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Combined use of aquifer contamination risk maps and contamination indexes in the design of water quality monitoring networks in Mexico

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RESUMEN

El uso de los mapas de riesgo de contaminación acuífera ha resultado una herramienta muy importante en el diseño de redes de monitoreo para la calidad del agua subterránea. Se analizan tres escenarios en donde se han realizado mapas de riesgo a la contaminación de acuíferos como etapa inicial en el desarrollo de diseño de redes de monitoreo para la calidad del agua subterránea. En el primer caso se analiza el Valle de León. Su principal fuente potencial de contaminación es de tipo difusa y corresponde a la zona urbana de León, Guanajuato, donde se registran altos valores de vulnerabilidad e índices de contaminación. En el segundo caso se analiza el valle del río Turbio, en el cual sobresalen como fuentes potenciales de contaminación el río Turbio y una empresa relacionada con el procesamiento de cromo; estas fuentes son consideradas de tipo lineal y puntual, respectivamente. Los valores más altos de vulnerabilidad se registran en las zonas de recarga del acuífero, así como en algunas zonas dentro del valle. Los mayores índices de contaminación se observan en algunos segmentos en la intersección de la fuente potencial de contaminación y zonas con alto grado de vulnerabilidad. El tercer escenario se ubica en la región al sur de León, en el graben de Penjamo Abasolo, el cual es atravesado por los ríos Turbio, Lerma y Guanajuato, considerados como fuentes lineales, así como algunas fuentes difusas como son zonas inundadas e irrigadas con aguas residuales. Los valores más altos de vulnerabilidad se registran en las principales zonas de recarga. En esta región los puntos críticos se presentan en la intersección de zonas altamente vulnerables y los ríos Turbio, Lerma y Guanajuato. En los tres escenarios se observó la conjugación de tres elementos como son zonas de alta vulnerabilidad, presencia de una fuente potencial de contaminación y altos índices de contaminación, que en conjunto deben ser elementos importantes en el diseño de las redes de monitoreo para calidad del agua subterránea.

PALABRAS CLAVE: Vulnerabilidad, índices de contaminación, monitoreo de la calidad del agua.

ABSTRACT

Three scenarios are analyzed where risk maps were developed as the initial stage in the design of groundwater quality monitoring networks. In the León Valley, the main potential source of contamination is a diffused source which corresponds to the urban area, where high vulnerability values and indexes of contamination have been recorded. In the river valley, the Turbio river and a chromium processing plant stand out as potential sources of contamination. These sources are considered to be of the linear and point source type, respectively. The highest vulnerability values exist in the recharge areas, as well as in some areas inside the valley. The highest contamination indexes are observed at the intersection of the potential source of contamination with areas of high vulnerability. The third scenario is located in the region south of León, in the Penjamo-Abasolo graben, which is crossed by the Turbio, Lerma and Guanajuato rivers. The rivers are considered linear sources, and occasionally diffused sources when the rivers are in flood or irrigated with wastewaters. The highest vulnerability values are found in the main recharge areas. In this region the critical points are located at the intersection of highly vulnerable areas with the Turbio, Lerma and Guanajuato rivers. In each of these three scenarios the combination of three assessment parameters — areas of high vulnerability, presence of a potential source of contamination, and high contamination indexes is presented as a first step in the design of groundwater quality monitoring networks.

KEY WORDS: Vulnerability, contamination index, water-quality monitoring.

INTRODUCTION

The continuous exploitation of aquifers results in changes in their groundwater chemical quality. In some situations, such variations are a consequence of the extraction of water with a longer residence time or with a longer flow path. On the other hand, the confluence of contamination sources and the generation of cones of depression have also induced such changes in the quality of the water. The study of these changes requires the design of monitoring networks. The institutions confronting this problem are in search of tools that will help them establish more effective monitoring systems to understand and cope with these changes in groundwater quality.

As a first strategy, one of the most successful tools for monitoring system design has been the use of aquifer contamination risk maps and contamination indexes. Among the mapping systems used are those derived from the DRASTIC (Aller *et al.*, 1985), and SINTACS (Civita and De Maio, 1997) methods. Among indexes, the water quality index and the contamination index are frequently used. These methodologies have been applied to three different scenarios: the León Valley, the Turbio River Valley, and the Penjamo – Abasolo graben (Figure 2).

