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Aquifer vulnerability mapping in the Turbio river valley, Mexico: A validation study

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RESUMEN

Evaluaciones de vulnerabilidad acuífera pueden realizarse mediante métodos como DRASTIC y AVI. Los mapas generados normalmente no son validados o verificados con datos de campo. Este trabajo propone alternativas de validación para mapeos de vulnerabilidad. El mapa DRASTIC del Valle del Río Turbio, en el Estado de Guanajuato, comprende un área de 1300 km^2. Este fue comparado con otro mapa de vulnerabilidad generado por el método AVI. Se realizó también una comparación de los parámetros DRASTIC. Se propone y justifica una modificación para el rango original para la profundidad al nivel estático DRASTIC, con un reescalamiento basado en su peso efectivo. Las tendencias de vulnerabilidad obtenidas fueron correlacionadas con información hidrogeoquímica. La distribución de valores para cloruros y SDT reflejan las áreas más vulnerables definidas por DRASTIC y AVI. Estas áreas corresponden al cauce del sistema fluvial León-Turbio. Algunas fuentes potenciales de contaminación están localizadas en zonas vulnerables. Los resultados demuestran la importancia de alternativas de validación. También muestran como en las zonas más vulnerables, solutos provenientes de fuentes de contaminación están afectando la calidad del agua subterránea.

PALABRAS CLAVE: Vulnerabilidad acuífera, contaminación acuífera, DRASTIC, AVI.

ABSTRACT

Aquifer vulnerability assessments can be made using quantitative methods such as DRASTIC and AVI. Their typical output maps are generally not validated or verified with field data. This paper proposes validation alternatives for aquifer vulnerability mapping. The DRASTIC mapping of the Turbio river valley, in Guanajuato State, Mexico comprises an area of 1300 km^2. Comparing it with another aquifer vulnerability map generated by the AVI method, it could be validated. DRASTIC parameter comparison was also applied. A rescaling of the original DRASTIC rating range is proposed and justified based on the analysis of its effective weight. The vulnerability tendencies obtained were correlated with observed hydrogeochemical information. The observed values for chloride and TDS agree with the vulnerable areas defined by DRASTIC and AVI. Those areas correspond to the riverbed of the León-Turbio fluvial system. Some potential pollution sources are located in the vulnerable zones. The results demonstrate the importance of validation alternatives. They also show how in the most vulnerable areas, solutes coming from pollution sources are affecting the groundwater quality.

KEY WORDS: Aquifer vulnerability, aquifer pollution, DRASTIC, AVI.

INTRODUCTION

In the late 1960's the French hydrogeologist Margat introduced the term "aquifer vulnerability" (Vrba and Zaporozec, 1994). This concept is based on the hypothesis that the physical environment provides some protection to groundwater against pollutants from anthropogenic activities or surface natural processes. One of the objectives of an aquifer vulnerability map is to show the different protection levels that the geological media can offer. The use of aquifer vulnerability maps allows identifying the more vulnerable portions of an aquifer and to establish a risk level from potential sources of pollution.

During the last twenty years a great variety of aquifer vulnerability assessment and environmental impact assessment techniques and methodologies have appeared; such as GUS (**G**roundwater **U**biquity **S**core), GOD (**G**roundwater occurrence, **O**verall aquifer class, **D**epth to groundwater), and SINTACS (Civita *et al*., 1990; Gustafson, 1989). The parameters used in the different methodologies vary. The methodologies more widely accepted by practitioners are DRASTIC (Aller *et al.,* 1985) and AVI (Van Stempvoort *et al.,* 1992), **A**quifer **V**ulnerability **I**ndex. Their results are represented in isoline maps. Methodologies for their validation have not been reported. Validation is necessary to support reliability and to reduce the subjectivity in the rating selection in DRASTIC.

The use of vulnerability maps or thematic maps is not common in developing countries. In Mexico its use is being promoted by some local water institutions such as the Guanajuato State Water Commission, CEASG (Rodríguez *et al.,* 2000).

THE GEOLOGICAL AND HYDROLOGICAL FRAMEWORK

The Río Turbio Valley is located in the western-central part of Guanajuato State, southwest of León (Figure 1).

Volcanic and sedimentary rocks from the Tertiary (Oligocene) to recent can be found in the valley (Figure 2a). The oldest rock is the Cuatralba ignimbrite (Tic). Basaltic rocks of the Dos Aguas Formation are interstratified with this ignimbrite. Their emplacement is contemporaneous with the Cuatralba ignimbrite (Quintero, 1986). An undifferentiated Tertiary granular unit (Tci) covers the basalts and the ignimbrites. These sedimentary deposits filled the tectonic depressions as alluvial fans. The Pliocene-Quaternary volcanic rocks are basaltic flows (Qb). The Quaternary sediments include unconsolidated continental clastic deposits (gravels, sands, clays, residuals soils). These sediments are located in the plain and the piedmont (Qal).

The structural framework and the geological units distributed in the basin control the hydrodynamics of the Río Turbio Valley aquifer system. There are three fault systems in the valley, N-S San Francisco del Rincón graben; E-W Jalpa graben; and NE-SW Plan de Ayala graben (Figures 1, 2a and 2b). The fault systems act as hydraulic barriers (N-S system) or as permeable areas (E-W and NE-SW systems), allowing aquifer recharge (Figures 2a, 2b).

There are two types of aquifer media, one of them is granular and the other fractured. The first one is located north of Turbio Valley, San Francisco del Rincón and Plan de Ayala. The fractured aquifer defined by the Cuatralba Ignimbrite and basaltic rocks is located in the center and south of the valley.

The granular aquifer contains undifferentiated Tertiary granular and Quaternary sediments, 400 m in thickness, with volcanic rock intercalations in the valley periphery. The granular aquifer is partially confined by clay layers whereas the fractured one is unconfined (Figure 2a). The sediment thickness in the center and south of the valley decreases considerably. In some areas, sediments are not present and volcanic rocks, tuffs, ignimbrites and basalts prevail. The volcanic rocks are not continuous; locally, they are intercalated and wedged. Their thickness is greater than 500 m.

The piezometry clearly reflects the aquifer characteristics and the differences between the granular and fractured media. Two piezometrical areas are evident (Figures 2b and 2c). The zone with higher groundwater levels is located toward the north (granular), whereas lower groundwater levels are located toward the south of the valley (fractured/volcanic). The granular and fractured aquifers are hydraulic ally separated by a NE-SW fault of low permeability (Figures 1, 2a, 2b and 2c).

