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Belmonte-Jiménez, Salvador I.; Campos-Enríquez, J. Oscar; Alatorre Zamora, Miguel A.
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Vulnerability to contamination of the Zaachila aquifer, Oaxaca, Mexico

S. I. Belmonte-Jiménez[1,2], J. O. Campos-Enríquez[3] and M. A. Alatorre-Zamora[4]
[1] *Posgrado en Ciencias de la Tierra, UNAM, México, D. F., México*
[2] *CIIDIR-Oaxaca, Instituto Politécnico Nacional, Oaxaca, México*
[3] *Instituto de Geofísica, UNAM, México, D. F., México*
[4] *Depto. de Física, División de Ciencias Básicas, CUCEI, Universidad de Guadalajara, México*

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RESUMEN

El acuífero del valle de Zaachila fue evaluado usando los métodos convencionales DRASTIC, AVI, y GOD. La profundidad al nivel freático fue monitoreada y determinada a partir de un sistema de pozos. La dirección preferencial del agua subterránea es de N a S. La conductividad hidráulica varía en un rango de 1.81647E-05 a 1.70411E-04 m/s, mientras que la transmisividad se encuentra entre 22.01 y 220.85 m^2/día. La recarga anual neta fue estimada en 98 mm/año. El acuífero está constituido principalmente por arena, grava y diferentes contenidos de arcilla. El espesor del suelo es en algunos sitios hasta de 1.5 m y está constituido por limos, arcilla y material arenoso. Según GOD, existen algunas zonas del acuífero con valores de media a alta vulnerabilidad. DRASTIC asigna una alta vulnerabilidad a la mayor parte del área. Los valores más altos se observan en las zonas meridionales y centrales del área, de la ciudad de Oaxaca hacia el sur incluyendo San Bartolo Coyotepec, así como la población de Zaachila y el aeropuerto. AVI asigna al valle valores de alta a muy alta vulnerabilidad. El análisis de sensibilidad indica que la profundidad al nivel freático es el principal parámetro que influye en la determinación de la vulnerabilidad, seguida por el impacto a la zona vadosa y el tipo del suelo.

PALABRAS CLAVES: Vulnerabilidad, contaminación, acuífero, Zaachila.

ABSTRACT

The aquifer of Zaachila was evaluated following conventional methods (DRASTIC, AVI, and GOD). Depth to the water table was established from a set of wells. Accordingly, the groundwater flows from N to S. Hydraulic conductivity ranges between 1.81647E-05 and 1.70411E-04 m/s, while transmissivity varies between 22.01 and 220.85 m^2/day. The net mean annual recharge was estimated at 98 mm/year. The aquifer is constituted mainly by sand, gravel and clay. The soil cover is up to 1.5 m thick and is constituted by lime, clay and sandy material. According to GOD, some zones of this aquifer have a medium to high vulnerability. DRASTIC assigns a high vulnerability to large part of the area. The highest values are observed in the southern and middle sections, from Oaxaca city to the south including San Bartolo Coyotepec, as well as Zaachila town and airport. The AVI method assigns to the valley a high to very high vulnerability. A sensitivity analysis suggests that depth to water table is the key factor determining vulnerability, followed by impact to the vadose zone and soil type.

KEY WORDS: Vulnerability, contamination, aquifer, Zaachila.

INTRODUCTION

Groundwater contamination is a world wide problem affecting water supply quantity and quality in many countries. Degradation of the quality of groundwater is nature-related in some cases, but in general is due to human activity.

Of almost 320 hydrologic basins in Mexico, 20 present serious contamination problems affecting approximately 75% of the population. About 80% of sewage goes into ground water (Guzmán, 1995), and 120 basins are over-exploited (CNA, 2004).

Groundwater degradation in Mexico is mainly due to sedimentation, saline intrusion and pollution of surficial water bodies and soils that leach into the groundwater.

About 80% of the water supply for the city of Oaxaca (Figure 1) is obtained from the Valles Centrales aquifer (CNA, 2000). In recent years the groundwater supply has decayed due to pollution by residual waters discharged into the Atoyac river (Belmonte *et al*., 2001).

When little information is available, the assessment of vulnerability can be very difficult. According to Margat

(1968) and Albinet (1970) (in Sappa and Vitale, 2001) geology and soil cover protect groundwater from pollution. Vrba and Zaporozec (1994) proposed methodologies based on edafological concepts and in the characteristics of flow in the saturated zones.

Later studies take into account the thickness of the unsaturated zone, changes in piezometry, net recharge, qualitative parameters of the water, hydraulic parameters, and others.

Vulnerability of an aquifer is related to its capacity to resist anthropogenic and natural impact (Foster e Hirata, 1991). It is associated to the probability that a contaminant reaches a specific area of the aquifer (National Academy Council, 1993).

Vulnerability is not an absolute property. It is relative and adimensional (Martínez *et al*., 1998). This paper evaluates the vulnerability to anthropogenic contamination of the Zaachila aquifer (Figure 1). Zaachila aquifer is one of the aquifers which supply water to the city of Oaxaca and neighboring urban areas. The valley is crossed from N to S by the Atoyac river, which carries residual waters.

STUDY AREA

The study area is part of the Valles Centrales, central Oaxaca State, southern Mexico (Figure 1). It is located immediately to the S of Oaxaca city, between 96°40' and 96°47' of west latitude, and between 16° 54' and 17° 05' of northern latitude. It comprises an area of about 200 km^2. The valley has a mean elevation of 1500 m above sea level.

The Atoyac river is the most important stream in this valley. It begins in the Etla valley immediately to the N of Oaxaca city. It enters the Zaachila valley from the north and joins the Salado river coming from Tlacolula Valley. It exits the valley by its southern end.

Between Zaachila and Zimatlan there is frequent flooding due to clayey soils, often lasting several months after the end of the rain season. The Atoyac river is fed by groundwater, in the order of 1 million m^3/year (Chávez, 1977). It also collects untreated sewage from the city of Oaxaca which may be considered a linear contamination source. Along the river are many wells that supply water to the city. From 1962 to 2001, the mean annual precipitation and temperature was 700 mm and 18 °C respectively (CNA, 2001). The mean annual evapotranspiration is of about 602 mm/year, calculated from the Turc equation (Turc, 1955).

GEOLOGICAL SETTING

The study area is located in the Zapoteco tectono-estratigraphic terrane (Sedlock *et al*., 1993). The basement is the pre-Cambrian Complejo Oaxaqueño constituted by metasedimentary rocks such as gneiss of the granulite facies and marbles (Ortega, 1981). The basement crops out to the north and west of the valley. Sedimentary and metamorphic rocks (sandstone, lutite, and limestones) crop out to the east. The infill of the sedimentary basin is constituted by conglomerates comprising fragments of gneiss, schistes, limestones, and unconsolidated volcanic rocks. Residual soil, gravels, sands and clay cover the stratigraphic column.

The main tectonic feature is the Oaxaca fault characterized by a mean N 10° W orientation. It consists of a group of parallels faults (Centeno, 1988; Nieto *et al*., 1995). This fault constitutes the eastern limit of the Zaachila valley. To the south of Oaxaca City, the fault is discontinuous, cutting across several minor E-W oriented depressions. The Donaji fault intersects the Oaxaca fault around San Felipe del Agua, to the E of Oaxaca City. Other structures located in the area are the Coyotepec anticline, and the Monte Alban synclinal.

The aquifer is located in a half-graben of tectonic origin. The area of alluvial fill corresponds mainly to two units. The unsaturated zone consists of sands, silts and clays. It has a thickness of up to 9.5 m. The saturated zone is a mixture of sand, silt and clay with a thickness from 10 to 120 m. These materials are product of the erosion of the higher parts of the region. In spite of the excessive exploitation of the aquifer, during the rainy season the water level recovers -an indication of vulnerability. Lateral changes in resistivity (i.e., Steinich *et al*., 1997) of the vadose zone may be due to changes in the litology or to changes in the quality and quantity of pore water, mainly in areas with contamination from residual waters or infiltration of contaminated irrigation waters.

QUALITATIVE CHARACTERIZATION OF THE AQUIFER

The Zaachila valley is fairly flat. The relief is characterized by slopes between 0 and 6 % (INEGI, 1998).

The depth to the water table was obtained from wells localized in the study area (Figure 2). Most measurements were done in dug wells with an average diameter of 1 m and domestic use. Piezometric measurements were conducted in 1999, 2000, and 2001 (Belmonte *et al*., 2001). In some wells the measurements in 2001 were 3.8 m lower than in the first set of measurements. The minimum and maximal values are respectively 1.5 and 9.5 m. Thus the water table is shallow.

Figure 3 shows the potentiometric surface for August, 2001. Water flows with a mean N-S direction, but in the southern portion the flow direction is NE-SW.