METHODS

The DRASTIC (Aller *et al.*, 1985) and SINTACS (Civita and De Maio, 1997) methodologies consist of numerical classifications developed to evaluate the potential contamination of groundwater. These classifications are based on seven factors which strongly influence the intrinsic vulnerability. The initials of the acronyms DRASTIC (Aller *et al.*, 1985), and SINTACS (Civita and De Maio, 1997), are derived from these seven factors (Figure 1):

The methodology of the DRASTIC, SINTACS, and other similar methods can be expressed as (Civita and De Maio, 1997):

$$I = \sum_{j=1}^{7} P_j W_j \ , \qquad (1)$$

where I is the potential contamination index, W_j is the weight assigned to each parameter, and P_j it is the value of each parameter.

The normalization of SINTACS is according to the following relationship (Civita and De Maio, 1997):

$$In = \frac{Ix - \mathrm{Im}in}{\mathrm{Im}ax - \mathrm{Im}in} * 100 \ , \qquad (2)$$

where In is the normalized index, while I_{max} and I_{min} are, respectively, the maximum and minimum raw values of the SINTACS index.

THE GROUNDWATER QUALITY INDEX

The groundwater quality index (ICA) provides a global value of the water conditions. It comprises selected individual values of a series of physical, chemical, or biological parameters, measured either in the field or in the laboratory (Conesa, 1993). The calculation uses the physico-chemical components of an analysis of normal water (major ions, pH, temperature, and electrical conductivity), although the relevance of the index depends on the number of elements analyzed. For making the evaluation, a weight and percentage value according to the concentrations or values of the parameter in question is assigned, according to the following relationship (Conesa, 1993):

$$ICA = k \frac{\sum C_i P_i}{\sum P_i} \ , \qquad (3)$$

where, C_i = function percentage value assigned to the parameters according to the concentrations, P_i = I weight assigned to each parameter, and k = constant that takes the values shown in Table 1. The constant, k, is related to aesthetic characteristics of the sample, such as the water's appearance and odor.

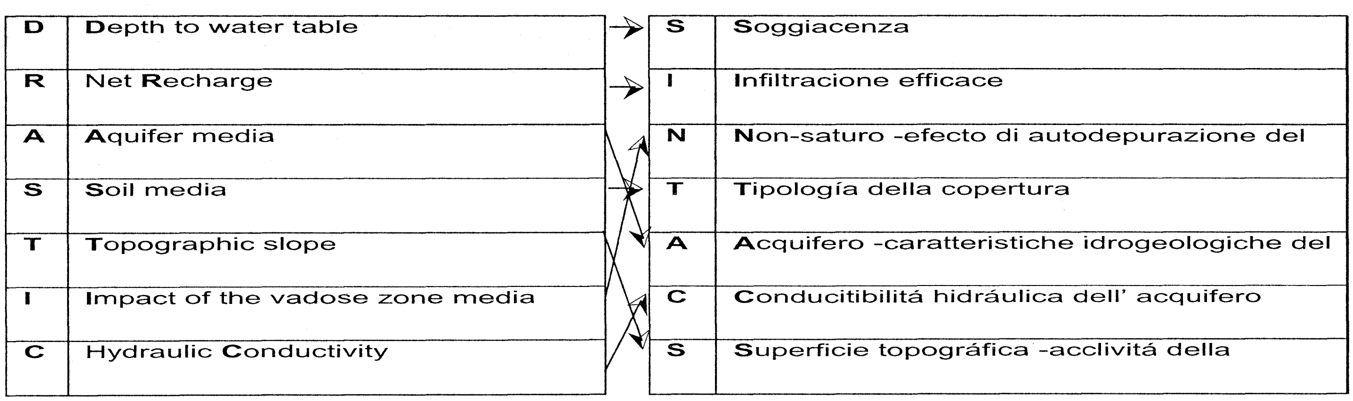

Fig. 1. Parameters of the DRASTIC and SINTACS methods.