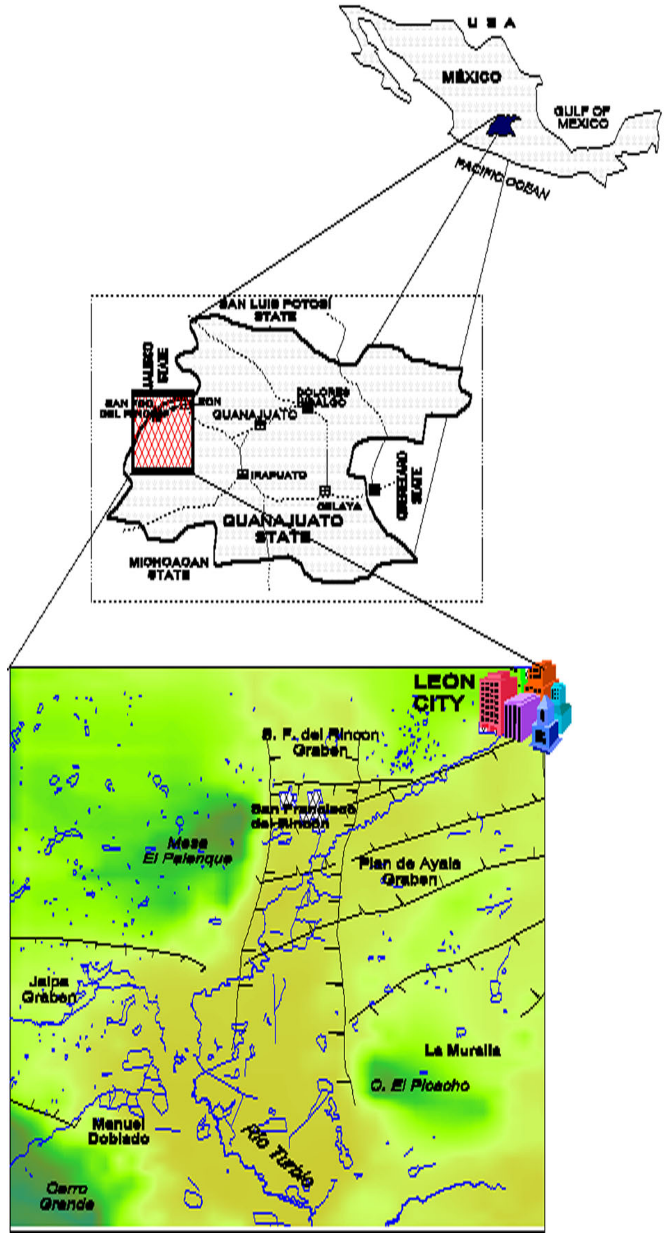

Fig. 1. Location map. Turbio River Valley, Guanajuato State, Mexico.

DATA PROCESSING

The DRASTIC approximation

The DRASTIC approximation is a scheme of numerical classification based on seven rating factors, from which DRASTIC takes its name: *D* = **D**epth to water table, *R* = Net **R**echarge, *A* = **A**quifer media, *S* = **S**oil media, *T* = **T**opography, *I* = **I**mpact of the vadose zone and *C* = Hydraulic **C**onductivity (Aller *et al.,* 1985). The product of each rating factor r by the assigned weight w produces a weighted DRASTIC value $\Delta_r\Delta_w$ at selected points or wells (Table 1);

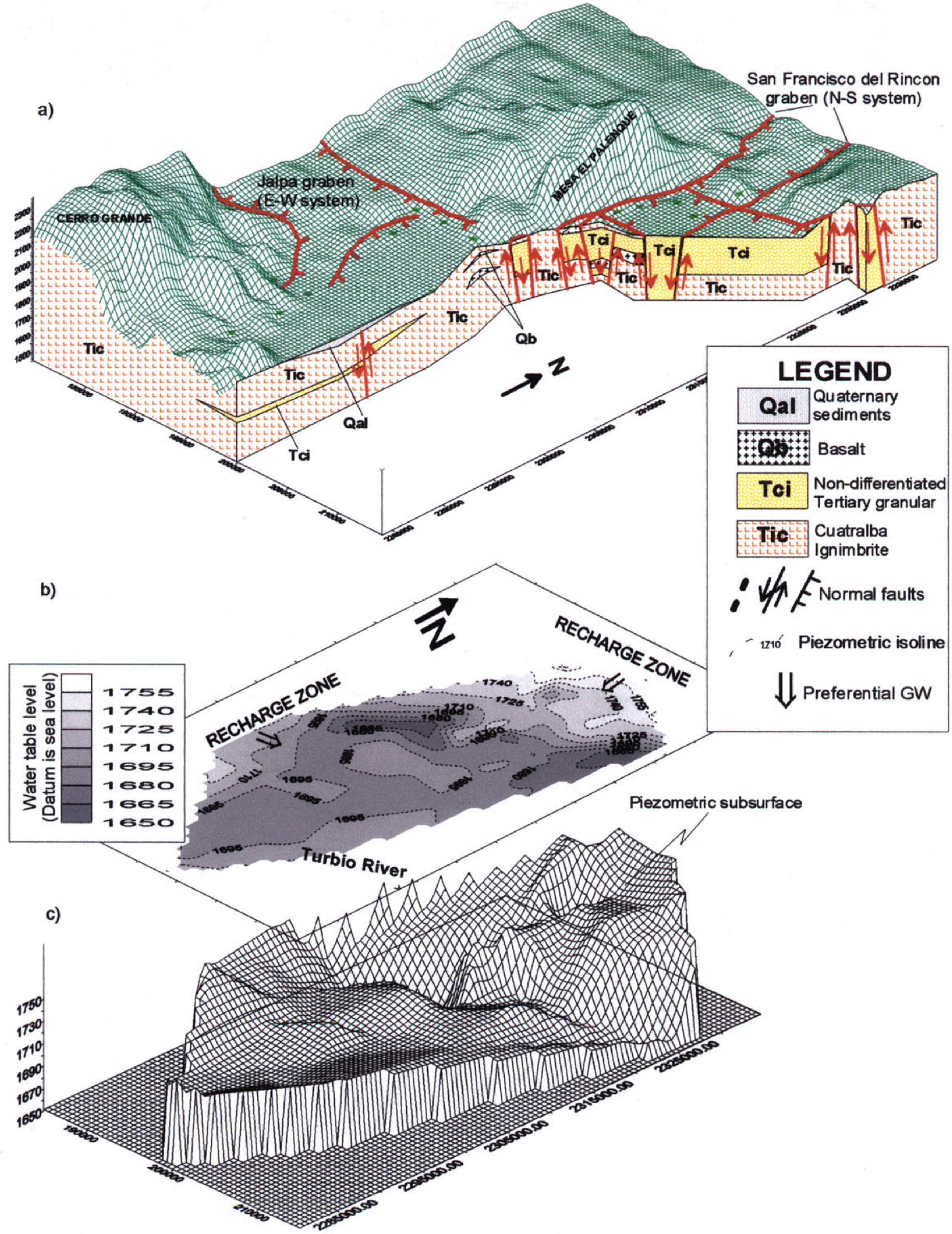

Fig. 2. (a) Geological model of the Río Turbio valley. (b) Fault system and piezometry. (c) 3D piezometry showing the two main aquifer systems.

Table 1

Assigned weight and range of rating values for DRASTIC (After Aller *et al.,* 1985)

Factor	Weight (*w*)	Range of rating values (*r*)	Parameter range
Depth to water table	5	1 – 10	4 – 170 m
Net **R**echarge	4	1 – 5	50 – 95 mm
Aquifer media	3	5 – 10	Gravel/sand – Fractured basalt
Soil media	2	1 - 10	Absent - Clay
Topographic slope	1	1 – 10	0 > 18 %
Impact of the vadose zone media	5	4 – 10	Clay/silt – Fractured basalt
Hydraulic **C**onductivity	3	1 - 10	2.69×10^{-3} – 2.7×10^{-7} m/s

Table 2

DRASTIC rating ranges for Aquifer Media (Aller *et al*., 1985)

	Aquifer Media Ranges	Rating, *Ar*
Weight of **A**quifer Media ***Aw = 3***	Massive shale	1 - 3
	Metamorphic/igneous rocks	2 - 5
	Weathered metamorphic / igneous rocks	3 - 5
	Glacial till	4 - 6
	Bedded sandstone, limestone, and shale sequences	5 - 9
	Massive sandstone	4 - 9
	Massive limestone	4 - 9
	Sand and gravel	4 - 9
	Basalt	2 - 10
	Karst limestone	9 - 10

$$D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w = Vi \quad (1)$$

Where *Vi* is DRASTIC Index

The objective of a DRASTIC map is to show the spatial variation *Vi* of the vulnerability. It implies variations in the parameters considered *Vi*. If the parameter *Vi* does not vary, its graphic representation is a smooth plain. That equivalent to introducing a constant in the summary equation. Consequently this parameter can be ignored.