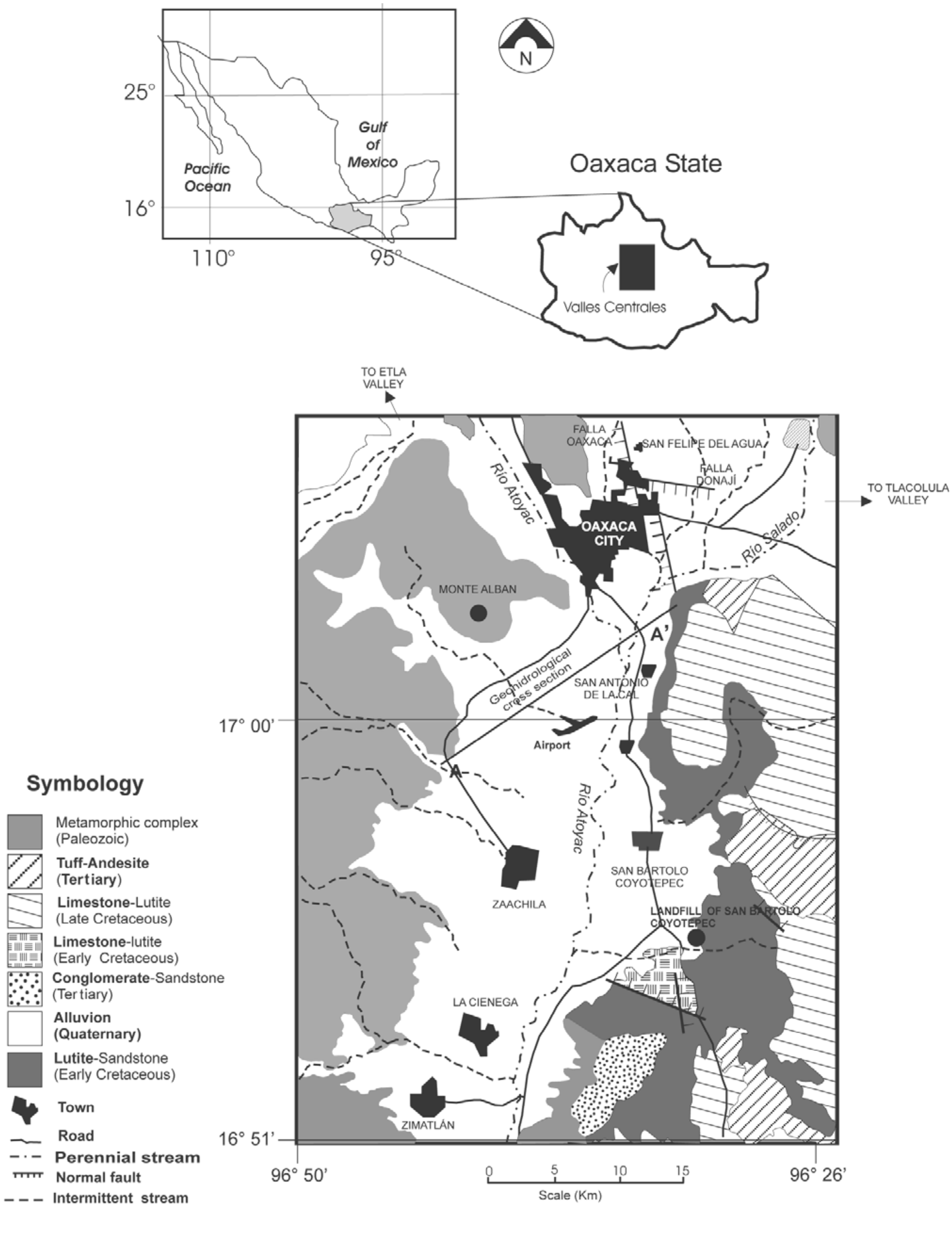


Fig. 1. Location and simplified geology of the Zaachila valley (Oaxaca, southern Mexico). Taken from INEGI (1998).

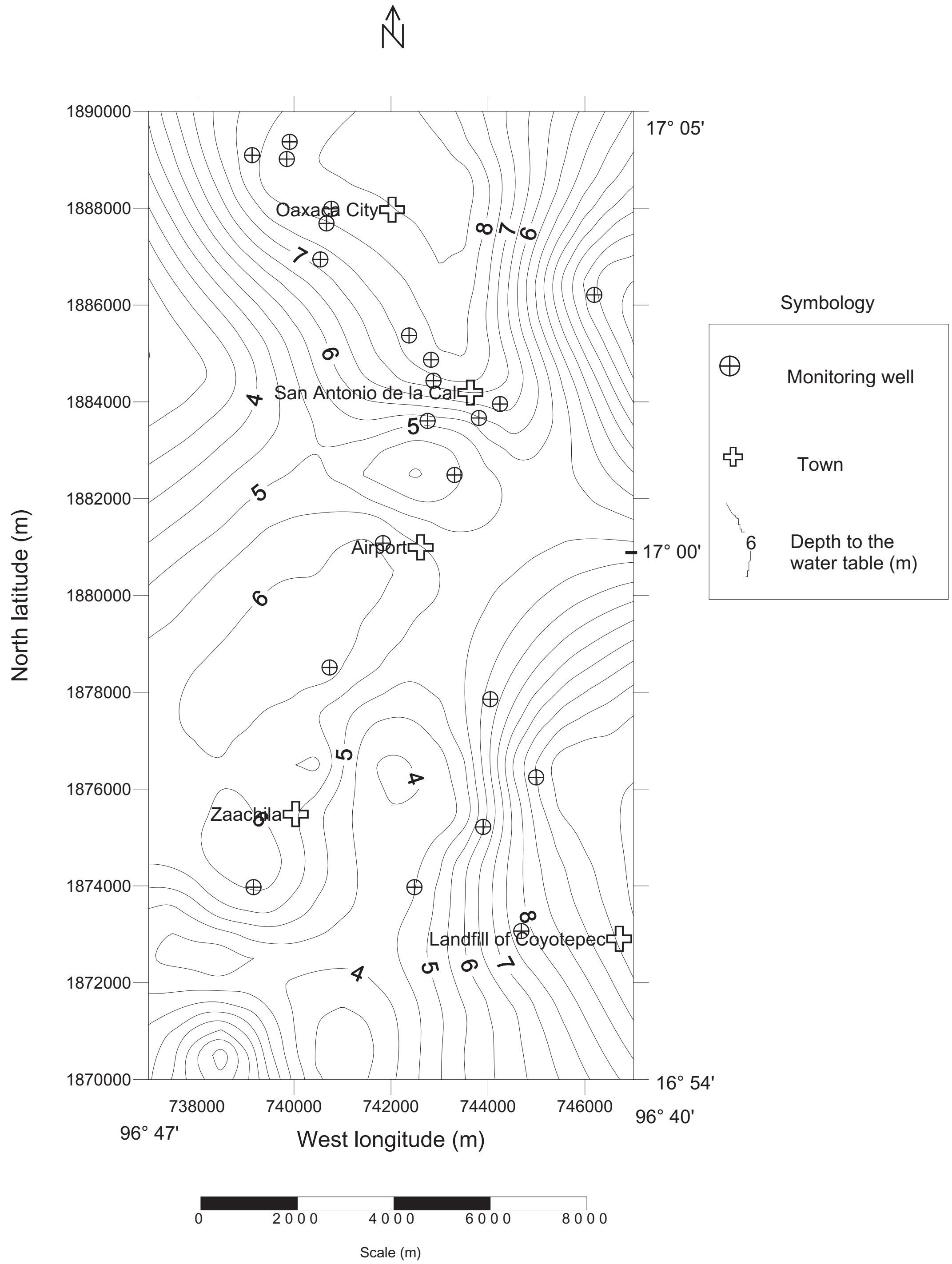


Fig. 2. Depth to the water table in the Zaachila valley corresponding to August, 2001.

In the northern part of the valley, the hydraulic gradients range between 1.5 x 10^{-3} y 3.5 x 10^{-3}. To the west we have values of 2.3 x 10^{-3}. The south, around Zimatlan, shows hydraulic gradients are of 20 x 10^{-3}. Near the dump of San Bartolo Coyotepec we have a hydraulic gradient of 9.6 x 10^{-3}.

The mean net recharge is 98 mm/year depending on precipitation and evapotranspiration. This value was obtained from R=P-Er, where R is the net recharge, P the precipitation and Er the evapotraspiration (Aller *et al*. 1987, Custodio and Llamas, 1983 and Gehrels, 2000).

The aquifer thickness varies between 10 m and 120 m. Lateral width is about a third of the length. Recharge is constituted by infiltration in the valley and from the neighboring ranges to the west and east, and from underground flow from the neighboring valleys of Etla and Tlacolula.

Hydraulic conductivity was obtained from K=T/H. Transmissivity T was obtained from pumping-tests in 12 complete wells assumed homogeneous and isotropic. The values obtained for T range between 22.01 and 220.85 m^2 /day. The Theiss simplified method was used to interpretate the pumping-test data (Fetter, 2001). Thickness of the saturated zone was obtained from DC, vertical electrical soundings (Schlumberger array), and an induction electromagnetic coils study. The data from these soundings were inverted after Cooper (2000) and Pérez *et al*. (2001) respectively. A linear regression was obtained between the T values from well tests inside the valley and the geophysical transversal resistivity.