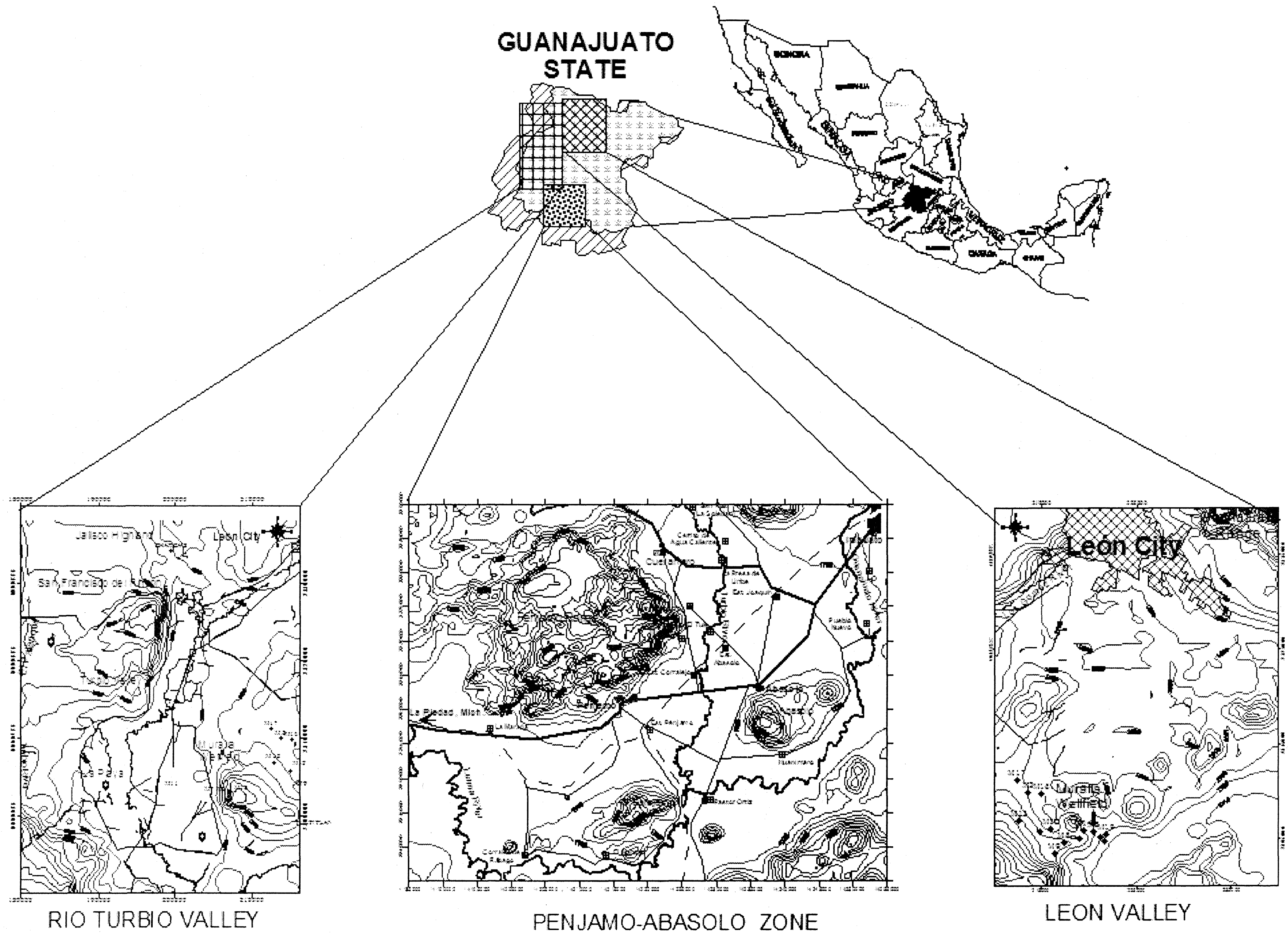

Fig. 2. Location of the three areas under study: the Turbio River Valley, the León Valley and the Penjamo – Abasolo graben.

Table 1

Intervals of weight for waters with physical characteristics of contamination (Conesa, 1993).

k	CHARACTERISTIC OF THE WATER
1.0	For clear waters without apparent contamination.
0.75	For waters with slight color, scum, and cloudy, not natural appearance
0.50	For waters with polluted appearance and strong odor
0.25	For black waters with evident fermentation and odors

The minimum ICA value is 0 whereas the maximum is 100. A smaller ICA represents a low water quality and a higher ICA is indicative of better groundwater quality.

CONTAMINATION INDEX

The contamination index represents the sum of the individual factors of the components that exceed the permissible values for contamination of the NOM-127 or EPA regulations (Backman *et al.*, 1998). With this index, the groundwater contamination can be assessed:

$$C_d = \sum_{i=1}^{n} C_{fi} \, , \qquad (4)$$

where $$C_{fi} = \frac{C_{Ai}}{C_{Ni}} - 1 \, . \qquad (5)$$

C_{fi} = contamination factor for the ith component, C_{Ai} = analytic value of the ith component, C_{Ni} = permissible highest concentration of the ith component ($_N$ means normative value according to NOM-127, EPA).