Aller and collaborators (1985) proposed tables with ranges and ratings for each parameter. The maximum DRASTIC value is 230 whereas the minimum is 23. Users must choose an adequate rating depending of the influence of the selected parameter on the vulnerability. The parameters that presented most subjectivity are the aquifer media and the Impact of the vadose zone (Tables 2 and 3).

The input parameters were taken from previous hydrogeological studies (Ariel Construcciones, 1969, 1982;

Table 3

DRASTIC rating ranges for Impact of the Vadose Zone Media (Aller *et al*., 1985)

	Impact of the Vadose Zone Media Ranges	Rating, ***Ir***
Zone Vadose ***Iw = 5***	Aquitard	1
	Silt/Clay	1 - 2
	Shale	2 - 5
	Limestone	2 - 7
	Sandstone	4 - 8
	Bedded limestone, sandstone and shale	4 - 8
	Sand, silt with clay	4 - 8
	Metamorphic/igneous rocks	2 - 8
	Sand and gravel	6 - 9
	Basalt	2 - 10
	Karst limestone	8 - 10

CEASG, 1995; GEOPSA, 1998). The piezometry of CEAG (1995) was used for depth to water table. The aquifer and vadose zone stratigraphy was obtained from lithological columns taken from 52 wells and from the reinterpretation of more than 40 vertical electrical soundings. Climatic data from five meteorological stations and rainfall and temperature maps were used to estimate real evapotranspiration, using the Turc equation (Turc, 1955), and net recharge. Soil type and topography were taken from INEGI 1.50,000 scale (1973a; 1973b).

The data density for each parameter is variable, but the whole area was considered. In some parts with scarce information data were supported by geological and hydrogeological regional tendencies.

The final DRASTIC index for each point was obtained by the sum of all ratings multiplied by the assigned weight in the DRASTIC approximation, the results are shown in Figure 3. Maps were generated with the DRASTIC values using Kriging. Values higher than 150 were obtained in the surrounding ranges located to the valley borders and toward south of San Francisco del Rincón (Figure 3). 130 – 150 values predominate in the northern, central area and SE. 110-130 values are distributed south of the central area, to the east and NW. The lower values were distributed locally to the east, NW and a little zone in the central area. As expected this vulnerability zoning is in agreement with the local hydrogeological. The S-E area corresponds to fractured rocks. The central vulnerability areas reflect mainly the riverbed.

In the north part, the Turbio River is located mainly in relatively high vulnerability areas 130-150. This is consistent with the hydrogeologic model: in the Valley are located two important tectonic grabens filled with permeable granular material. Other southern zones with high vulnerability are related to permeable basalts and ignimbrites.

Low vulnerability values (< 110) were found locally to the east of the Turbio River. In that area clayey granular material, with low permeability are reported in the lithological columns (CEASG, 1995). High DRASTIC vulnerability was obtained in the Turbio River Valley surroundings, due to the high permeability of the fractured basalts of the vadose zone.

The AVI index.

AVI is the simpler and faster quantification method. AVI only uses the vertical hydraulic conductivity K and the thickness b of the layers located over the water table to estimate the hydraulic resistance $c = S\, b_i / k_i$ (Van Stempvoort *et al.*, 1992). This index quantifies the aquifer vulnerability by hydraulic resistance of each layer to vertical water flow and represents an estimation of the average travel time of a pollutant from the surface to the water table.

The data sources for AVI are not the same for the DRASTIC method. The AVI map is supported only by 52 wells with lithological data. The hydraulic conductivity K of the granular aquifer varies from 1.4×10^{-3} to 1.0×10^{-7} m/s whereas in the fractured media the value varies from 1.4×10^{-3} to 3.7×10^{-5} m/s (Table 4). Most of these values were obtained from 42 pumping tests (Ramos and Rodríguez, 1998). K values were also measured in selected outcrops using a constant head permeameter. Data from geological sections were supported with the stratigraphical and geophysical information. A hydraulic conductivity value was chosen for each layer. For the same geologic unit, lateral variations were not considered. A thematic map was also generated (Figure 4) with log c values. Areas with AVI index smaller than 1 were classified as extremely high vulnerability (arrival time < 10 years), these values are located to the SW and SE. Indexes 1 to 2 correspond to high vulnerability (10 to 100 years), and are distributed all along the valley, along the riverbed. 2 to 3 represent moderate vulnerability (100 to 1000 years) corresponding to the east of the study area. (Table 5).

Table 4

Hydraulic conductivity (m/s) values for some aquifer material (Ramos and Rodríguez, 1998)

Lithology	Hydraulic Conductivity (m/s)
Gravel	1.4×10^{-3}
Gravel/sand/clays	3.7×10^{-5}
Sands	3.63×10^{-5}
Sand/clays	6.1×10^{-6}
Clays / sands	3×10^{-7}
Sand/silt/clays	3×10^{-7}
Clay	2.7×10^{-9}
Fractured basalt	5.4×10^{-5}
Fractured ignimbrites	1.91×10^{-5}
Tuff	$3.1\text{-}3.7 \times 10^{-5}$

Table 5

AVI and DRASTIC vulnerability ranges for the Turbio Valley

Vulnerability Ranges	**AVI** Index in years (c)	**AVI** Index in Log (c)	**DRASTIC** Index
Extremely high vulnerability	< 10	<1	>140
High vulnerability	10 - 100	1 – 2	120 –140
Moderate vulnerability	100 - 1000	2 – 3	100 – 120
Low vulnerability	> 1000	> 3	< 100

