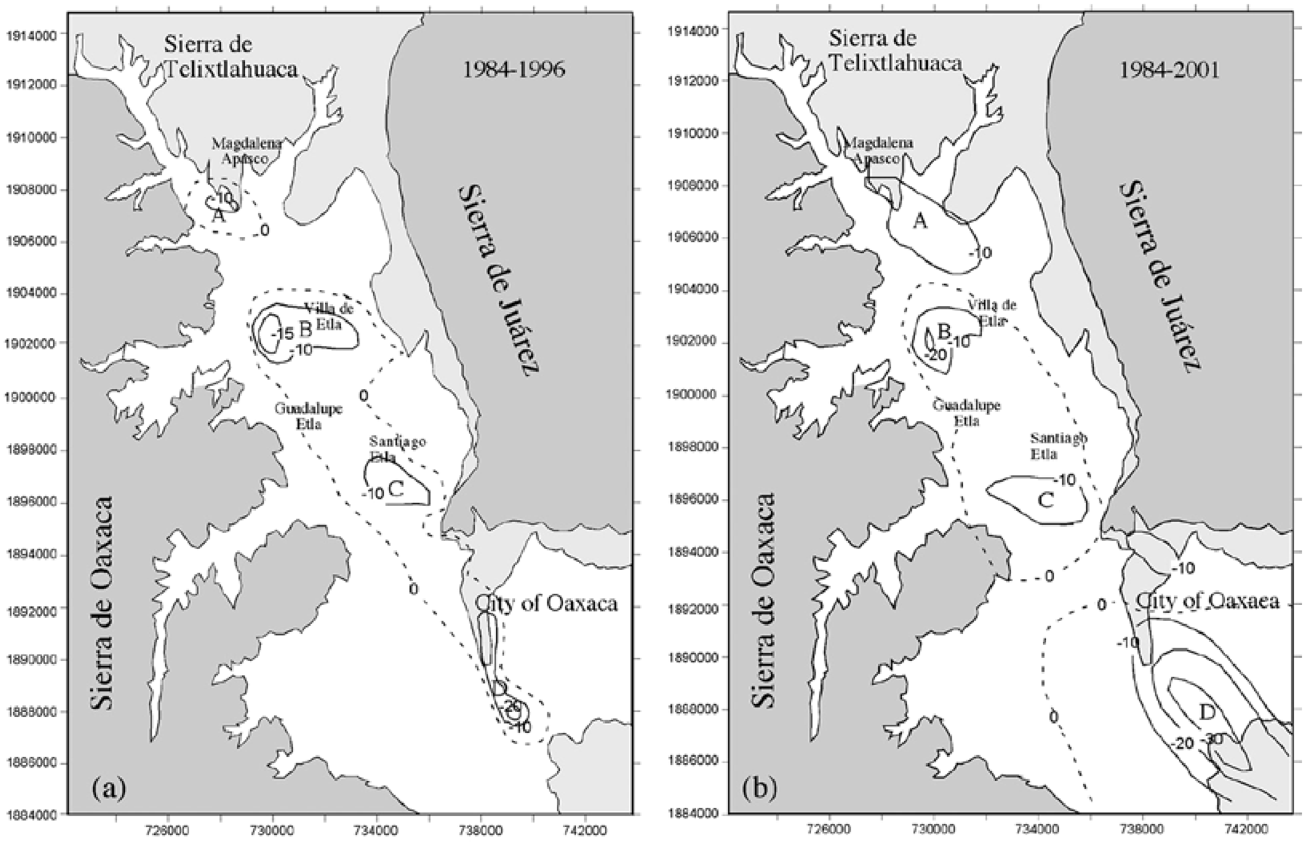

Fig. 4. Regions with significant drawdown of the water-table levels indicated by depression cones: A, B, C and D. The differences between water-table levels were calculated for the periods: a) 1984-1996 and b) 1984-2001.