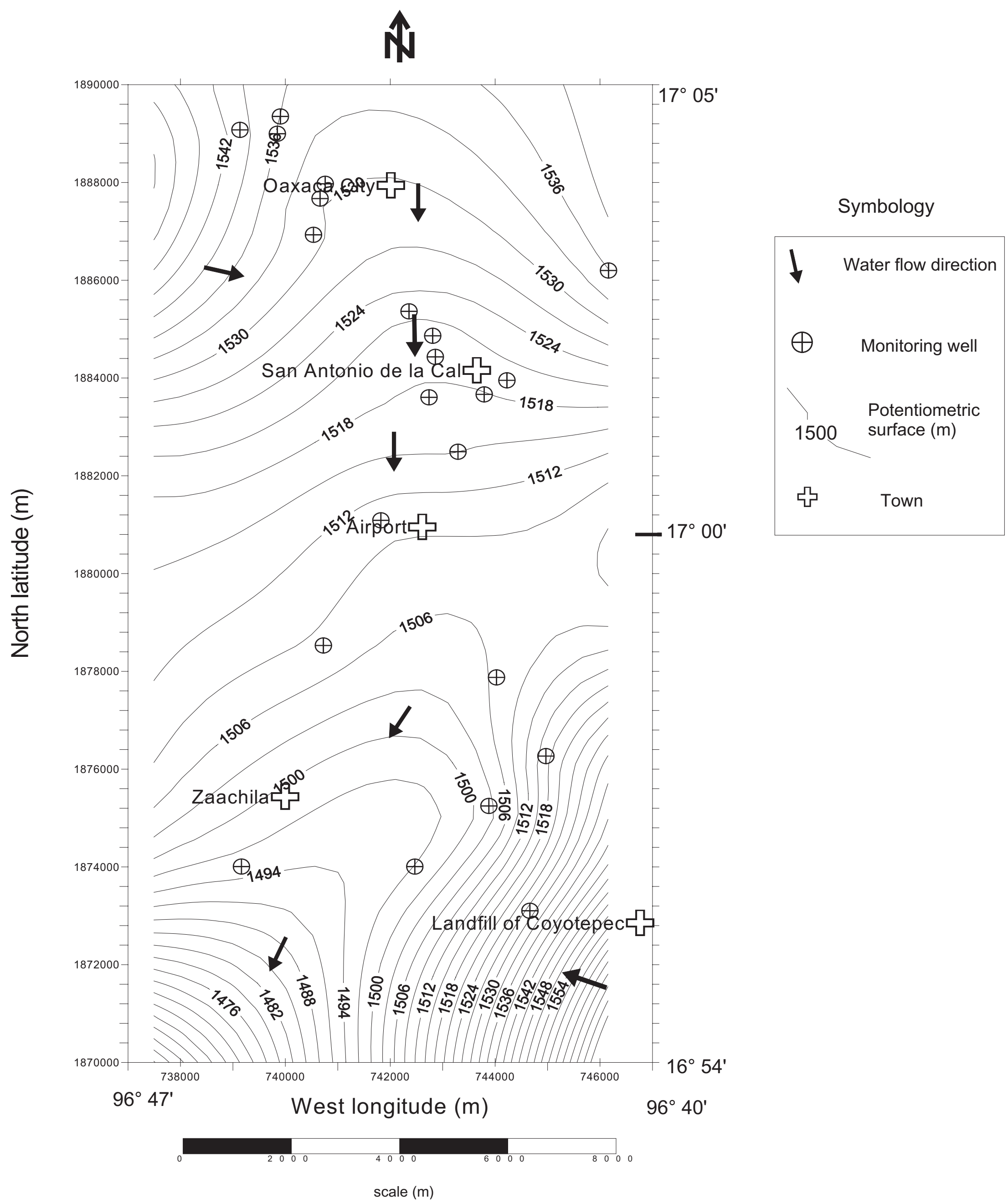


Fig. 3. Elevation to the potenciometric surface of the Zaachila valley corresponding to august, 2001. The general flow direction is N-S.

The regression relation was applied to estimate T from the Dar Zarrouk parameter in areas where the thickness of the saturated zone was not known due to lack of wells. The Dar Zarrouk parameter was calculated from the corrected transversal resistivity (Rc) from Schlumberger soundings, and electromagnetic induction soundings. The estimated values range from 1.81647E-05 to 1.70411E-04 m/s, corresponding to low conductivity. Figure 4 shows the map of hydraulic conductivities obtained for the Zaachila valley, and Figure 5 shows the distribution of transmissivity values.

The anisotropy index (λ) of the vadose zone was determined in two places from the variability of the electric resistivity. Azimuthal soundings (Wenner) with different spacings (5, 10 and 40 m) were carried in an area featuring by fine and poorly consolidated sands, and silty material

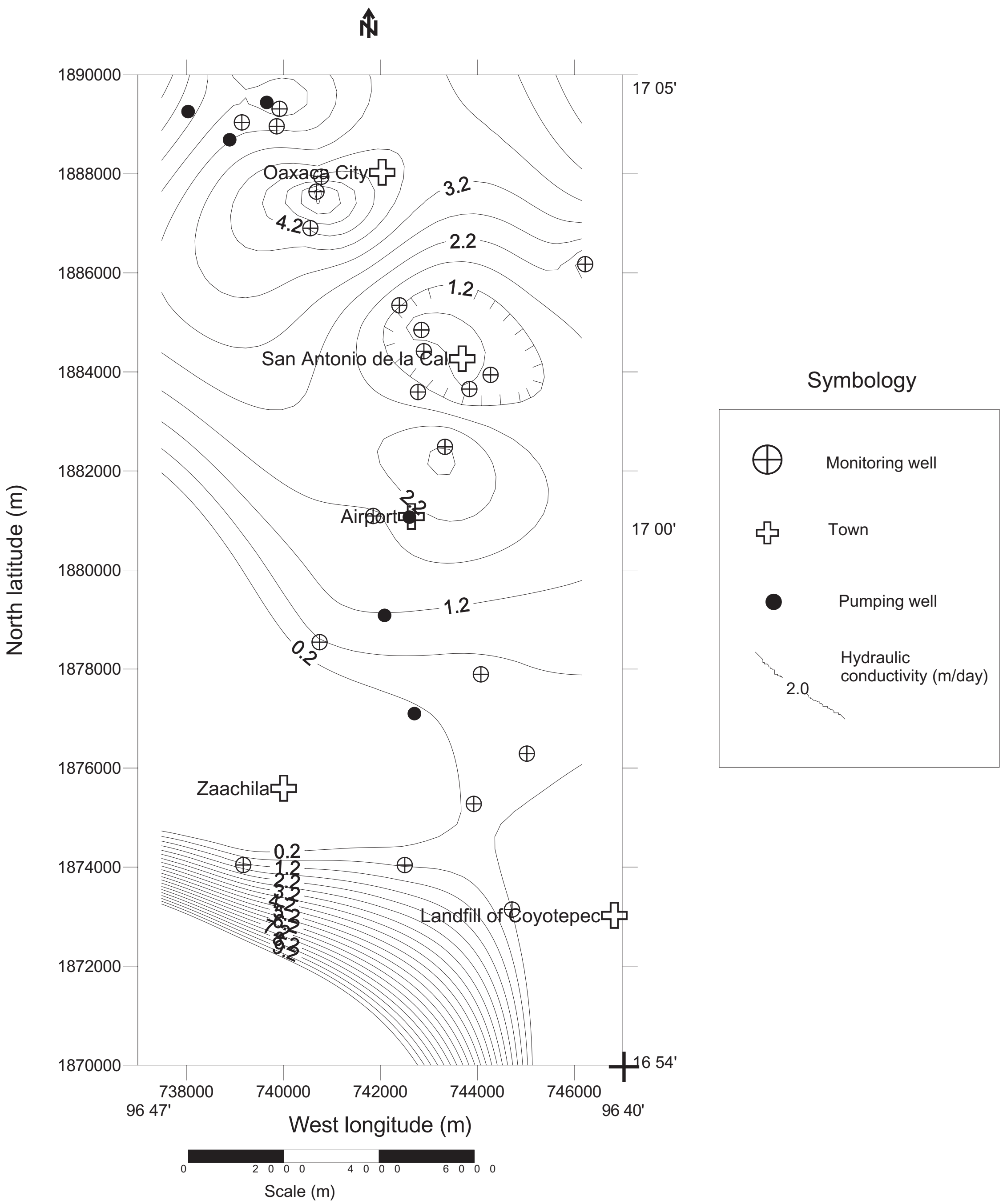


Fig. 4. Hydraulic conductivity (K in m/day) at the valle de Zaachila aquifer. The highest values are found at the northern portion (corresponding to fractured lutites and limestones outcrops) as well as at the southern portion (granular materials as gravel, sands and limes).

(Figure 6). The spacing a=AB/3 represents approximately the investigation depth.