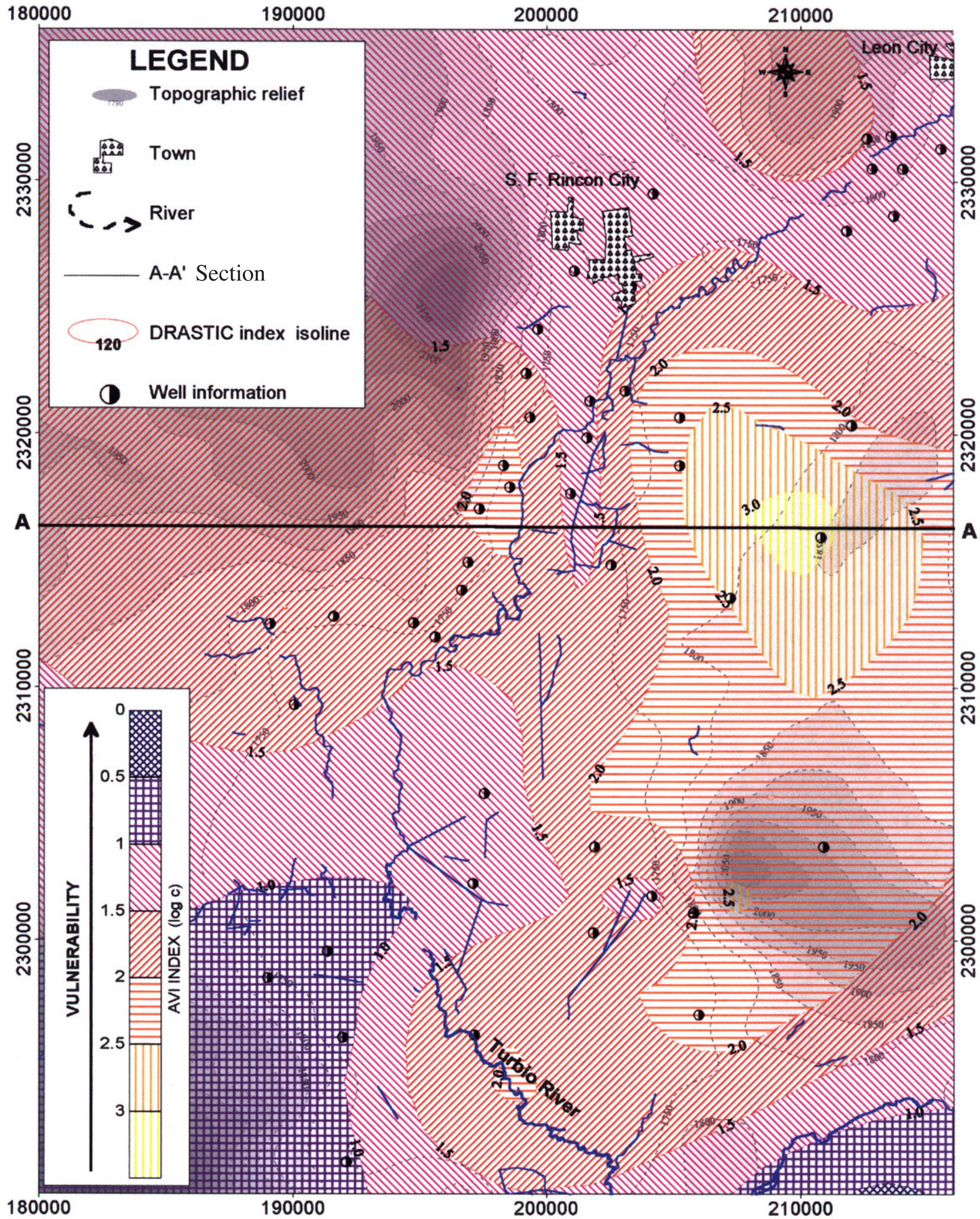

Fig. 3. Map showing the vulnerability index for the Río Turbio Valley as derived with DRASTIC.

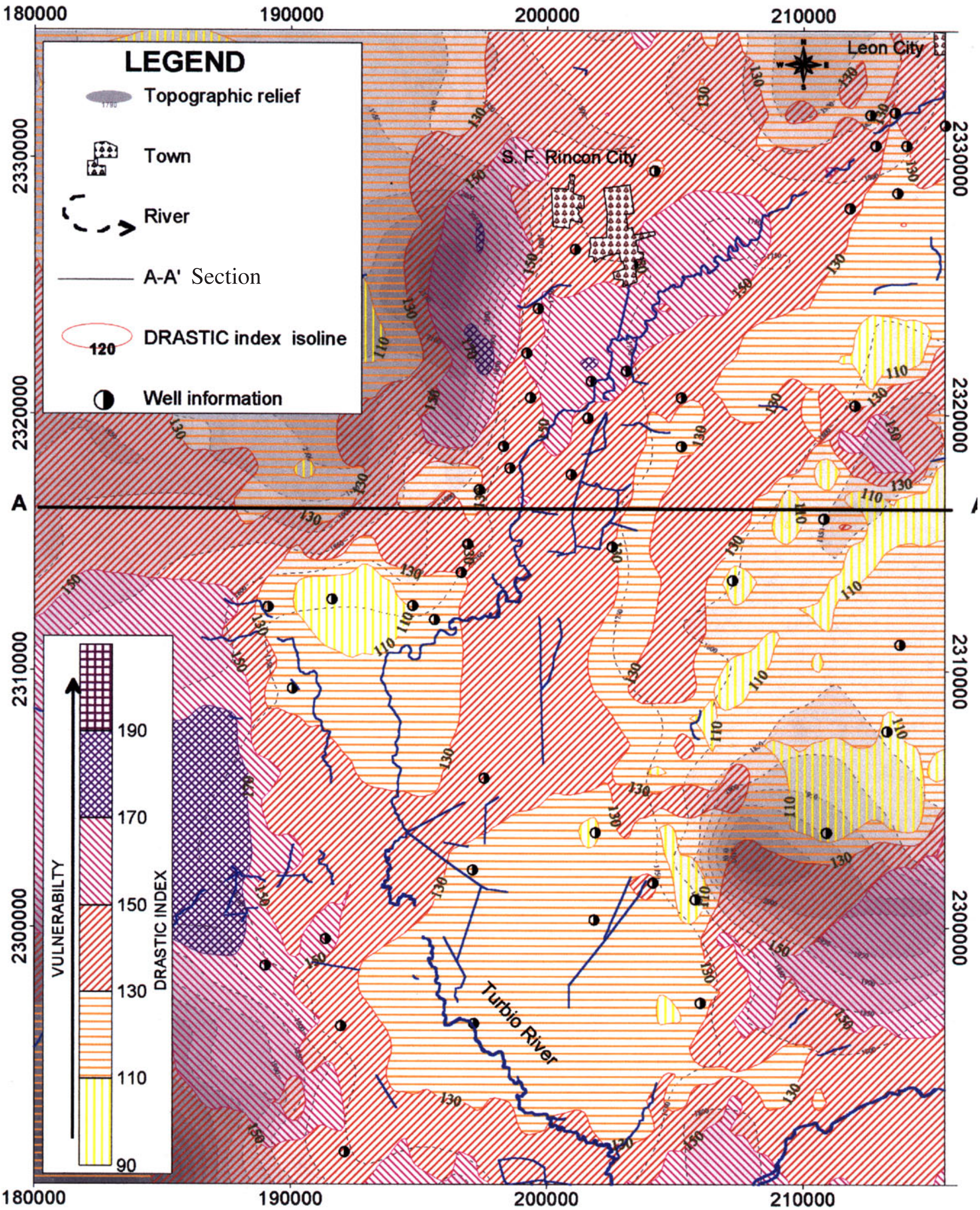

Fig. 4. Map showing the vulnerability index for the Río Turbio Valley as derived with AVI.

VALIDATION TESTING AND RANGE RESCALING PROPOSAL

Most vulnerability maps are not validated. The use of information that is not validated can result in erroneous conclusions and subjective environmental assessments. To avoid subjectivity, parameter comparison testing and mapping validation alternatives are necessary.

A comparison between the raw data map with the rating parameter map was carried out for each DRASTIC parameter. This analysis consisted of the comparison of tendencies of the input values with respect to the selected rating. Overlaying isoline map pairs carries out the comparison. The distribution of maximum and minimum tendencies must be similar. Good correlation coefficients were obtained for depth to water table, net recharge, topography and hydraulic conductivity, (e_D, 0.95; e_R, 0.91; e_T, 0.8; e_C, 0.74). For geology, vadose zone and soils is not possible to get a numerical correlation.

If variations were detected in the selection of the rating values r for one of the parameters and/or inadequate parameter identification, the conceptual model was reviewed and modifications in the rating range were done.

Adjustments for the water table depth were required. The maximum depth considered for DRASTIC is 30 m (assigned rating 1). However, in the study area the piezometric level varies from 40 to 140 m. To adopt the original rating implies that depth to the water table is not important, however previous studies (BGS, 1996; Rodríguez *et al.,* 1992; CEASG, 1995) reported anthropogenic contaminants in deep aquifer formations. The Cl and TDS gradient concentrations decrease from the river to the flanks because when the solutes are incorporated to the groundwater flow, they migrate laterally. In previous works, the Turbio River has been characterized as a linear pollution source (CEASG, 2000; Ramos, 2002). There are other punctual sources, but by the contaminant load, the main source is the Turbio River. AVI also reveals high vulnerability at sites with water table depth greater than 30 m. The transit time calculated with AVI shows that when the vadose zone is composed of very permeable materials, the aquifer systems become vulnerable.

The proposal for the range rescaling is simplified by a matrix representation (Rose 1993)

$$[T]\,[A] = [C]\ , \tag{2}$$

where ***A*** could be geological maps, well logging data, pumping tests, etc. ***T*** represents the transformations applied to a data series whereas ***A*** the assigned ranges to a critical parameters ***C***. Each parameter contributes with an effective weight to the final vulnerability index (Napolitano and Fabri, 1996). The critical parameter ***C*** can be affected by weighting function ***W***

$$[W]\,[C] = [\,Vi\,]\ , \tag{3}$$

W is the assigned weights and ***Vi*** the vulnerability index.