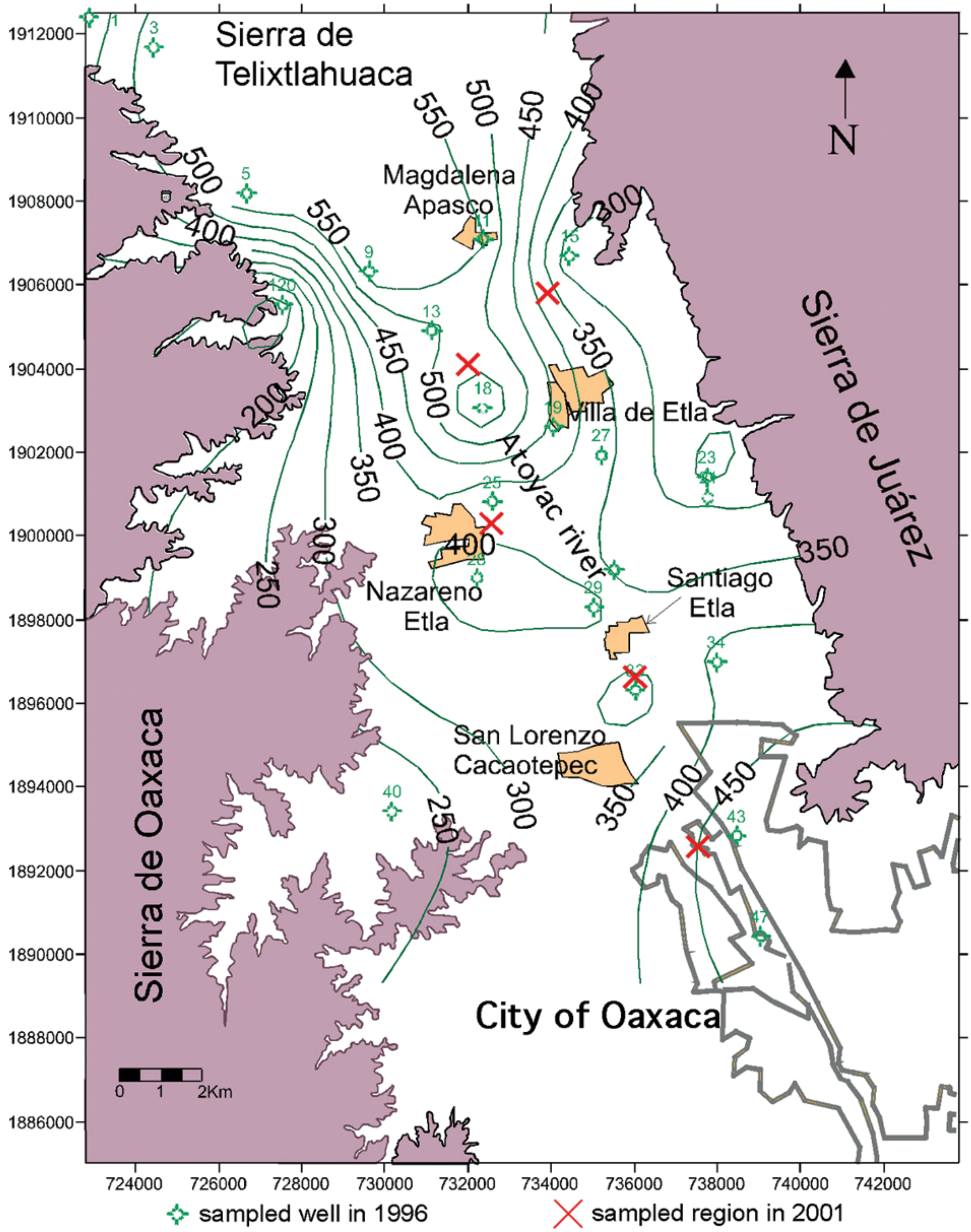

Fig. 5. Map of TDS values distribution for wells measured in 1996 (contours in mg/L). Wells chemical analyses conducted in 2001 are also shown.