The anisotropy index λ characterizes the excentricity of the measured curve with regard to a circle corresponding to an isotropic medium and to a value of 1.0. We obtained indexes of 1.130, 1.393, and 1.188 for values of a of 5, 10, and 40 m respectively. No preferential orientation is found. The anisotropy for a=10 m is the highest, and may be due to infiltration, yet the vadose zone can be considered isotropic in terms of hydraulic conductivity.

Because of the theoretical penetration depths the corresponding anisotropy values are associated with the zone above or below the water level. The water level behaves isotropically (λ =1.188).

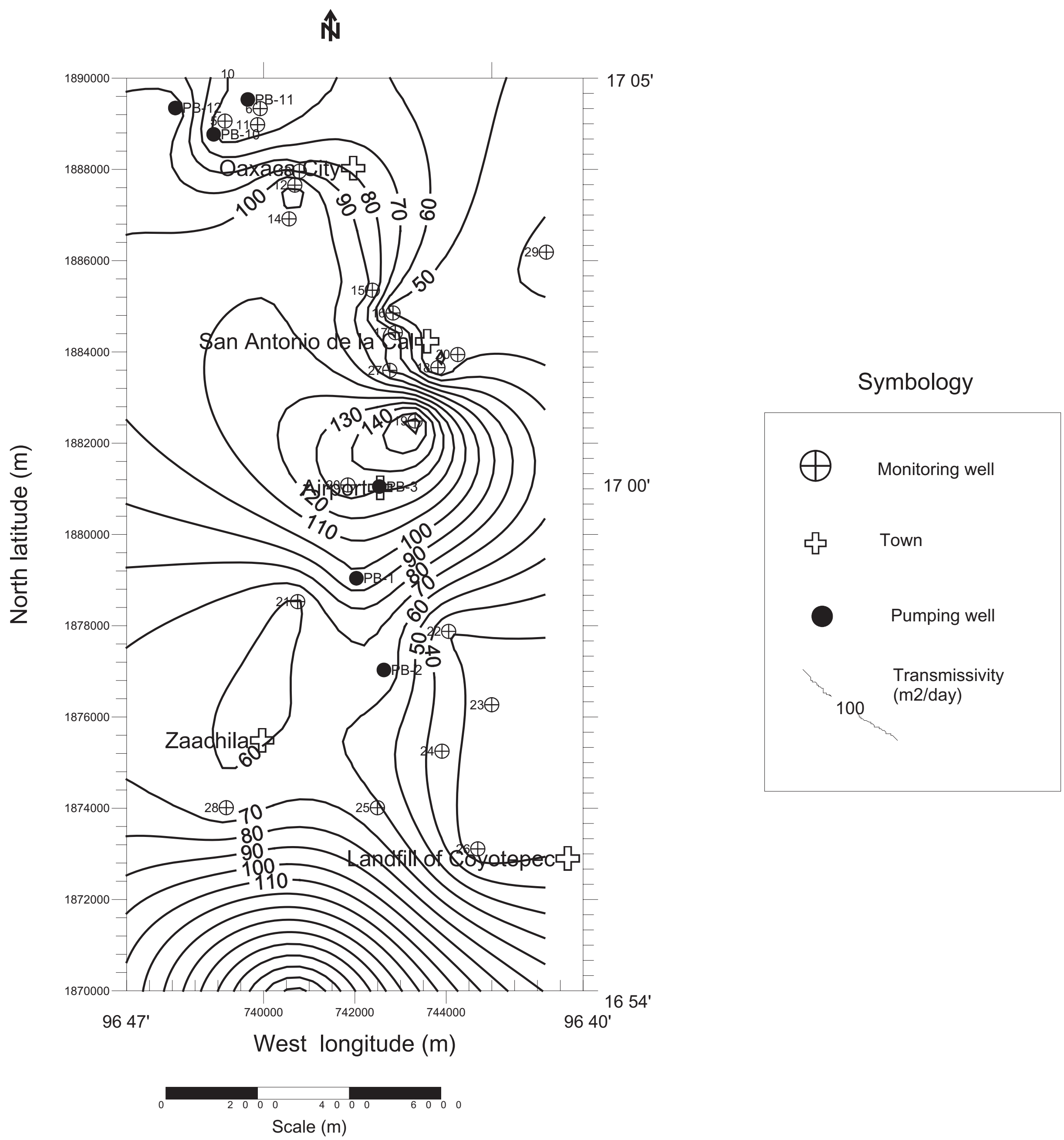


Fig. 5. Transmissivity (T in m^2/day) at the valle de Zaachila aquifer obtained by means of pumping-tests and from the Dar Zarrouk parameter. The highest values are between San Antonio de la Cal and the airport, and to the south at Zaachila town.

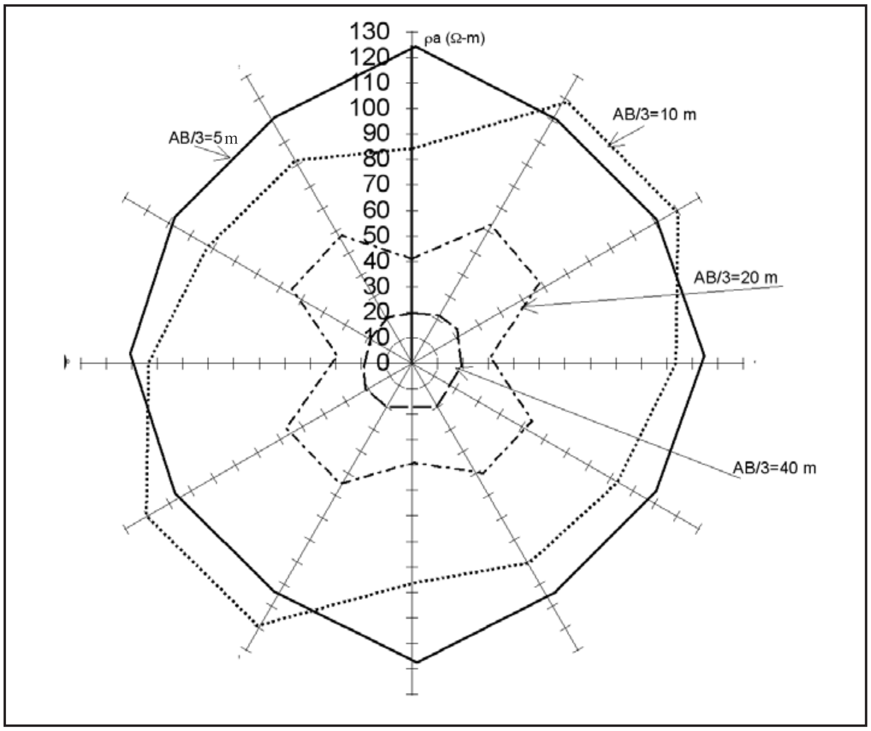


Fig. 6. Anisotropy curves from azimuthal measurements obtained at a same site. For azimuthal soundings (Wenner configuration) with different spacing of 5, 10, 20 and 40 m.

Lithology of the aquifer and of the unsaturated zone was based on information from five wells and from 30 vertical electrical soundings, plus five 5 profiles from time-domain electromagnetic soundings with lengths of up to 4500 m. The aquifer comprises sand, gravel, and clay. In some zones there are conglomerates, clayish limes, tuffs, and towards the edges we have limestones, gneiss, and metasedimentary rocks. The unsaturated zone is characterized by similar material, as found in the aquifer. Figure 7 shows a cross section of the Zaachila Valley system.

Twenty soil samples were analyzed by the Bouyoucos hydrometer method (Coras, 1987). The type of soil was determined with help of the texture triangle. Fine texture material (silt, clay), as well as sands, are the predominant materials present in different percentages and thicknesses not greater than 1.5 m. The main textures are: clays, fine sands, clays and granular sands, and sandy clays.

METHODOLOGY

Vulnerability to contamination of an aquifer is assessed by several methods, such as AVI, GOD, DRASTIC, SINTACS, SEEPAGE, EPIK, ERIS, and others. Each of these methods is based on different hydrogeological parameters. Assessment of vulnerability of a given aquifer with different methods can give different results. In this work we use index and superposition methods, namely DRASTIC, AVI and GOD. AVI and GOD consider the physical properties of the aquifer media, and DRASTIC includes the chemical properties of attenuation (Aller *et al.*, 1987).

These three methods were used to assess the range of results obtained with different sets of hydrogeological parameters. This analysis should provide criteria for future selection of a method depending on the available information.

The *DRASTIC* method

This method is based on seven parameters: 1) Depth to the water table, 2) net Recharge, 3) Aquifer media, 4) media Soil, 5) Topography, 6) Impact of vadose zone media, and 7) hydraulic Conductivity. Some parameters are quantitative, while others are related to the nature of the media. Each parameter can have values in a certain range (Aller *et al.*, 1987). The vulnerability index is given by:

$$\text{Vulnerability index} = DrDw+RrRw+ArAw+SrSW+TrTW+IrIw+CrCw. \quad (1)$$

The index r refers to the range, and w to the assigned weight.