The simplest expression of a weighting function could be a constant. In our case each parameter DRASTIC influenced the aquifer vulnerability index through its effective weighting Wxi (Napolitano and Fabri, 1996; Gogu and Dassargues, 2000).

$$Wxi = \frac{XriXwi}{Vi} * 100\ , \tag{4}$$

where *Xri* and *Xwi* are the ranges and the assigned weights for each parameter *X,* and *Vi* is the vulnerability index for each point (Eq. 1).

To complete this analysis an evaluation of the vulnerability variation Vvxi caused by a parameter omission was done (Lodwik *et al.* 1990)

$$Vvxi = \frac{Vi - Vxi}{Vi} * 100\ , \tag{5}$$

where

Vvxi = Variation index omitting a parameter X(D, R, A, S, T, I or C)
Vi = Vulnerability index in the point i.
Vxi = Vulnerability index calculated without a parameter, X(D, R, A, S, T, I o C).

The variability expression (Eq. 5) proposed by Lodwik *et al.,* (1990) apparently is different from that which by Napolitano and Fabri (1996) proposed to analyze the parameter weight (Eq. 4), but they are equivalent.

Table 6 shows the statistics of the calculated effective weights or variability for each DRASTIC parameter, using the original scale for depth. D and T show the lowest effective weights (Table 6).

The comparison of the variability between the original weight and the calculated weight of each parameter is shown in Table 7. When original ranges are considered, the depth (WX – D) and hydraulic conductivity (WC – D) are overestimated, whereas the other parameters are subestimated.

Table 6

Effective weights, Wxi and Vxi, using the original range for water table depth.

Parameter	WX-**D**	WX-**R**	WX-**A**	WX-**S**	WX-**T**	WX-**I**	WX-**C**
Minimum Wxi (Vvxi)	0.26	7.44	8.99	4.57	1.29	7.79	1.19
Maximum Wxi (Vvxi)	32.93	34.34	32.14	22.99	14.83	38.25	23.06
Mean Wxi (Vvxi)	**6.90**	**18.56**	**17.17**	**14.08**	**6.51**	**27.10**	**9.68**
Standard deviation	4.94	5.55	3.37	2.68	2.14	4.48	4.66

Table 7

Comparison of the variability between the original weights and the calculated weights for each parameter, considering the original range for depth.

Original	WX-**D**	WX-**R**	WX-**A**	WX-**S**	WX-**T**	WX-**I**	WX-**C**
Assigned weight, Xwi	**5**	**4**	**3**	**2**	**1**	**5**	**3**
Assigned Xwi %	21.74	17. 39	13.04	8.7	4.35	21.74	13.04
Mean Calculated weigth Wxi	6.90	18.56	17.17	14.08	6.51	27.10	9.68
Calculated weight, Xwi	**1.6**	**4.3**	**3.9**	**3.2**	**1.5**	**6.2**	**2.2**

To increase the effective weight of depth, the regional distribution of the water table depth and its maximum value were used (Figure 5). The selection of a new weight was made by trial and error looking for a similar distribution of DRASTIC index of the water table depth. The frequency distribution of the DRASTIC index for each value was calculated.

The correlation between the water table depth and its respective vulnerability index X_{ri} is shown in Figure 5. The higher frequency distribution for the original rating is concentrated in the index 1. When the scale is 10 times the original rating, a better distribution is obtained reaching values of 5, 7, 9 y 10. Best results in the frequency distribution of the vulnerability index X_{ri} were obtained for a scale 5 times the original. The distribution for this adjustment is similar to the distribution of the water table depth in the Valley (Figure 5).

The most similar distribution was obtained rescaling the original assigned value W_D, 5 times. Values grater than 5 produced different frequency distribution to that of the water table depth (Figure 5).

The effective weights were recalculated using the proposed range scale and a better correlation between the ranges and the effective weights were found, 21.3 for depth and 22.9 for I (Table 8).

Using the rescaling ranges the greater variations correspond, as expected, to depth and impact to the vadose zone, 21.38 and 22.96 respectively (Table 9).

Table 9 shows the comparison of the variability between the original weights and the calculated weights for each parameter after the rescaling of the original range for depth. The calculated weights and the assigned weights were similar. The estimated weight for impact to the vadose zone is greater than the assigned weight. The parameter with lowest weight is topography. Hydraulic conductivity also shows low weight in the vulnerability.

Impact to the vadose zone and the depth shows the greater variability. The lower variability corresponds to topography and hydraulic conductivity.

The rescaling, five times the original scale, means that 152 m was the maximum depth with a rating of 1 (Table 10). This modification allowed the inclusion of water table depth in vulnerability assessments for deep aquifer systems.

The comparison between DRASTIC and AVI final maps (Figures 3 and 4) permitted a reconsideration of the permeability values used for vadose zone material in DRASTIC. A correlation between both indexes emphasizes the relevance of water table depth in a vulnerability evaluation (Figure 6). Lowest hydraulic resistance and transit times

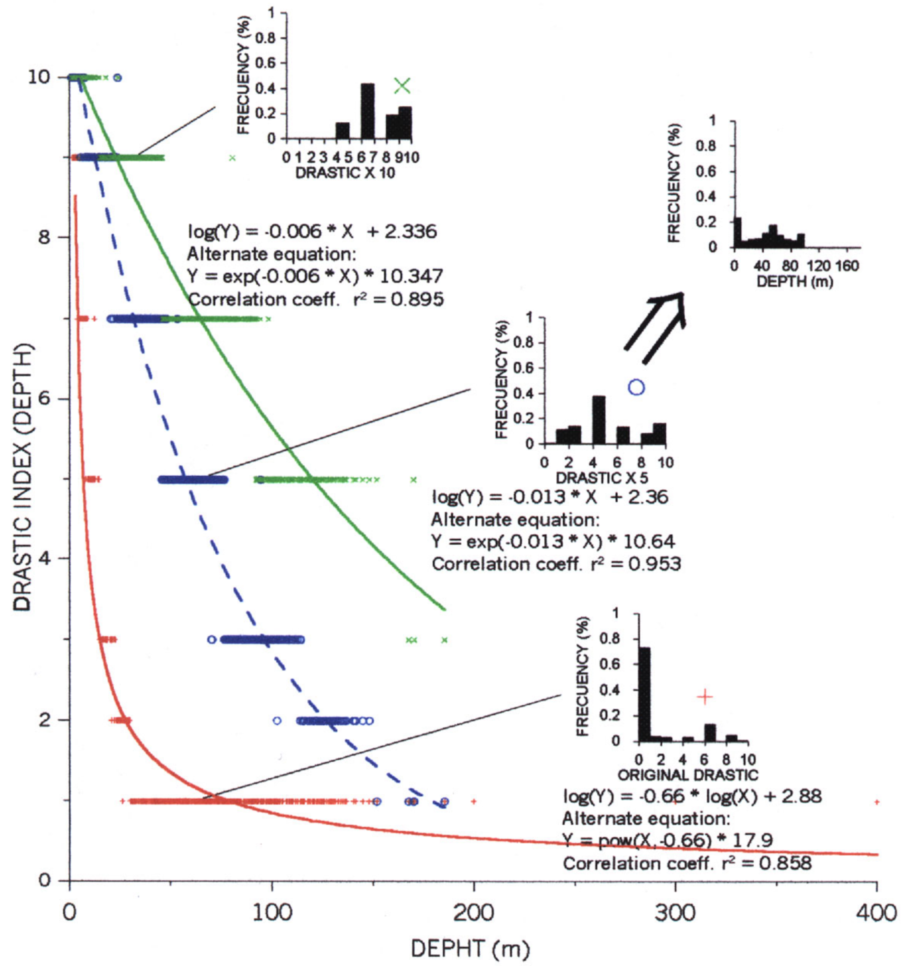

Fig. 5. Water table depth and DRASTIC index correlation with a frequency analysis of water table depth and DRASTIC index (original, 5x and 10x)

Table 8

Effective weights, considering the rescaling rating for water table depth.