The higher the value of C_d, the higher the contamination of the resource.

STUDY CASE 1: THE LEÓN VALLEY

In the León Valley, the stratigraphy of the region is divided in two groups: 1) Sierra of Guanajuato, with an igneous-metamorphic-sedimentary complex dated to the Mesozoic one, and 2) the Bajío Guanajuatense region that forms a part of the León and Turbio river valleys, composed of volcanic products and continental clastics of the Upper Cenozoic (Ramírez *et al.*, 1999).

The normal fault of the Bajío and Duarte regions, with a NW-SE orientation, controls the León valley, while a N-S fault controls the orientation of the Turbio River Valley. The León Valley is characterized by a cone of depression, the deepest portion (at depths greater than about 180 m) of which is located in the center of the León Valley, where there is a high density of wells for agricultural use. In the area of La Muralla, the depth to water table increase from 40 to 100 m.

The lowest DRASTIC values are 100; they occur south of the urban area where thick layers of loamy material are present. The highest DRASTIC vulnerability indexes range from 160 to 170, and they are observed in the area of La Muralla and Santa Ana del Conde (Figure 3). Values from 120 to 140 have been calculated in the urban area of León (CEASG, 2000).

The highest values of the contamination index are recorded in the urban area, with values up to 20, while the lowest values (near 1) are located to the south of the urban area (Figure 3).

The water quality indexes (ICA) calculated in the region range from 15 to 60. South of the urban area, ICA indexes smaller than 20 were classified as of low water quality, while indexes 50 to 60 correspond to moderate quality. The best quality water was located in the peripheries of the valley, with ICA values up to 60 (Figure 3).

STUDY CASE 2: TURBIO RIVER VALLEY

The Turbio River Valley is formed in a graven. The northern area is filled with sedimentary material composed of clays, sands and gravels, while in the southern part volcanic rocks predominate (Figure 4). The southern area is separated from the north by a fault with a NE-SW orientation (Ramos, 2002).

The highest DRASTIC vulnerability values (150 to 170) in the valley are located in the vicinity of the Turbio river (Ramos, 2002). Low vulnerability values (100 at 120) are recorded towards the northwest segment of the Turbio river, where the lithological profiles show the presence of loamier granular materials with lower permeability. The areas surrounding the Turbio river valley have high values of the DRASTIC index due to the high permeability of the fractured basalts in the vadose zone (Figure 4).

In its northern portion, the Turbio river is considered a linear permanent source of contamination. Several small dams (Maztranzo, San Germán, Silva) are located along the river; They permanently retain large volumes of wastewaters (Armienta *et al.*, 2001), making these reservoirs an intermittent diffuse source of contaminated water.