The *DRASTIC* method was originally proposed by Aller *et al*. (1987). No changes in the ranges and weights were found necessary. Transformation functions for the parameters were not used.

In this study we applied the DRASTIC pesticide since the valley has agricultural use. Weights that differ from the traditional method are media soil, topography, impact of vadose zone media and hydraulic conductivity.

The *GOD* method

This method was developed for areas with a lack of information about the subsurface and the groundwater (Foster y Hirata, 1991). It is very simple. It considers only three parameters: 1) Groundwater occurrence (inexistent = 0, existent = 1), 2) Overlying lithology (this index varies in a range from 0.4 to 1), and 3) Depth to groundwater (ranging from 0 to 1).

The *AVI* method

The name stands for Aquifer Vulnerability Index. The parameter called hydraulic resistance C corresponds to an estimation of the travel time of a contaminant through the unsaturated zone (Van Stempvoort *et al*., 1992). The hydraulic resistance, in years, is calculated by means of the following expression:

$$C = \sum_{i=n.of.layers} \frac{Di}{Ki}\ , \qquad (2)$$

where Di is the thickness of the unsaturated zone, and Ki represents the hydraulic conductivity. Values of the hydraulic resistance are given as Log C .

The available methods to assess vulnerability assume an aquifer system as constituted by three layers: soil, vadose zone, and the aquifer itself. This is a simplified aquifer system. The study area was discretized as square cells of 1000 m, which is appropriate for a study of intermediate scale where detailed information is unavailable. The values were assigned to the center of each elements (Figure 8).

The unsaturated zone was considered as a single layer. The larger the hydraulic resistance, the lower is the vulnerability. AVI is useful in small areas where DRASTIC is not advisable.

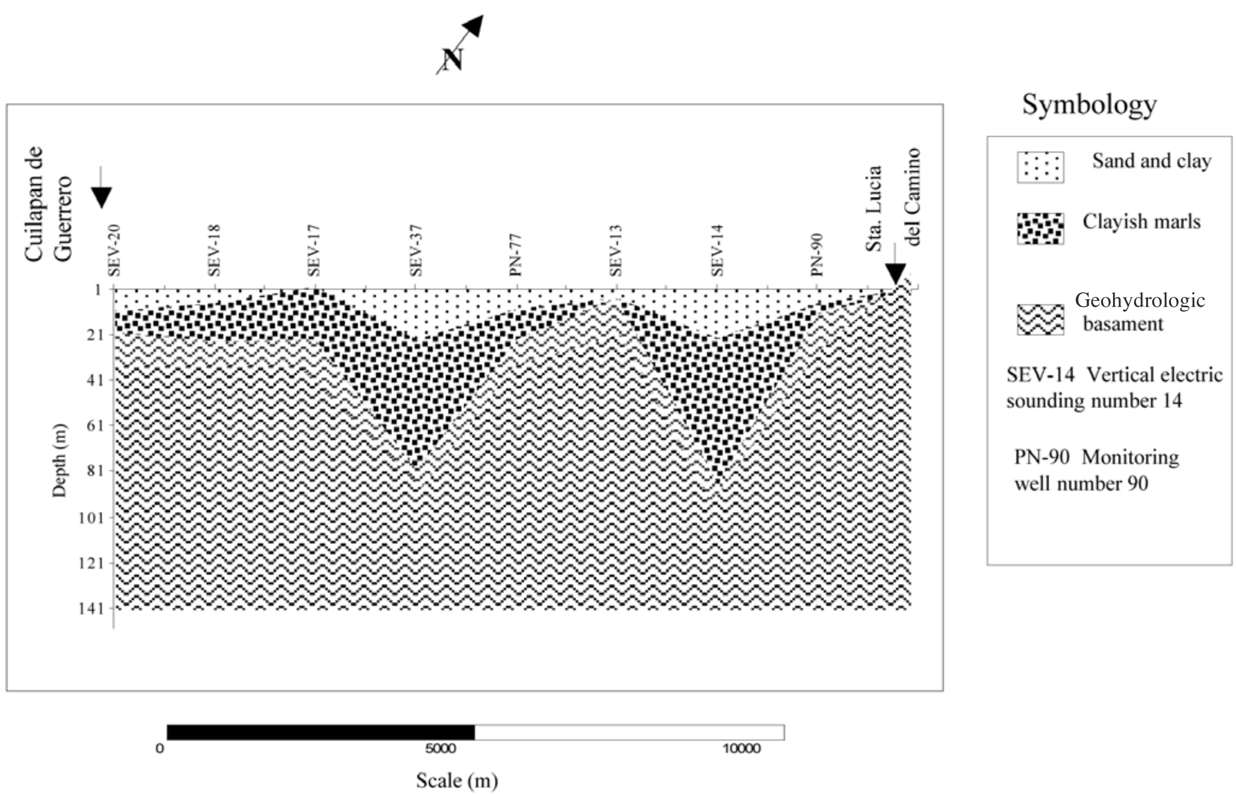


Fig. 7. Geohydrological cross section through Cuilapan de Guerrero and Santa Lucía del Camino (see location in Figure 1). The section comprises three layers: a) the non satured zone (sandy material with clay), b) the aquifer (marges and clays), c) the geohydrologic basement (meta sedimentary rocks). The section was based in geoelectric studies and well information.

Table 1 gives the weights and ranges used in each of the methods. For the DRASTIC method, given the geohydrological characteristics, we used the ranges and values proposed by Aller *et al*. (1987) for areas which use pesticides. Note the different weights assigned to the last four parameters in Table 1.

RESULTS AND DISCUSSION

To define the levels of vulnerability for the DRASTIC method we used the scaling established by Choza (1997) (low vulnerability from 0 to 100, medium vulnerability from 100 to 140, and high vulnerability for values higher than 140). Thus, the Zaachila aquifer has a high vulnerability to contamination in two areas (Figure 9). The first vulnerable area is located south of Oaxaca city, between San Antonio de la Cal and the international airport. The second area nearly covers the center and southern portion of the aquifer, from the airport southwards. It includes Zaachila, and the landfill of Coyotepec.

Figure 10 shows the vulnerability of the aquifer according to GOD. This method also defines two areas of high vulnerability, but these areas are of smaller dimensions. They are a part of the high vulnerability areas delimited by DRASTIC. The first area is located between San Antonio de la Cal and the airport, and the second area is near the center of the valley towards the south. The low vulnerability is defined by 0 and 0.3, medium vulnerability by values between 0.3 and 0.5, and high vulnerability by values higher than 0.5.

The AVI method defines one area of high, and another of very high vulnerability (Figure 11). The first is located around the area of the airport. The area of very high vulnerability includes the dumpsite of San Bartolo Coyotepec, Zaachila town and Oaxaca city. A low vulnerability is given by values greater than 3. Medium vulnerability corresponds to values between 2 and 3. Values between 1 and 2 correspond to a high vulnerability while a C smaller than 1 is associated to extremely high vulnerability. Recall that C is the log of the hydraulic resistance (R).

The differences between results are due to the number of hydrogeological parameters used in estimating the vulnerability.

The methods pesticide DRASTIC and GOD provide similar results, but DRASTIC may be considered more reliable since it is based on more hydrogeological parameters. However, for reconnaissance studies, the methods AVI and GOD provides good preliminary tools.

The values of total dissolved solids (TDS) (Figure 12), are large at the confluence of río Atoyac and río Salado, pos-

Table 1

Weights and ranges assigned to the hydrogeological parameters used in the assessment of the contamination vulnerability of the Zaachila valley aquifer. The weights used correspond to pesticide DRASTIC

Hydrologic parameter	Weight (w) for pesticide	Parameter range	Range of rating values (r)
Depth to water table (**D**)	5	4.6 – 9.1 m	7
		1.5 – 4.6 m	9
Net recharge (**R**)	4	98 mm/year	3
Aquifer media (**A**)	3	Metamorphic rocks, sandstone and limestone.	4
		Sand/gravel, alluvium	7
Soil media (**S**)	5	Clay, silt and fine sand	3
		Clay and coarse sand	7
		Sand	9
Topographic slope (**T**)	3	2 – 6 %	9
		0.3 - 2 %	10
Impact of the vadose zone media (**I**)	4	Metamorphic rocks, sandstone, limestone and clay.	4
		Sand-gravel, alluvium.	6
Hydraulic conductivity (C)	2	0.040746 – 4.0746 m/day	1
		4.0746 – 12.2238 m/day	2
		12.2238 – 28.522 m/day	4