Parameter	WXD	WXR	WXA	WXS	WXT	WXI	WXC
Minimum Wxi (Vxi)	4.74	6.80	7.33	3.59	1.01	5.83	0.97
Maximum Wxi (Vxi)	37.17	26.99	27.82	19.52	11.08	37.03	21.98
Mean Calculated Wxi (Vxi)	21.38	15.53	14.51	11.84	5.49	22.96	8.29
Standard deviation	4.90	4.09	2.89	2.01	1.74	4.26	4.22

Table 9

Comparison of variability between the original weights and the calculated weights after the rescaling of the original range for depth

Parameter	WXD	WXR	WXA	WXS	WXT	WXI	WXC
Assigned weight, Xwi	**5**	**4**	**3**	**2**	**1**	**5**	**3**
Assigned Xwi %	21.74	17.39	13.04	8.70	4.35	21.74	13.04
Mean Calculated weigth Wxi	21.38	15.53	14.51	11.84	5.49	22.96	8.29
Calculated weight, Xwi	**4.9**	**3.6**	**3.3**	**2.7**	**1.3**	**5.3**	**1.9**

Table 10

Original (Aller *et al*., 1985) and modified rating ranges for depth to water table.

Parameter	Depth to water table (m) (Original)	Depth to water table (m) (Modified)	Rating, ***Dr***
	0 - 1.5	0 - 7.5	10
Depth to	1.5 - 4.6	7.5 - 23	9
Water table	4.6 - 9.1	23 – 45.5	7
	9.1 - 15.2	45.5 - 76	5
	15.2 - 22.9	76 – 114.5	3
Dw = 5	22.9 - 30.5	114.5 – 152.5	2
	> 30.5	> 152.5	1

correspond with highest DRASTIC vulnerability indexes. The observed dispersion is mainly due to differences in data quality and availability; DRASTIC considered seven parameters and AVI only two (Figure 6). AVI uses punctual data (52 well information) and DRASTIC uses a more data density for each parameter. The information density is strong related to interpolation procedure impinging also in the observed dispersion.

VALIDATION TESTING

The vulnerability assessment furnished by DRASTIC was tested (Figure 3). The Turbio River was choosed as an active contamination source over one of the higher vulnerable areas. Chlorides and total dissolved solids (TDS) were selected as pollution indicators. Chemical analyses from 30 wells were considered. The Turbio River transports untreated urban and industrial wastewater from the cities of León and San Francisco del Rincón. Its water contains a high load of organic material. The tannery processes in León discharge about 80-ton/day of salt (Rodríguez *et al*. 1991). If the chosen area presents a high vulnerability, the aquifer must be polluted with contaminants coming from potential sources located over it, in this case the riverbed.

The observed high values of chorine and TDS correspond to some (Figures 7 and 8) high vulnerable areas

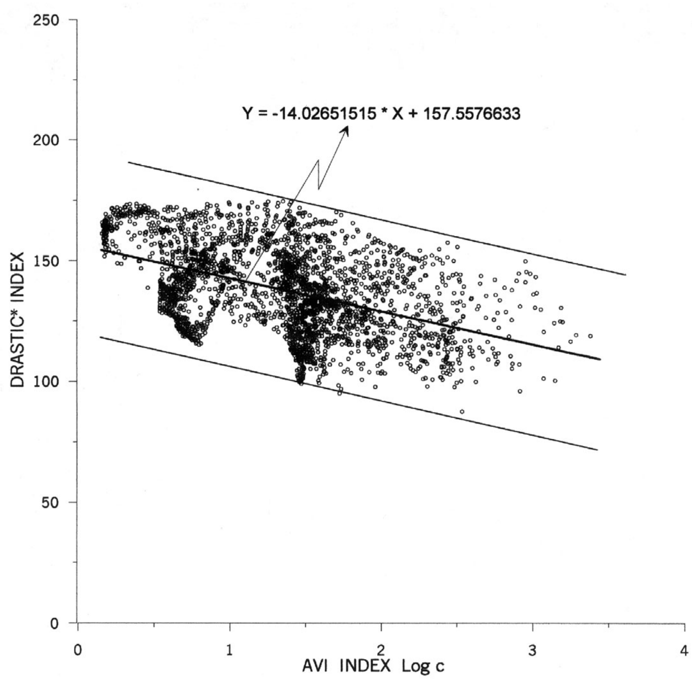

Fig. 6. DRASTIC and AVI indexes correlation.

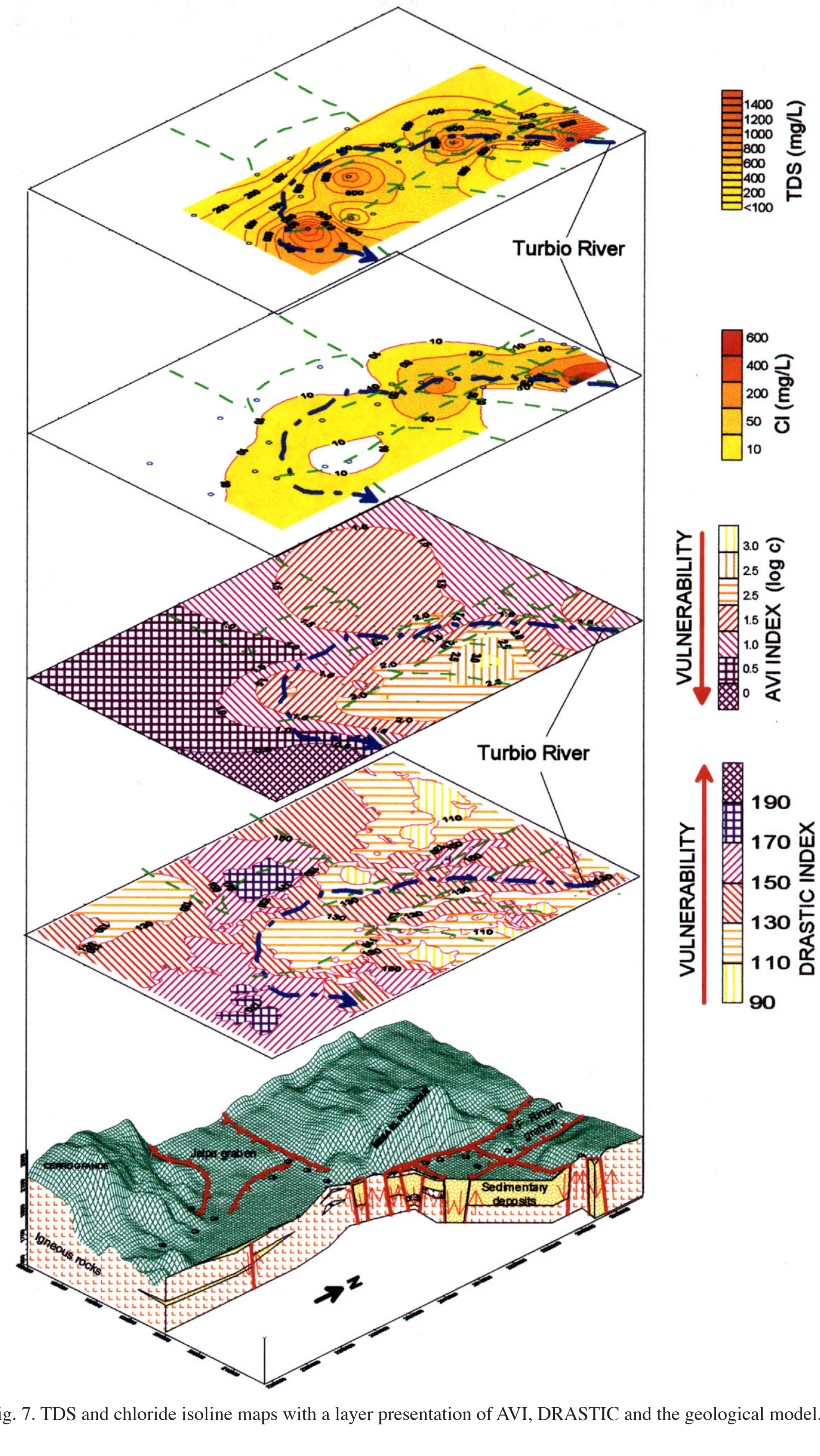

Fig. 7. TDS and chloride isoline maps with a layer presentation of AVI, DRASTIC and the geological model.