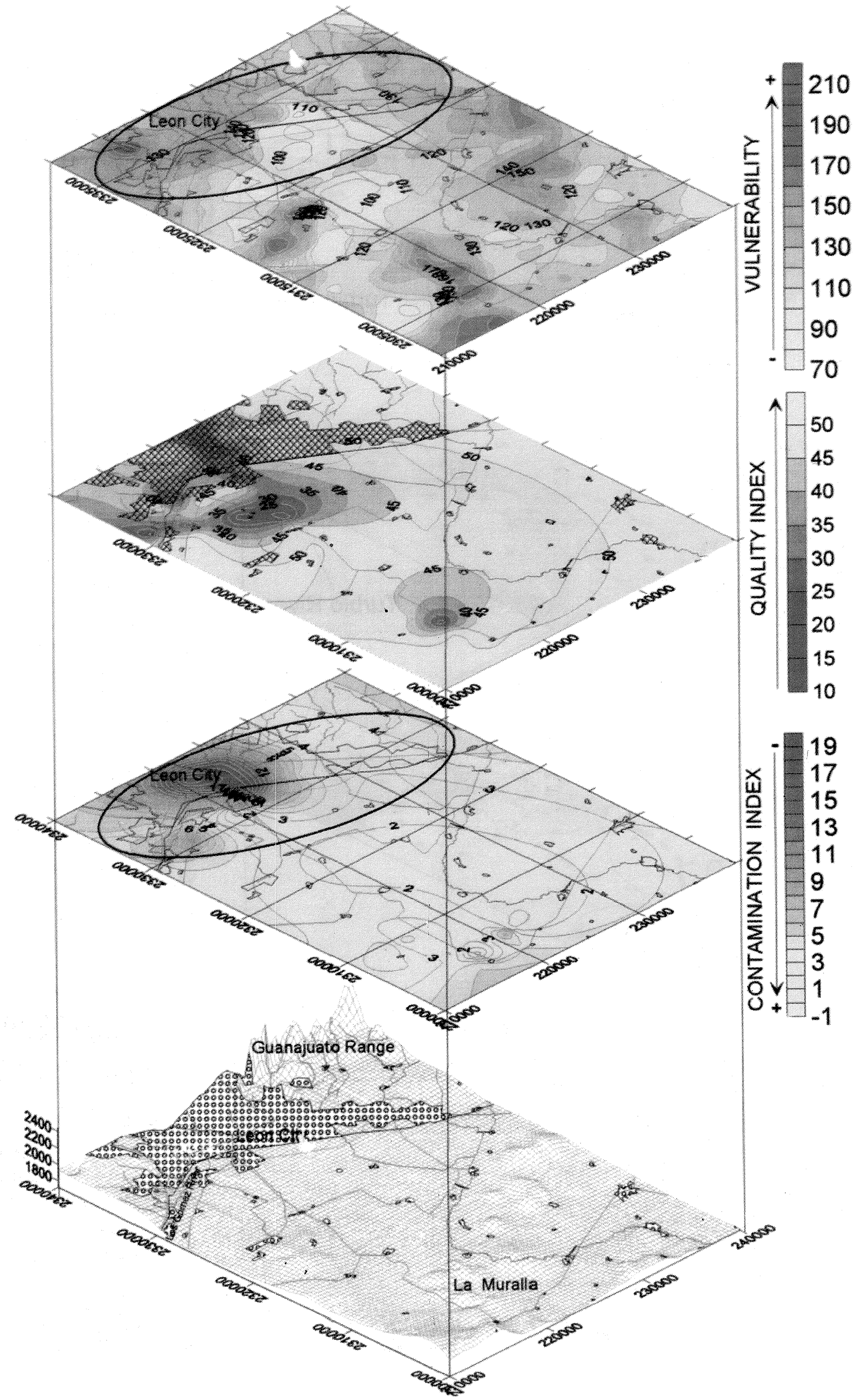

Fig. 3. Distribution of the DRASTIC vulnerability indexes (based in CEAG, 2000), and contamination indexes in the León Valley.