The precise definition of the boundary conditions is essential for the accuracy of the model. The natural boundaries of the aquifer system are the ranges of the Sierra de Juárez to the E, the Sierra de Oaxaca to the W and the Sierra de Telixtlahuaca to the N. These ranges also constitute the recharge zones and were properly considered in the model. The southeast section of the valley, towards the Zaachila valley, is proposed as the main discharge zone. The mountain fronts and its corresponding tributary recharge areas were treated in the model as a specific flow boundary in the uppermost layer (Table 2).

A steady state calibration of the ground water flow model was obtained using the estimated aquifer parameters (Table 1). The potentiometric surface map derived from the corresponding simulation of the steady state flow model (Fig. 6) reproduces the observations for 1984 (Fig. 3). This year was assumed to be the system initial state. In a next phase, a transient flow model, considering several wells whose extractions accounted for the total water exploited in the study are elaborated to simulate the time evolution of the underground flow. The simulation of water extraction of the 311 wells existing in the Etla valley was modeled by 25 wells. The location of these chosen wells properly agrees with the real location of the extracting wells, and the amount of extracted water of each one being equivalent to that of 12 wells together. The evolution of the aquifer, assuming all the conditions of intensive exploitation, was simulated for the last twenty years. Three numerical outputs corresponding to periods of 4380, 6205 and 7665 days (12, 17 and 21 years, respectively) are shown in Fig. 6. Ten representative observation wells located along the valley were selected in order to compare the observed and computed hydraulic heads. Fig. 7 shows the correlation between the water levels observed in the wells and those computed by the model for the monitored years 1984, 1996 and 2001. The corresponding standard deviation (between 3 and 8 %) can considered acceptable. Accordingly, we can conclude that the model reproduces satisfactorily the evolution of the aquifer for the moni-

Table 1

Hydrological properties for the assumed lithological units in the Valley of Etla and the boundary conditions

Hydrogeological unit	**Lithology**	**Estimated Thickness (m)**	**Hydraulic Conductivity (m/s)**		**Ss(1/m)**	**TP(%)**
			$K_x = K_y$	**K_z**		
layer 1						
Zone 1	Quaternary alluvial deposits (sands, boulders and gravels)	20 -60	1.E-05	1.E-05	0.0005	0.18
Zone 2	recharge zones					
Zone 3	shale, limestone and conglomerates		4.0E-06	4.0E-06	0.0005	0.18
Zone 4	Fractures		1.E-04	1.E-04		
layer 2	A clay and gravel body (aquitard)	0-30	1.E-07	9. E-06	0.00005	0.35
layer 3	Tertiary alluvial and lacustrine sediments, and probably pyroclastic deposits	300-500	5.E-05	5.E-05	0.0004	0.35
layer 4	Tertiary alluvial and lacustrine sediments, and probably pyroclastic deposits, (compressed)	300-500	1.E-06	1.E-06	0.00005	0.35
layer 5	Cretaceous and Jurassic limestone, sandstone and shale sequences	100-200	1.E-07	1.E-07	1.E-09	0.25
layer 6	Precambrian gneisses (Sierra de Oaxaca) and some Mesozoic sedimentary sequences and Mylonites (Sierra de Juárez)	undefined	1.E-09	1.E-09	1.E-09	0.05

Ss = Specific Storage coefficient, TP = Total Porosity, x = E-W direction, y = N-S direction and z = elevation