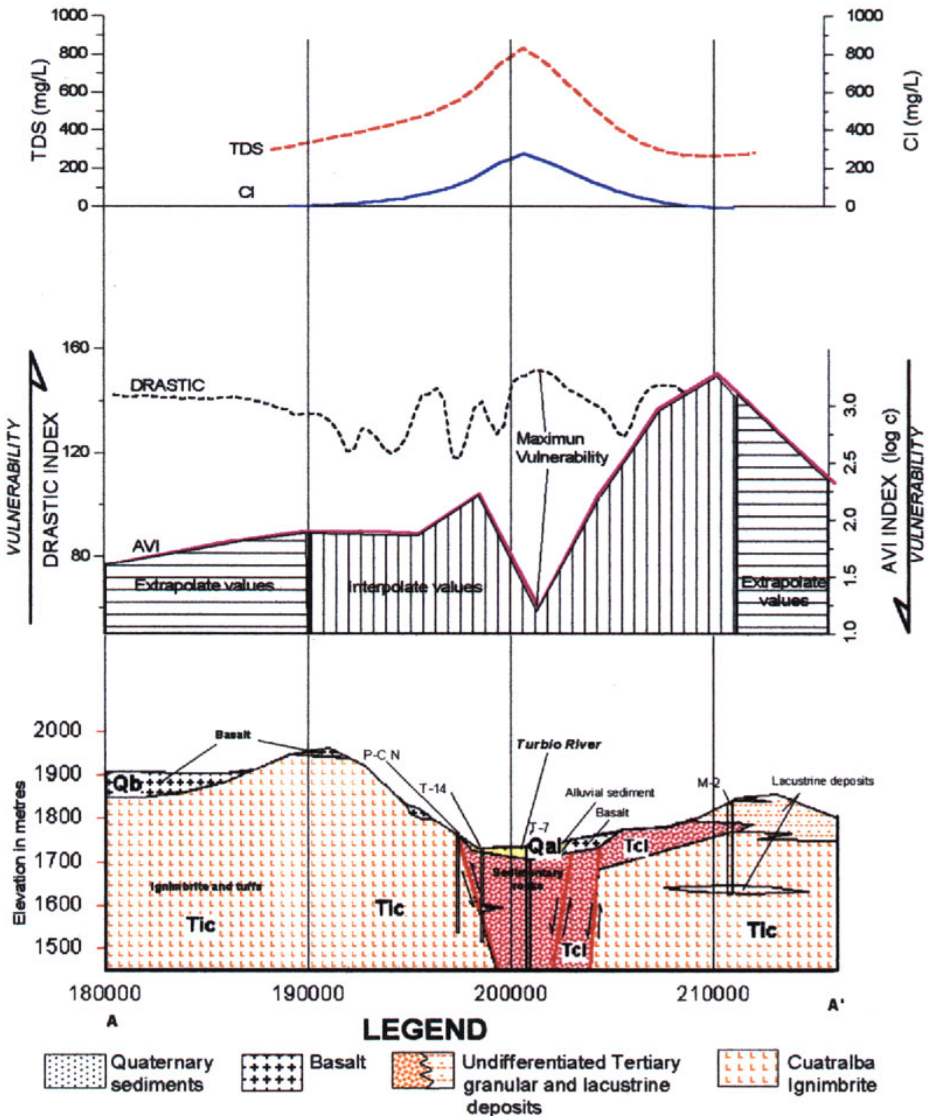

Fig. 8. Section A- A´ with chemical and vulnerability profiles.

defined by DRASTIC and AVI. Chemical data presented had a mean analytical error of 1 %.

To illustrate the validation test, a cross section A-A' (Figure 8) was analyzed. Its position was determined by the presence of wells with stratigraphic information and is shown in Figure 4. The section crosses the riverbed and a high vulnerability area. Maximum values of chloride and TDS correspond with the some highest DRASTIC and AVI vulnerability values.

Whereas DRASTIC covers the whole area, AVI is only supported by the 52 data wells. For this reason, the best correspondence between both maps occurs in the area covered by the 52 wells. In the AVI extrapolated areas, the correspondence is not so good.

RESULTS AND DISCUSSION

Aquifer vulnerability methods require validation schemes to reduce subjectivity in the selection of rating ranges and to increase reliability. The comparison between input parameters and rating parameter maps allowed the detection of anomalous tendencies and adjustments in input parameters or their rating range. The proposed validation alternatives for vulnerability mapping shown for the Turbio River Valley produced a less questionable aquifer vulnerability zoning. The AVI zoning was obtained only with 52 stratigraphic columns and piezometric data, whereas for DRASTIC the area, 1300 km^2, were covered also with the 52 stratigraphic columns, but additional geologic information was obtained from geoelectrical data. Locally, the geological homogeneity permitted the extrapolation of well data. The DRASTIC fitting for water table depth considered more than 150 m as the minimum rating to maintain a similar range division with the original scheme. DRASTIC incorporated meteorological, soil and topography data.

The data density and the difference in parameters used in both methods can explain the dispersion in the Figure 6. Both maps are showing different vulnerability approximations. In this case the DRASTIC map is more reliable because is incorporating a greater data density and seven parameters.

While some authors sustain (Konikov and Bredehoeft, 1992) that validation has no place in hydrology modeling, others (De Marsily *et al.,* 1992) support its verification and even its validation by statistical techniques (Flavelle, 1992). DRASTIC and AVI are not predictive models. Their objective is to represent the possibility of aquifer pollution by surface sources. Pollution can be verified with chemical data. If groundwater pollution corresponds to vulnerable areas, in some sense, the vulnerability mapping is validated. The simultaneous use of two vulnerability quantification methods, DRASTIC and AVI, allowed improvements in the vulnerability mapping, even though the methods are based on similar parameters, stratigraphy and water table depth.

The effective weight calculation allowed the detection of parameters that require modification. If specific local conditions fall out of the original ranges, as was the case for water table depth, a justified rescaling could be realized. SINTACS (Civita and De Maio, 1997) is in fact a rating DRASTIC modification. Civita and De Maio use a rating for water table depth, three times the original DRASTIC rating.

Regionally, good groundwater quality was reported in the volcanic media (SAPAL, 2001), whereas in the shallow aquifer systems a wide variation in mineralization was observed due to the influence of irrigation. The regional background concentrations of chloride varied from 20 to 50 mg/l (Rodríguez *et al*., 1992; BGS, 1996). Distribution of chloride and TDS are shown in Figure 7. The differences in concentrations could be explained in terms of the chlorine high solubility and its nonreactivity. Chlorine arrives to groundwater whereas the TDS could be retaining in the vadose zone. The Turbio River water is extensively used for irrigation to the north of the river. Toward the south along the river, water quality improves (lower chloride content). After Silva Dam, in the center of the Valley, the river receives untreated urban wastewaters coming mainly from small settlements. The TDS gradient has the maximum values at this point along the riverbed.