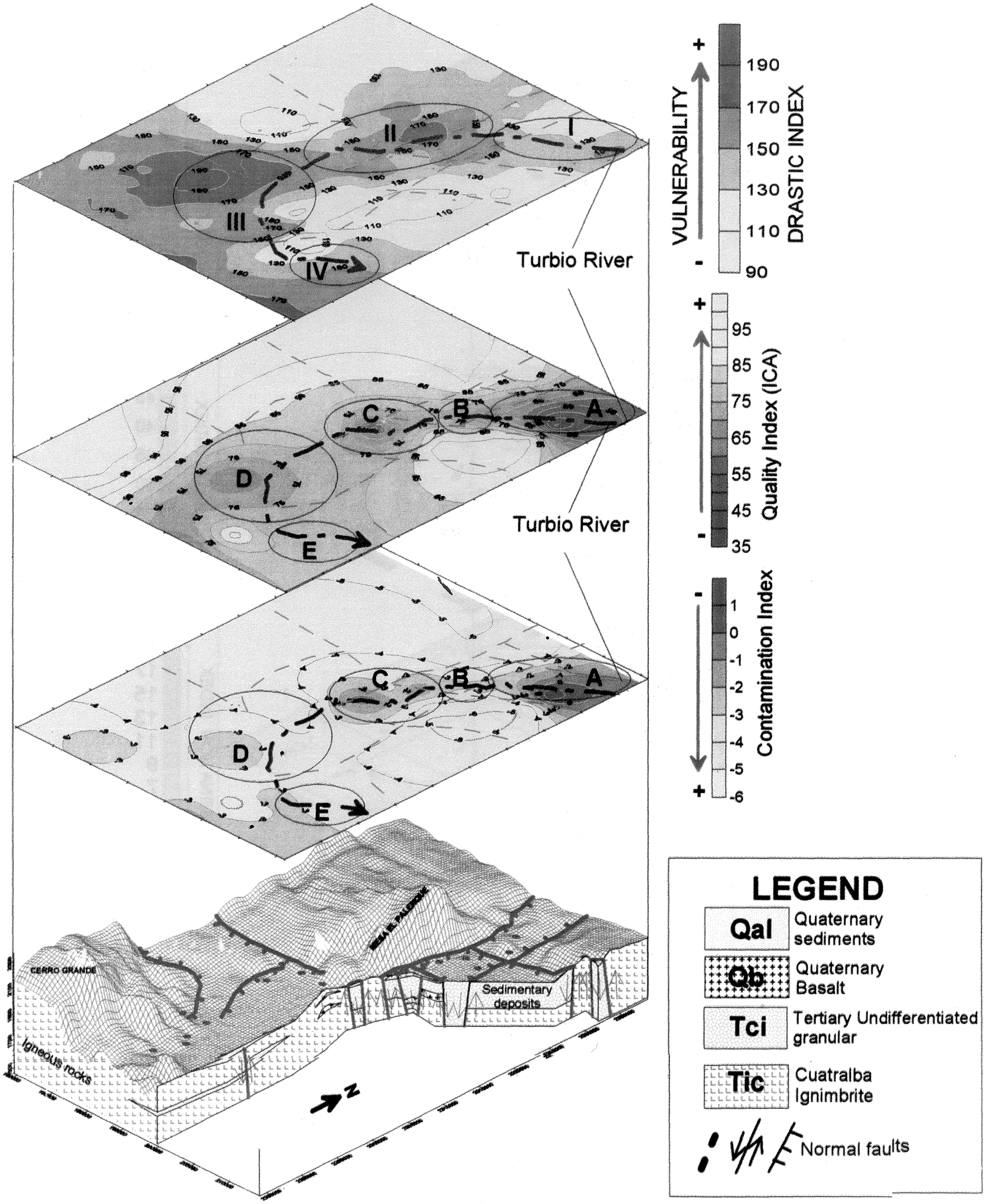

Fig. 4. Distribution of the DRASTIC vulnerability values, water quality index (ICA) values, contamination index values, and the geologic model in the Turbio River Valley (modified from Ramos, 2002).

The combination of the DRASTIC vulnerability map, and the sources of potential contamination generate the risk map, in which four contamination risk areas are defined (Figure 4):

I. Southwest of León city, in the Los Gómez river, with vulnerability values from 150 to 170.

II. The southern area along the of the San Francisco del Rincón town, where the Turbio river has vulnerability values from 150 to 170.

III. The region located to the south of the valley, an area intercepted by the Turbio river. The highest vulnerability values (170 to 190) are located to the east of the area.

IV. This area is located at the outlet of the valley, in the area of Las Adjuntas. It shows values from 130 to 150, and it is also intercepted by the Turbio river.

For evaluation of both the C_d, and water quality (ICA) in the valley of the Turbio river, major ions and Fe^{3+} were quantified (CEASG 1995). Many ions, such as Cl^-, SO_4^{2-}, Mg^{2+}, Na^+ and Fe^{3+}, have concentrations above the standards,.

The water quality indexes (ICA) calculated in the region run from 38 to 100 (Ramos, 2002). In the area under study, the lowest groundwater quality values were obtained in the vicinity of the Turbio river. The best quality water was located in the peripheries of the valley, with ICA values of 90 to 100 (Figure 4).

The C_d in the area is in the range from -6 to 1 (Ramos, 2002). The highest C_d values —those of relevant impact to the quality of the groundwater, are located in the San Germán reservoir, where the parameter reaches values of up to 1. In the central part of the valley, the values ranged from -4 to -3. These areas were classified as high-priority areas, or those of first order with high vulnerability, high C_d, and poor water quality. The areas of second order were those areas with low C_d and good water quality (Figure 4).

High-Priority Areas

A) This area corresponds to the Risk Area I, it has the highest C_d (more polluted) values of -3 to 1, and ICA indexes of 60 to 35.

C) The Risk Area II shows C_d values from -4 to -3, and ICA of 80 to 55.

D) The Risk Area III also had C_d values from -4 to -3, with ICA from 65 to 80.

Second Order Areas

B) This is a part of the Risk Area II, with C_d values from -4 to -3, and quality indexes from 75 to 85.

E) The Risk Area IV, showing C_d values from -4 to -3, and ICA 80.

STUDY CASE 3: PENJAMO-ABASOLO

The Penjamo-Abasolo graben is located in the region south of León, which is crossed by the Turbio, Lerma and Guanajuato rivers.