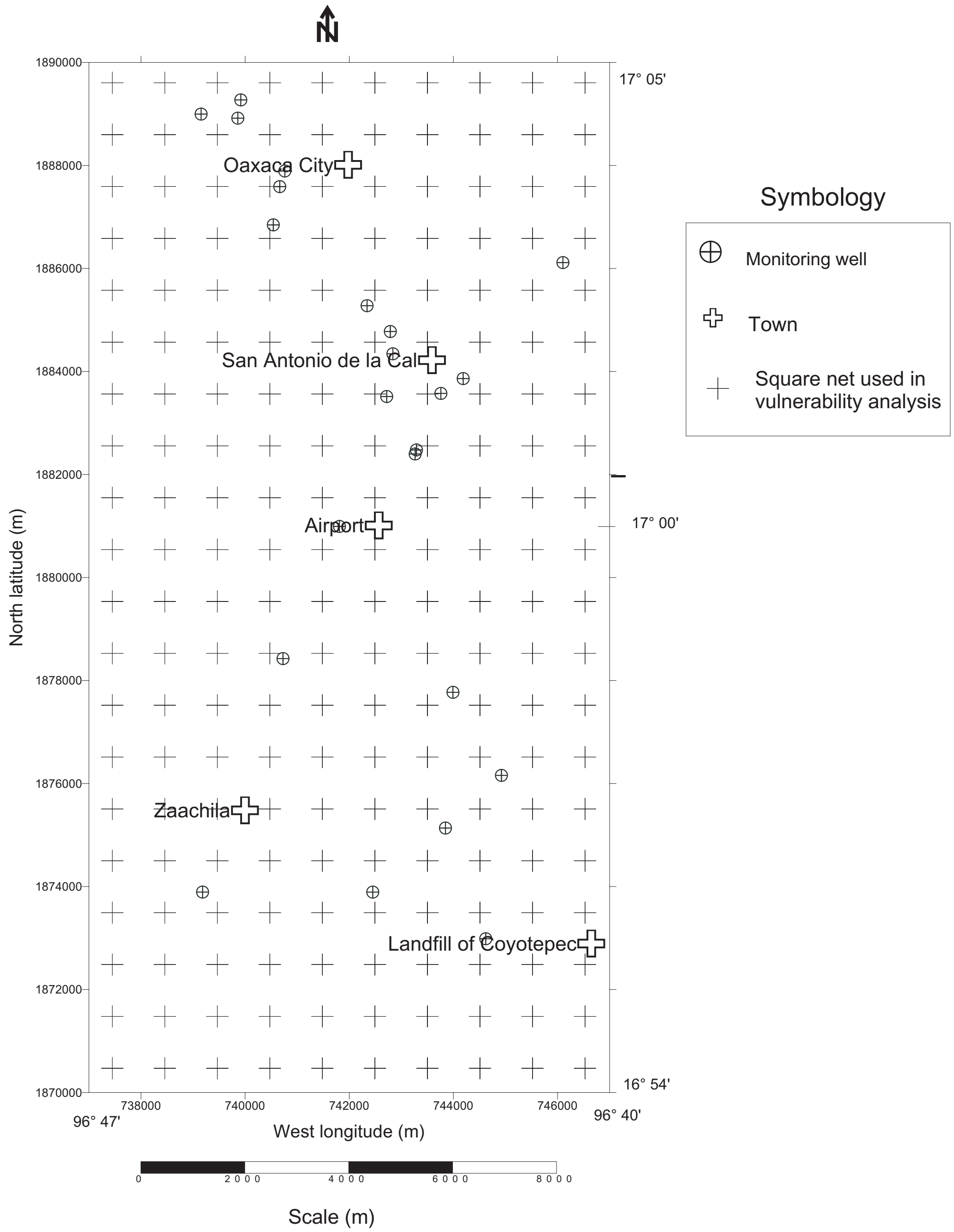


Fig. 8. The net used in the assessment of the contamination vulnerability, and in the respective sensitivity study. The cells are 1 km^2. Also indicated is the location of the wells used.

sibly because of the discharges of residual waters. The area between San Antonio de la Cal and the airport features high to very high vulnerability for all three methods.

The methods do not consider directly the effect of faults and fractures. However, they enter through the hydraulic conductivity, e.g. in the eastern border zone of the aquifer. The Oaxaca fault system appears not to affect the ground water flow substantially.

Vulnerability maps can support decisions about the uses of the soil and identificating potential risks for pollution of underground water. However, the methods must correspond to the objective of the study.

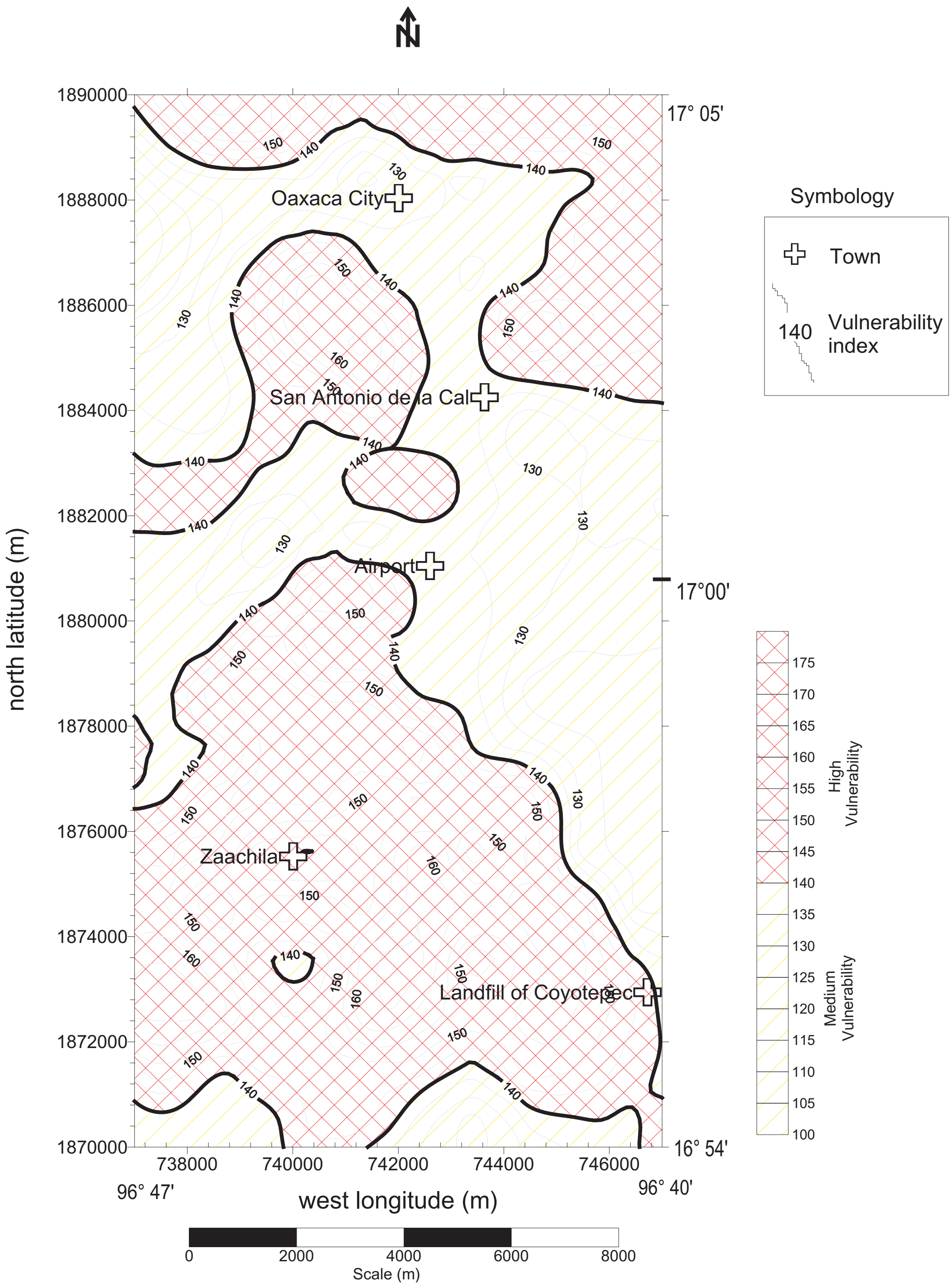


Fig. 9. Vulnerability index, according to the DRASTIC method, for the Zaachila valley (Oaxaca, southern Mexico). We observe values larger than 140 corresponding to a high vulnerability to contamination by superficial sources.

To establish which of the parameters is most susceptible to aquifer contamination, we conducted a sensitivity analysis using the results from the DRASTIC method.