The vulnerability of the area of section A-A' (Figure 8) can be related to the granular media and the local fault system. Both factors facilitate the migration of contaminants from surface to water table. To the west (A) the AVI index is lower than the side east (A') due to the presence of lacustrine deposits to A' side. The observed differences between AVI and DRASTIC in this profile is mainly due to the data density (DRASTIC > AVI) as was previously discussed in Figure 6. The data density could also explain the apparently oscillations in the DRASTIC index. But in both cases the maxims in vulnerability correspond with the riverbed and the higher solute concentrations, Cl and TDS.

Some potential sources of aquifer pollution are located in the valley: diffuse sources such as the industrial zone SFR-Leon and irrigated lands, linear sources such as the Turbio River and point sources such as gas stations, cemeteries and industrial waste landfills. Most of these are located over the more vulnerable areas. Groundwater is the most important water supply source in the valley. The maps discussed here are being incorporated in urban planning. Regional water authorities are taking them into account in their water management programs.

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BIBLIOGRAPHY

ALLER, L., T. BENNET, J. H. LEHR, R. J. PETTY and G. HACKETT, 1985. DRASTIC; A Standard System for Evaluation Groundwater Pollution using Hydrogeologic Setting, EPA/600/2-85/018 US EPA.

ARIEL CONSTRUCCIONES, 1969. Estudio geohidrológico formal en la zona del Valle de León y Río Turbio. (Hydrogeologic study of the Leon Valley and Turbio river) SARH Technical Report, Mexico

ARIEL CONSTRUCCIONES, 1982. Estudio Geohidrológico Cuantitativo de la Cuenca del Río Turbio. (Quantitative hydrogeologic study of the Turbio river Basin) SARH Technical Report, Mexico.

BGS, 1996. Effects of wastewater reuse on urban groundwater resources of Leon, Mexico BGS CNA, SAPAL Technical Report WD/95/64

CIVITA, M., A. CHIAPPONE, M. FALCO and P. JARRE, 1990. Preparazione della carta di vulnerabilita per la rilocalizzazione di un impianto pozzi dell´acquedutto di Torino. Proc. Ist. Conv. Naz. Protezione e Gestione del-le acque sotterane: Metodologie, Tecnologie e Obietti-vi. *Morano sol Panero*, 2, 461-462.

CIVITA, M. and DE MAIO, 1997. SINTACS. Un Sistema Parametrico per la Valutazione e la Cartografia della Vulnerabilitá Degli Acquiferi All'inquinamento. Metodologia & Automatizzazione. Pitagora Editrice Bologna. pp 191.

DE MARSILY, G., P. COMBES and P. GOBLET, 1992. Comment on "Ground Water models cannot be validated" by Konikow L. And Bredehoeft. *J. Adv. Wat. Res., 15,* 367-369.

FLAVELLE, P., 1992. A quantitative measure of model validation and its poptential use for regulatory purposes. *Adv. Wat. Res., 15*, 5-13.

GEOPSA, 1998. Complementación y calibración del modelo matemático del Valle del Río Turbio. (Calibration of the Turbio river Valley mathematical modeling). CEASG Preliminary Report. Mexico

GOGU, R. C. and A. DASARGUES, 2000. Sensivitivity analysis for the EPIK method of vulnerability assessment in a small karstic aquifer, southern Belgium. *Hydrogeol. J.,* 8, 3 337-345.

GUSTAFSON, D. I., 1989. Groundwater Ubiquity Score: A simple method for assessing pesticide leachability. *Environmental Toxicology and Chemistry 8,* 337-357.

CEASG (Ingeniería Geológica Computarizada), 1995. Resultados de los análisis físico-químicos y bacteriológicos realizados dentro del Valle del Río Turbio. (Results of the chemical and bacteriological analysis of the Turbio river Valley). *CEASG Technical Report*.

INEGI, 1973a, Cartas edafológica, escala 1:50 000, F14-C41, F14-C51.

INEGI, 1973b, Cartas topográficas, escala 1:50 000, F14-C41, F14-C51.

KONIKOW, L. and J. BREDEHOEFT, 1992. Ground Water models cannot be validated. *Advances in Water Resources*, *15*, 75-83.

LODWIK, W. A., W. MONSON and L. SVOBODA, 1990. Attribute error and sensitivity analysis of maps operation in geographical information systems – suitability analysis. *Int. Jour. Geog. Info. Syst*. 4 413-428.

NAPOLITANO, P. and A. G. FABBRI, 1996. Single parameter sensibility analysis for aquifer vulnerability assessment using DRASTIC and SINTACS in Kova K. And Nachtnebel H. P. (eds) Proc. HydrolGis Application of Geographic Information Systems in Hydrology and Water Resources Management. IAHS Publ. 235, 559-566.

QUINTERO, O., 1986. Geología de los alrededores de Comalja de Corona, Edo. de Jalisco. (Geology of the Comalja de Corona surroundings, Jalisco) Proceedings Primer Simposio de Geología regional de México. IG-UNAM. pp. 6-25.

RAMOS, L., J. A., 2002. Validación de mapas de vulnerabilidad acuífera e impacto ambiental: Caso Río Turbio, Guanajuato. Tesis de Doctorado en Ciencias, DGEP-UNAM, 106 pp.

RAMOS, L., J. A. and C. R. RODRÍGUEZ, 1998. Análisis de la vulnerabilidad del sistema acuífero del Valle del Río Turbio, estado de Guanajuato. (Vulnerability analysis of the Turbio river Valley aquifer system, Guanajuato) Proceedings, 4º Latinoamerican Congress of Ground Water, *ALSHUD*, Montevideo Uruguay. Pp. 682-699.

RODRÍGUEZ, R., M. A. ARMIENTA, S. VILLANUEVA, P. DIAZ and T. GONZÁLEZ, 1991. Estudio Hidrogeoquímico y Modelación Matemática del Acuífero del Río Turbio para definir las acciones encaminadas a proteger de contaminantes la fuente de abastecimiento de la Cd. de León, Gto. (Hydrogeochemical study and mathematical modeling of the Turbio River aquifer) Technical Report il 140 pp. IGF-UNAM, CNA-SARH. Mexico.

RODRÍGUEZ, R., M. FIGUEROA, A. RAMOS, A. BÁEZ, R. QUIROZ, L. CISNEROS and R. SÁNCHEZ, 2000. Estructuración de mapas temáticos de índices de vulnerabilidad de las subcuencas de los ríos Turbio y Guanajuato. (Elaboration of vulnerability index maps for the Turbio and Guanajuato rivers Sub-basins) Technical Report 150 pp. *UIA CEASG*. Mexico

ROSE, L., 1993. A study of the DRASTIC methodology with emphasis on Swedish conditions. *Ground Water,* 32, 2.

SAPAL-IGEOF, 2001, Estudio Isotópico e Hidrogeoquímico de La Zona León-Río Turbio, Guanajuato. Reporte Técnico, Instituto de Geofisica-UNAM, 78 pp.

TURC, L., 1955. Le bilan d´eau des sols. Relations entre les précipitations, l´évaporation et l´écoulement. *Ann. Agro*. 5-131.

VAN STEMPVOORT, D., L. EWERT and L. WASSENAAR, 1992. AVI: A method for Groundwater Protection mapping in the Praire Province of Canada. PPWB Report No. 114. National Hydrology Research Institute, Saskatoon Saskatchewan, Canada.

VRBA, J. and A. ZAPOROZEC, 1994. Guidebook on Mapping Groundwater Vulnerability. International Association of Hydrogeologists. Vol. 16, 131 pp.

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