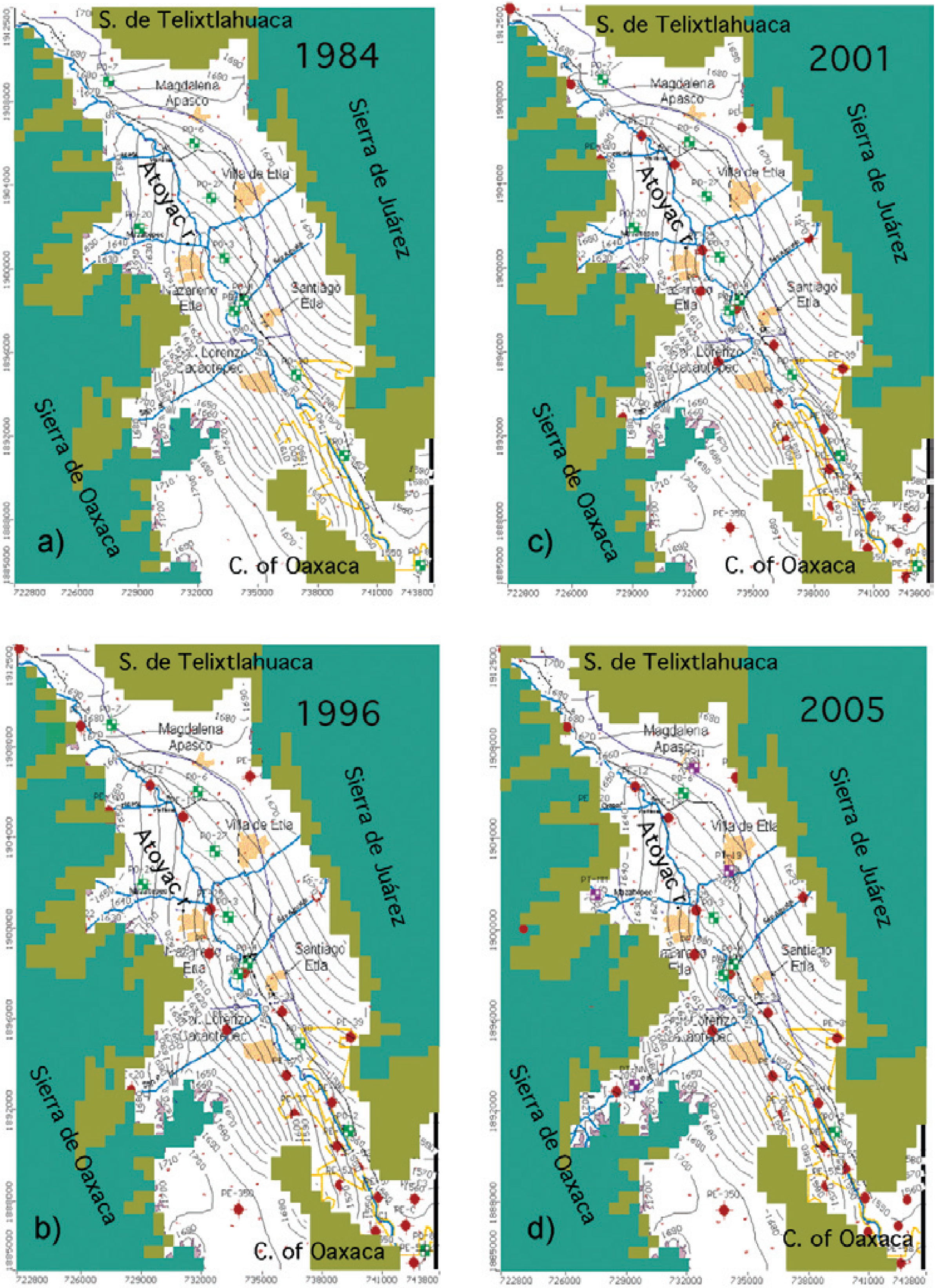

Fig. 6. The potentiometric surface maps derived from the numerical simulation are showed: a) Steady state regime (1984) and evolution of the system for b) 1996, c) 2001, and d) 2005. The model uses the boundary conditions of Table 1.

Table 2

The boundary conditions used for whole modeled area

Boundary Condition	General Head B. (GHB) Maximum elevation	Minimum elevation	Time (days)	Conductance (m2/day)
North	1650	1705	12015	
West	1700	1650	12015	
East	1800	1550	12015	
South	1650	1550	12015	
Atoyac River	1700	1550	12015	550

tored years. Additionally, it can be noticed that for 2001, in the area of the city of Oaxaca, the potentiometric surface is below the lower limit of the shallower aquifer (green zones, Fig. 6), and consequently the corresponding shallow wells will not extract more water.