The stratigraphy of the region is very similar to the Turbio River Valley. The valley is filled with sedimentary material composed of clays, sands and gravels, and the surrounding ranges are of volcanic origin.

The minimum SINTACS values in Penjamo-Abasolo region were found near the town of Manuel Doblado, to the east of Cueramaro, to the south of Irapuato, east of Penjamo, and in the surroundings of Penjamillo (Figure 5). Highest values were found in the recharge areas. Other areas with high vulnerability are located in isolated hills in the valley (CEAG, 2001).

With the use of the groundwater contamination risk map, seven potential contamination areas were identified (Figure 5):

I. This area is located to the east of Cueramaro, and it presents vulnerability values from 20 to 50 units. It is along the Turbio river.

II. The second area is located in the Penjamo-Abasolo graben, also along the Turbio river, where vulnerability values from 40 to 60 units were identified. This area is affected by geologic structures (faults and fractures) with NS, E-W NE-SW orientations.

III. This is the area SW of Irapuato city, along the Guanajuato river, where vulnerability values from 40 to 70 units were calculated. The geologic structures that intercept the area have NE-SW and NW-SE orientations.

IV. This area is associated with the Guanajuato river between Zapote de Peralta and Numarán, where vulnerability values were determined to be from 40 to 70 units. This increase corresponds to the presence of fractured substrata, and the presence of geologic structures with N-S, E-W and NE-SW orientations.