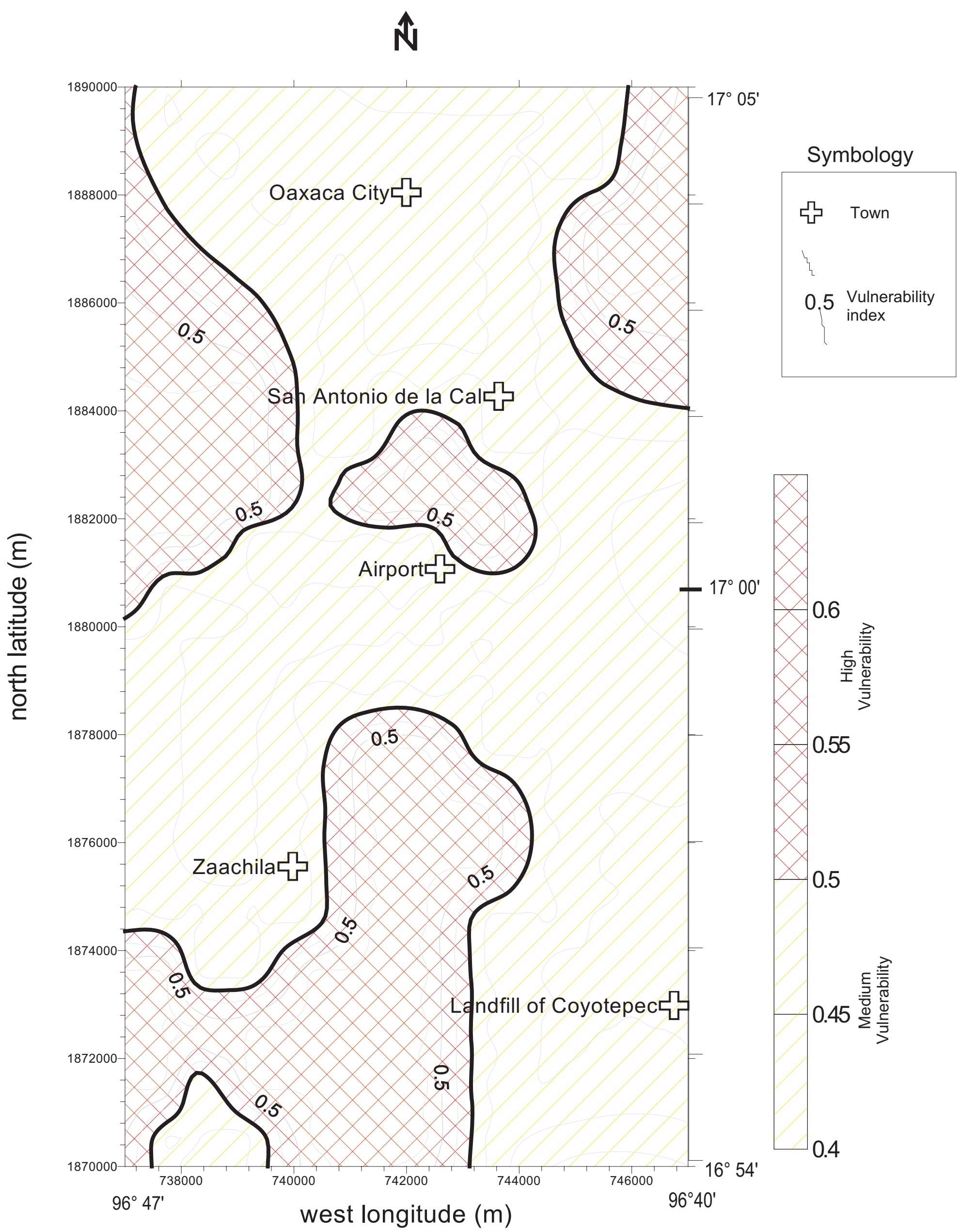
We calculated the sensibility *Si*, the variation index *VXi*, and the effective weight factors *Wxi* from the following expressions (Lodwik *et al.*, 1990; Gogu and Dessargues, 2000):

$$Si = \left| \frac{Vi}{N} - \frac{Vxi}{n} \right| \qquad (3)$$

$$VXi = \frac{Vi - Vxi}{Vi} 100 \qquad (4)$$

$$Wxi = \frac{X_{Wi} X_{ri}}{Vi} 100 \ . \qquad (5)$$

Vi is the vulnerability index for the i-th cell, *N* is the total number of parameters used in obtaining the vulnerability for each of the cells. *Vxi* represents the vulnerability index of



Scale (m)

Fig. 10. Vulnerability index, according to the GOD method, for the Zaachila valley (Oaxaca, southern Mexico). We observe values larger than 0.5 corresponding to a high vulnerability to contamination by superficial sources. However, values corresponding to a medium vulnerability are predominant.

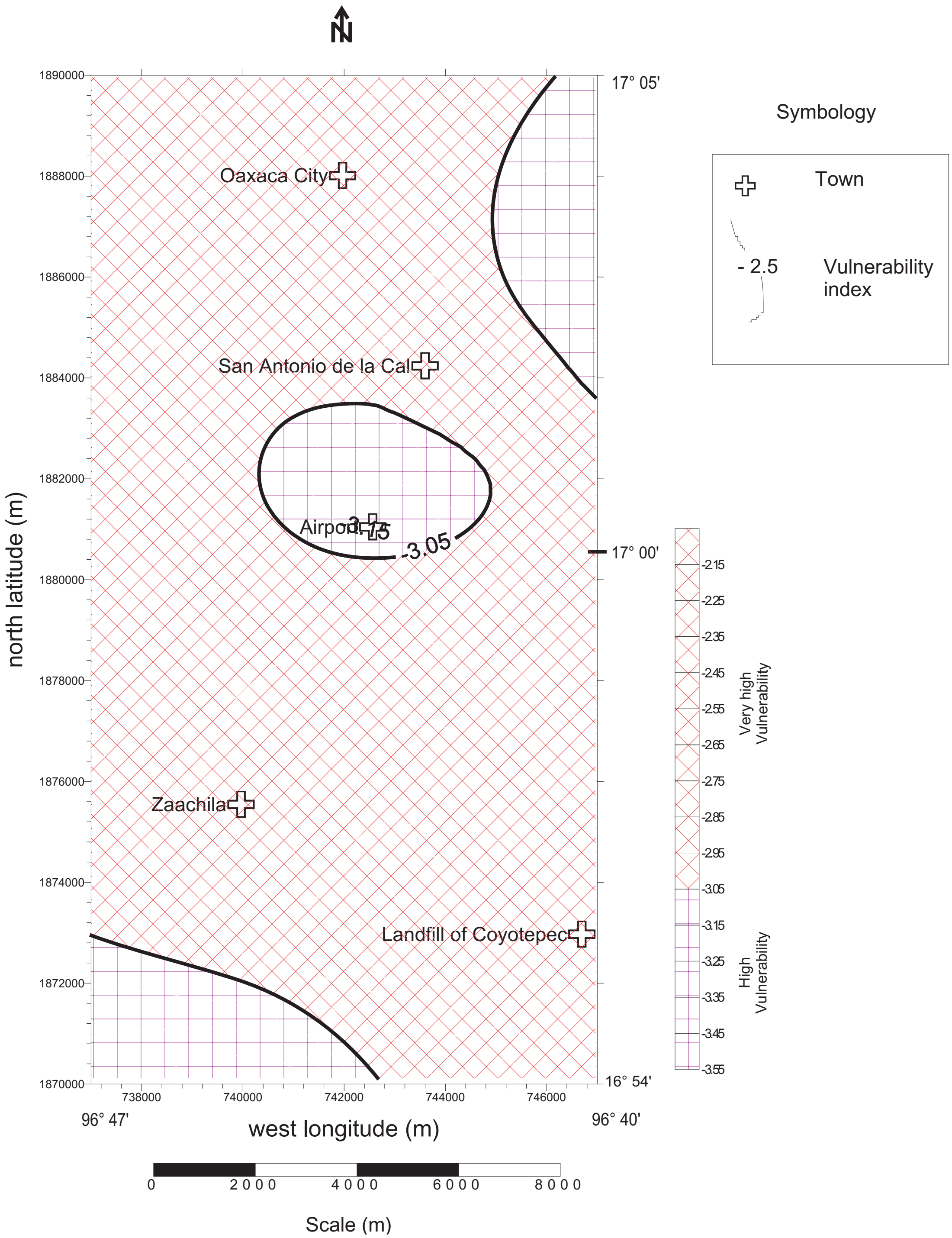


Fig. 11. Vulnerability index, according to the AVI method, for the Zaachila valley (Oaxaca, southern Mexico). Values correspond to the Log of the hydraulic resistivity C. Values corresponding to a very high vulnerability are predominant. Only three minor areas of high vulnerability are observed, at the airport and NE, and SW portions of the study area.

the i-th cell excluding the *Xi* parameter, and *n* is the number of parameters used in the sensitivity analysis. In equation (5), *Wxi* is the effective weight associated with the parameter; *Xri* is the range value assigned by DRASTIC to the *Xi* parameter, and *Xwi* is the weight of each parameter *Xi*. For each cell, the sum of the seven effective weights must be

100%. We assume that each cell has the same hydrogeological properties.

In Table 2, the parameter most sensitive to contamination is depth to the water table, followed in importance by topography, soil type, impact on the vadose zone, aquifer lithology, net recharge, and hydraulic conductivity.

The variation index revealed a similar parameter behavior (Table 3). The highest values are associated with the depth to the water table (13.50), and to the topography (4.24).