Predictive scenarios

In order to predict the evolution of the aquifer system and assuming ground water exploitation conditions similar to those of 2001, we computed the potentiometric surface for the year 2015 (Fig. 8a). We observe that the potentiometric level remains practically unchanged in the flanks of the valley, under a constant extraction regime, from 1996 to 2001. Nevertheless, a drawdown in the potentiometric level of 6 m is observed, in about 10 years, at the southeastern portion of the valley. Another predictive scenario was analyzed by relocating the extracting wells, from the city of Oaxaca to the recharge zones, close to the feet of the Oaxaca and Juarez ranges, for a ten-year period of extraction. The corresponding results (Fig. 8b) indicate a slight recovering (1 m) of the potentiometric level just to the southeastern end of the model (city of Oaxaca). The corresponding redistribution of the extraction wells into

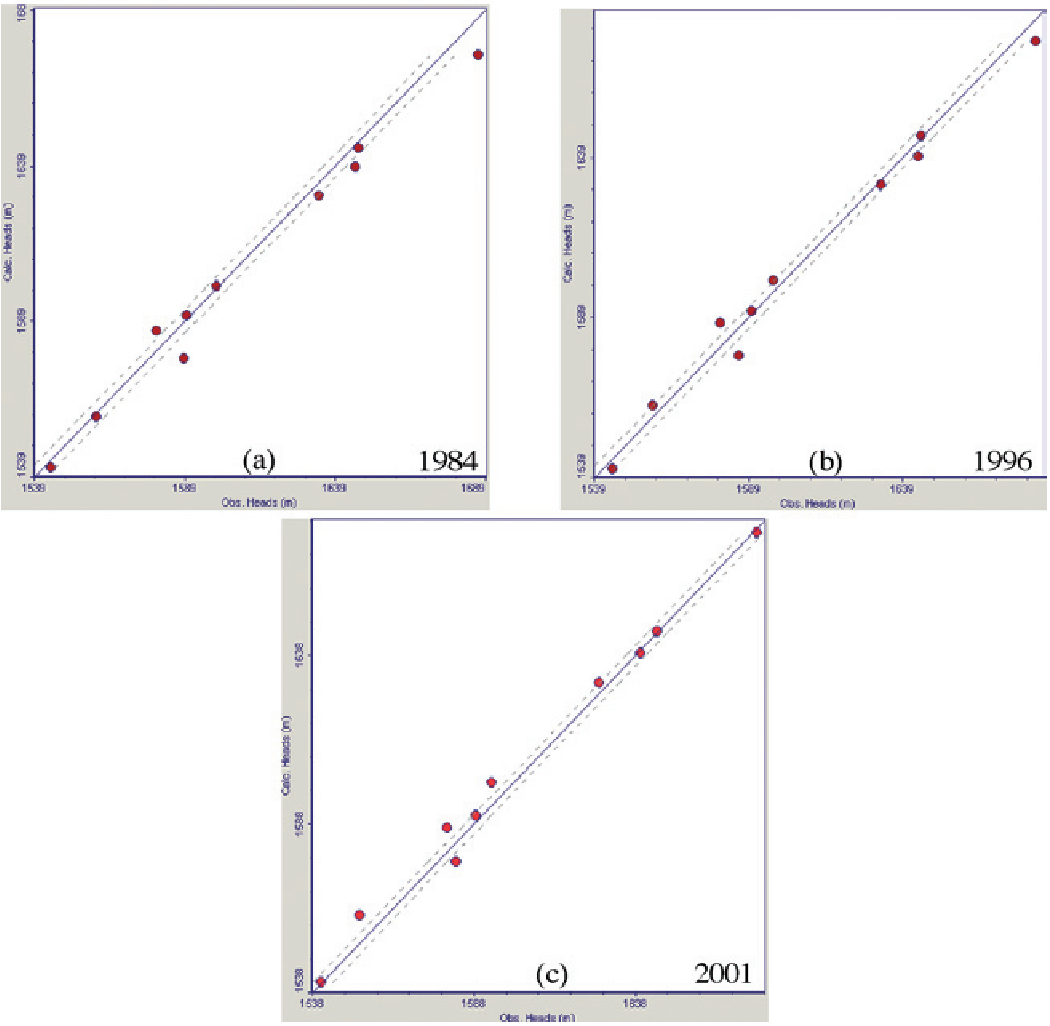

Fig. 7. Correlation between measured and computed hydraulic heads from the large-scale flow model in transient state: a) stationary regime (1984) and for the evolution in time corresponding to the years: b) 1996 (4380 days), and c) 2001 (6205 days). Scatter plots, for the cases a, b and c, show a confidence interval from 92 to 97% with a standard error around 4 m.

the recharge zones, that not only stops the water table decline, but also allows a slight recovery in the levels, should be take into account for future decisions.

Transport Model