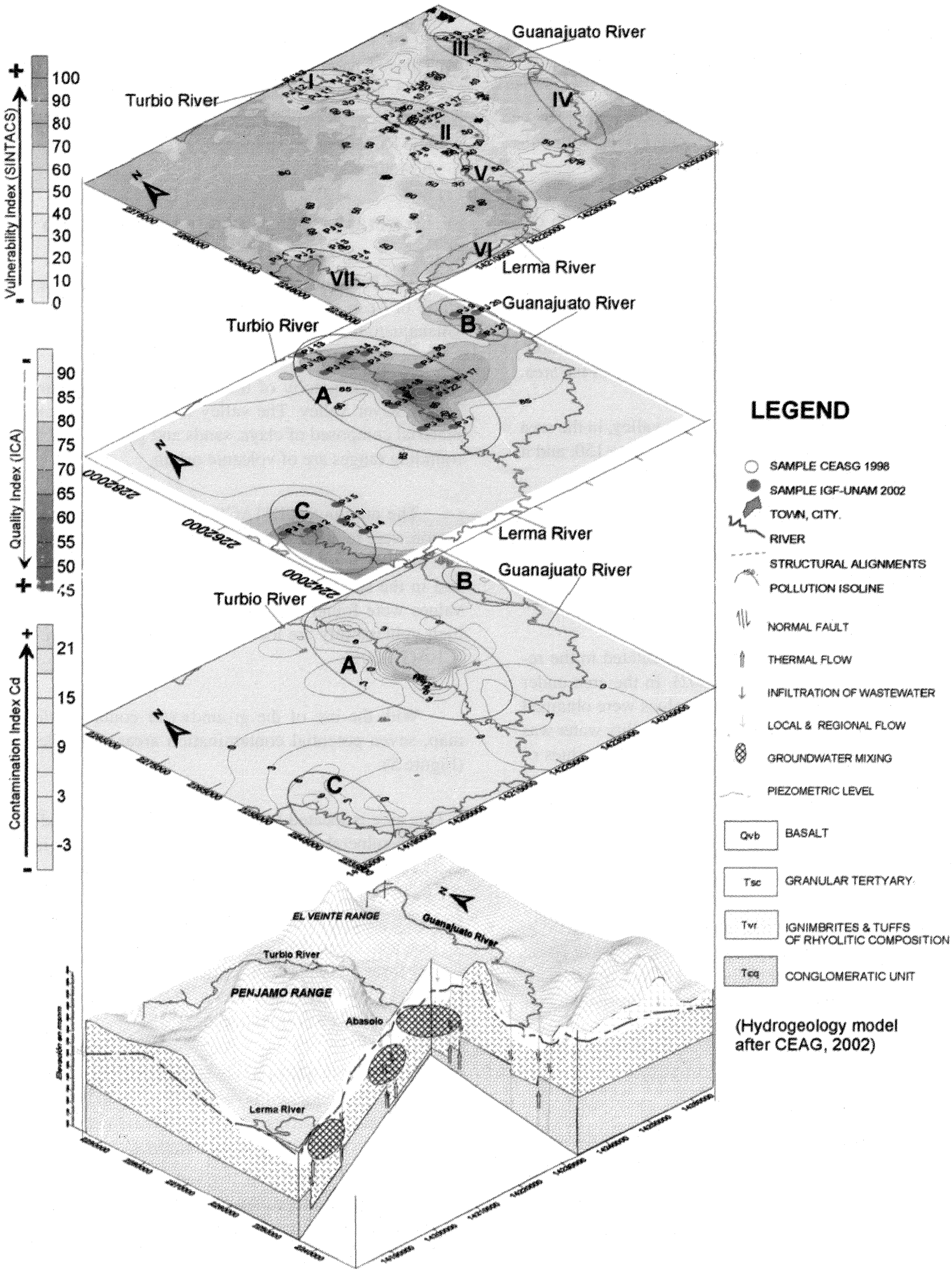

Fig. 5. Distribution of the normalized SINTACS vulnerability values, water quality index (ICA) values, and contamination index values in the area of Penjamo-Abasolo (taken from CEAG, 2001).

V. A fifth area is associated with the intersection of the Turbio and Lerma rivers, where vulnerability values from 40 to 90 were identified. Such values are related to the presence of NE-SW and NW-SE structures, as well as to the proximity of fractured rocks.

VI. This area is located around the E-W segment of the Lerma river where values from 30 to 50 were determined. In this area, the river transects fractured basalts.

VII. Finally, along the border of the states of Michoacán and Guanajuato, in the Penjamillo graben, vulnerability values from 40 to 90 units were determined. This area is associated with the west flank of the Lerma river, in the Penjamillo area.

The main regions identified as anomalous in the area under study are aligned with the beds of the Turbio, Guanajuato, and Lerma rivers. From this, the influence of the superficial waters on the region's aquifers recharge can be deduced, as well as the role played by the geologic structures (faults and fractures) in the distribution of the pollutants.

The area that presents the highest C_d and ICA values is associated with the Penjamo-Abasolo graben from which the aquifer is being recharged by infiltrating waters of the Turbio river, and up flowing thermal waters that directly contaminate the groundwater with arsenic (Figure 5).

The groundwater quality indexes vary from 43 to 90 units. The C_d contamination indexes fluctuate from zero to 83 units; higher C_d values correspond to higher contamination. The distribution map of C_d and ICA values allows the identification of three main areas (CEAG, 2001):

A. Values up to 43 units were determined north of the city of Abasolo (Penjamo-Abasolo graben, and the Cueramaro area). The hydro-chemical anomalies seem to have a natural origin related with the up flowing of thermal waters through the fault and fractures of the area. Anthropogenic factors associated with infiltration of surface waters from the Turbio river through geologic structures, also causes some contamination (Figure 5).

B. To the southwest of the area under study, at the limits of the States of Michoacán and Guanajuato (Penjamillo Graben), with values up to 67 units. Here, the aquifers are fed by the surface waters of the Lerma river (of anthropogenic origin). Thermal subterranean flows probably modify the area's groundwater quality. Notably, in this area the piezometric levels are the most shallow in the whole region (Figure 5).

C. The region located southwest of Irapuato city is associated with the course of the Guanajuato river (Figure 5). Contamination in the area is closely related with anthropogenic factors, bacteriological analyses of local wells detected the presence of colliform and faecal colliform bacteria.

CONCLUSIONS

Contamination vulnerability values in the urban area of León are not particularly significant. However the contamination and water quality indexes are high. For this reason, León has been defined as a high-priority, or first order area for a possible monitoring network.

The Turbio river influences the contamination, and water quality indexes of the region. The distribution of the areas with the highest contamination index values are located in the northern region along the river, where this water body acts as an active, linear and permanent source of contaminants. With the use of the contamination risk map, four risk areas were defined, and in combination with the contamination and water quality indexes, three high-priority, or first order areas, as well as two second order areas were delimited.

In the Penjamo-Abasolo region, seven groundwater contamination risk areas were outlined. With the results of the contamination and water quality indexes, three high-priority, or first order areas, as well as three second order areas were identified (CEAG, 2001).

Analysis of existing data that can be used to make a DRASTIC or a SINTACS map together with calculations of water quality and contamination indexes can be an important tool to delineate first order regions that are in need of a monitoring network.

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