The effective weight factor indicates which parameters influence the vulnerability. These are the depth to the water table, followed by the topography, soil type, the impact in

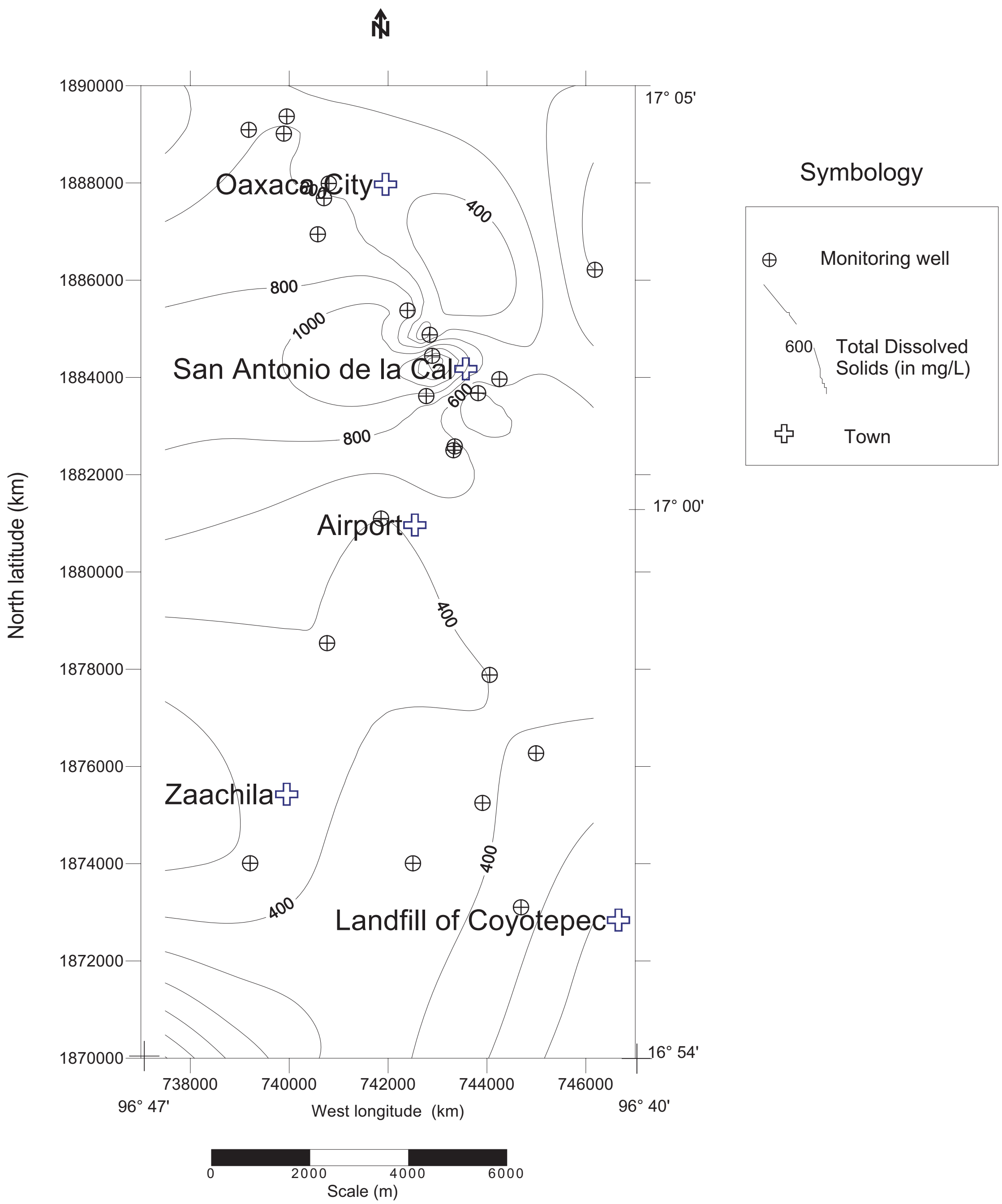


Fig. 12. Total Dissolved Solids (TDS in mg/l) in the Zaachila valley. The highest values are found in the zone of convergence of the streams río Atoyac and río Salado (possibly influenced by the discharges of residual waters).

the vadose zone, aquifer lithology, net recharge, and hydraulic conductivity (Table 4).

CONCLUSIONS

The aquifer of valle de Zaachila is located in a half-graben of tectonic origin. It is an unconfined aquifer, formed basically by two units. The non saturated zone has a thickness of up to 9.5 m formed by sands, silts and clays. The saturated zone consists on a mixture of the same materials with a thickness from 10 m to 120 m. The geohydrological basement topography is irregular and constituted by metasedimentary rocks.

The anisotropy index (λ) of the vadose zone in two places amounts to 1.130, 1.393 and 1.188 for depths of 5, 10, and 40 m respectively.

The potentiometric surface indicates that the regional flow has a preferential north-south direction. However shal-

Table 2

Sensitivity of the excluded parameter in the DRASTIC method for the Zaachila valley aquifer

Parameter of sensibility	D	R	A	S	T	I	C
Average	2.84	-1.56	-0.14	0.81	0.90	0.36	-3.22
Standard deviation	0.84	0.34	0.46	1.93	1.08	0.44	0.34
Medium	2.52	-1.55	-0.05	-0.54	1.21	0.45	-3.21
Maximum	5.00	-0.50	0.60	4.36	1.93	1.10	-2.17
Minimum	0.38	-2.26	-1.79	-2.48	-3.12	-1.12	-3.93

Table 3

Variation of the excluded parameter in the DRASTIC method for the Zaachila valley aquifer

Variation index	D	R	A	S	T	I	C
Average	13.50	-7.20	-0.54	3.24	4.24	1.84	-15.07
Standard deviation	4.48	0.91	2.16	8.77	5.46	2.21	0.21
Median	12.71	-7.27	-0.22	-2.94	5.35	2.13	-15.09
Maximum	33.33	-3.33	3.42	23.11	10.47	6.28	-13.43
Minimum	1.68	-8.85	-7.86	-12.47	-14.36	-4.93	-15.36

Table 4

Effective weights associated to the parameters in the DRASTIC method for the Zaachila valley aquifer

Effective weight factor	D	R	A	S	T	I	C
Average (%)	25.86	8.11	13.82	17.06	17.92	15.86	1.37
Standard deviation	3.84	0.78	1.85	7.52	4.68	1.90	0.18
Median	25.18	8.05	14.09	11.77	18.87	16.11	1.35
Maximum	42.86	11.43	17.21	34.09	23.26	19.67	2.78
Minimum	15.72	6.70	7.55	3.60	1.97	10.06	1.12
Theoretical weight	5	4	3	5	3	4	2
Effective weight (%)	19.23	15.48	11.54	19.23	11.53	15.38	7.69
Calculated weight (Xwi)	6.7	2.1	3.6	4.4	4.7	4.1	0.36

low flows exist with direction SE-NW near the dumpsite of San Bartolo Coyotepec, and NW-SE west of Oaxaca city.

Hydraulic conductivity ranges between 1.81647 E-05 and 1.70411 E-04 m/s, while transmissivity ranges between 22.01 and 220.85 m^2/day. The net mean annual recharge to the aquifer is estimated at 98 mm/yr.

Summarizing, the aquifer of the valley of Zaachila presents medium to high vulnerability, which makes it susceptible to pollution and degradation by superficial sources of contamination.

The use of three different methods enabled us to analyze their performance (depending on the number of geohidrological parameters involved) to obtain criteria for future choice of a specific method depending on the available information.

The results obtained from DRASTIC and GOD are similar. However, the DRASTIC method seems to be more reliable because it is based on more geohydrological parameters. GOD and AVI methods can be used in areas with little geohydrological information.

The scale of this study is intermediate and can be used as a basis for more detailed studies, for example at the dumpsite of San Bartolo Coyotepec, or in areas in the neighborhood of the Atoyac river.

The sensitivity analysis shows that the contamination of the aquifer of the Zaachila valley is most sensitive to depth to water table, because this aquifer is relatively shallow. Impact to the vadose zone, topography, soil type, aquifer lithology, net recharge and hydraulic conductivity are also factors of risk.

Sensitivity of aquifer contamination to net recharge and hydraulic conductivity is very low. Soil type presents the major spatial variability. On the other hand, the net recharge is fairly constant in the study area. The effective weight factors for impact on the vadose zone, aquifer lithology and soil type are close to the theoretical values. The effective weight factor for net recharge and hydraulic conductivity deviates significantly from its theoretical values.

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Salvador I. Belmonte-Jiménez[1,2], J. Oscar Campos-Enríquez[3] and Miguel A. Alatorre Zamora[4]

[1] Posgrado en Ciencias de la Tierra, UNAM, Del. Coyoacán, 04510 México, D. F., México
[2] CIIDIR-Oaxaca, Instituto Politécnico Nacional. Hornos 1003, Xoxocotlán, Oaxaca, México.
E-mail: sjimenez@ipn.mx
[3] Instituto de Geofísica, UNAM, Del. Coyoacán, 04510 México, D. F., México.
E-mail: ocampos@geofisica.unam.mx
[4] Dpto. de Física, Div. de Ciencias Básicas, CUCEI, Universidad de Guadalajara, Jal., México.