Transport simulations were based on the previous transient model employing the MT3D module (Zheng, 1990) of mass transport. The pollution by fertilizers, and leakage of the sewage network was simulated assuming that the fluid has a high salt content and taking into account the local distribution of TDS sources over the aquifer surface. The combined effect of the hydrodynamic dispersion coefficient due to water circulation and the natural flow direction produces a slight enlargement of the punctual polluted zones. In nature, the flow direction of the aquifer favored the pollution of the Atoyac River (principal surface drain) by fertilizers. However, the obtained model does not reproduce the natural observations showed in Fig. 5, because the dispersivity effect is of a very local nature around the punctual sources. Our transport model is limited because the natural effect of dispersivity due to the sewage network is greater than that we considered in the model, and more important, the real sources of pollution are not point-like distribution. An assessment of the vulnerability of the Etla and Zaachila Valleys shallow aquifers were undertook by Belmonte-Jiménez *et al.* (2003, 2005).

Conclusions

The evolution of the potentiometric surface from 1984 to 2005 shows that in the northern portion, and the eastern and western borders of the valley, no major changes are observed. However, since 1996 four depression cones (10 m) evolved along the axis of the valley; in 2001, an important depression in the potentiometric surface of about 30 m is observed in the city of Oaxaca (SE portion of the valley). The geometrical model (Fig. 2) obtained from previous studies and lythological descriptions from some wells were employed to build up a six-layer model. A predictive scenario for the next 10 years, assuming the actual extraction regime is maintained suggests that the drawdown in the potentiometric surface (around the city of Oaxaca) could persist (a further decrease of about 6 m more is modeled). The fall in the potentiometric surface

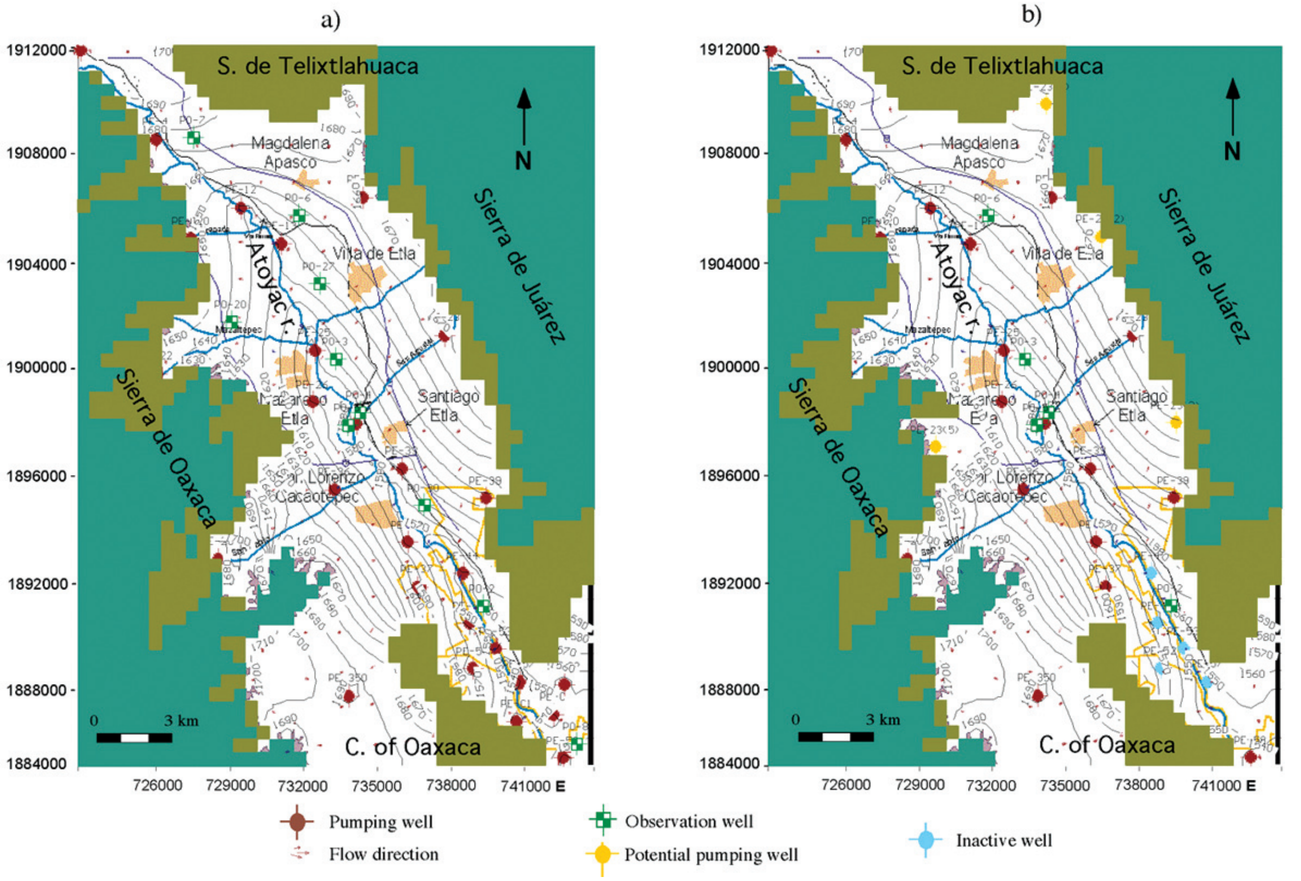

Fig. 8. Predictive models for the year 2015: a) assuming the present extraction regime in wells and b) assuming redistribution in location of pumping wells (yellow dots) towards the recharged zones. The water table levels present a slight recover at the southeastern portion of the valley.

could be associated to the extraction wells located to the SE of the valley or to the overall excessive amount of water being extracted in all valley. A redistribution of the pumping wells in the model from the city of Oaxaca towards the recharges zones (mountain borders), considered as an alternative scenario for the next 10 years, predicts that the decline in the water-table is stopped and enables a slight recovery (~1m) in water levels.

If the actual ground water exploitation conditions in the Etla valley aquifer persist, it would give rise to serious problems such as water shortage and important pollution. The TDS concentrations (< 500 mg/L) in ground water for the year 2001 are in agreement with the Mexican Official law, recently, an increase, of about 120 mg/L identified in some wells, indicates the existence of some pollution processes. The main superficial sources of pollution are fertilizers and local wastewater leakage. This aquifer system provides about 70 % of water supply for population centers in the valley (including the city of Oaxaca). Therefore in the future, the regular monitoring of table levels and chemical compositions of waters, in addition to predictive models of evolution of aquifer should be taken into account for preserving and correcting the extraction regimes, and to prevent contamination.

Acknowledgments

This study was financed by the DGIA-UNAM (México), PAPIIT research projects IN107602 and IX103304. The authors are indebted to CNA (Comisión Nacional del Agua) and IPN-CIIDIR-Oaxaca for providing some original data. The authors would like to thank Oscar Escolero and Cinna Lomnitz for helpful comments.

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